NETL ANNUAL ACCOMPLISHMENTS 2022

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

MESSAGE *FROM THE DIRECTOR*

For more than 100 years, NETL has advanced the development of innovative technologies to ensure affordable, abundant, and reliable energy that drives a robust economy and national security. Today, our talented researchers and project partners from across the nation are advancing cutting-edge technologies to manage carbon across the full life cycle and enable environmental sustainability for all Americans. These efforts are making significant strides toward clean energy goals calling for a net-zero carbon emission electricity sector by 2035 and economy-wide net-zero emissions by 2050.

Leveraging the power of workforce inclusivity and diversity, highly skilled innovators at NETL's research laboratories in Albany, Oregon; Morgantown, West Virginia; and Pittsburgh, Pennsylvania, conduct a broad range of research activities that support the DOE's mission to ensure America's security and prosperity by addressing its energy and environmental challenges through transformative science and technology solutions. Our work is driving innovation and delivering solutions that have an impact on the region, nation, and world.

I am pleased to present the ***National Energy Technology Laboratory's (NETL) FY 2022 Annual Accomplishments***. These accomplishments demonstrate the impressive impact made possible through research aligned with the Department of Energy's Office of Fossil Energy and Carbon Management's seven Research, Development, Demonstration, and Deployment (RDD&D) priorities:

- Hydrogen with Carbon Management
- Point-Source Carbon Capture
- Carbon Dioxide Conversion
- Carbon Dioxide Removal
- Reliable Carbon Storage and Transport
- Domestic Critical Minerals Production
- Methane Mitigation

The Lab's research portfolio supports critical domestic energy initiatives that touch the lives of virtually all Americans. Our innovations support and inform energy strategies that can turn the threat of climate change into an opportunity to revitalize the U.S. energy and manufacturing sectors while creating good-paying jobs, spurring economic revitalization, advancing environmental justice, remediating environmental degradation, and supporting energy workers in communities across the country.

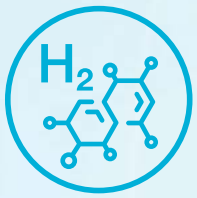
The innovations and discoveries from our Lab today are building a foundation for new industries with new jobs and informing energy policies that stimulate our economy, ensure our security, and protect our health. This critical work is forging a bright future for many generations by enhancing America's energy independence while decarbonizing our nation.

Sincerely,

Brian J. Anderson, Ph.D., Director
National Energy Technology Laboratory

Department of Energy's Office of Fossil Energy and Carbon Management (FECM)
Research, Development, Demonstration, and Deployment (RDD&D)

FECM RDD&D PRIORITIES



HYDROGEN WITH CARBON MANAGEMENT

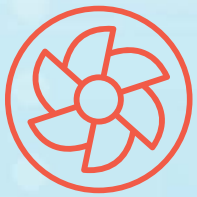
FECM will invest in RDD&D for hydrogen production coupled with carbon capture and storage using sustainably sourced carbon-based feedstocks (e.g., biomass, fossil fuels and plastics, including wastes). FECM will invest in the advancement and utility-scale demonstration of hydrogen supply and utilization technologies such as hydrogen storage, reversible solid oxide fuel cells and 100% hydrogen- fired turbines, supporting DOE's Hydrogen Shot target.

POINT-SOURCE CARBON CAPTURE

FECM will invest in RDD&D to reduce the cost, increase the efficacy, and advance the deployment of commercial-scale Point-Source Capture technologies in the power and industrial sectors, coupled to permanent storage.

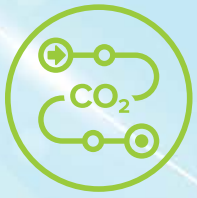
CARBON DIOXIDE CONVERSION

FECM will accelerate capabilities for large-scale conversion of CO_2 into products that advance net-zero and justice goals, facilitated by markets for CO_2 as a feedstock. FECM will help accelerate the path to a net-zero refinery, advance mineral carbonation approaches, and expand the availability of synthetic fuels.



CARBON DIOXIDE REMOVAL

FECM will invest in a diverse set of Carbon Dioxide Removal (CDR) approaches to support DOE's Carbon Negative Shot of just, sustainable, and scalable CDR at costs below $100/net metric ton of CO_2-equivalent (CO_2e). This full suite of CDR approaches will help address emissions from extremely hard-to-decarbonize sectors and eventually address legacy emissions. Near-term focus areas include advancing Direct Air Capture coupled to durable storage and creating a framework for developing the full portfolio of CDR methods.



RELIABLE CARBON STORAGE AND TRANSPORT

FECM will establish the foundation for a successful carbon transport and storage industry, supporting the transition from carbon production to storage by making advancements in storage technologies and transport mechanisms, providing technical assistance in Class VI well permitting, and supporting large-scale transport and storage facilities and regional hubs.

DOMESTIC CRITICAL MINERALS PRODUCTION

FECM will help grow an environmentally and economically sustainable, secure, diverse, and resilient domestic critical minerals and carbon ore resource recovery industry, especially coupled to remediation of legacy wastes. FECM will support demonstrations for extraction and remediation to processing and refining for building a strong critical minerals supply chain while creating good-paying jobs.

METHANE MITIGATION

FECM will invest in minimizing the environmental impacts associated with the extraction of fossil energy sources produced in the United States, including coal, oil and natural gas, with a specific focus on methane mitigation. FECM plans to advance cost-effective technology to efficiently identify, quantify, and predict methane leaks across sectors more efficiently and improve the accessibility and reliability of methane emissions data.

TABLE OF CONTENTS

*Green represents accomplishments performed under **NETL's Research and Innovation Center(RIC)**.*
*Blue represents accomplishments performed under **extramural projects**.*

FECM RDD&D PRIORITIES:

HYDROGEN WITH CARBON MANAGEMENT · POINT-SOURCE CARBON CAPTURE · CARBON DIOXIDE CONVERSION · CARBON DIOXIDE REMOVAL · RELIABLE CARBON STORAGE AND TRANSPORT · DOMESTIC CRITICAL MINERALS PRODUCTION · METHANE MITIGATION

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OTHER ACCOMPLISHMENTS:

*Green represents accomplishments performed under **NETL's Research and Innovation Center(RIC)**.*
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FECM RDD&D PRIORITIES:

HYDROGEN WITH CARBON MANAGEMENT | POINT-SOURCE CARBON CAPTURE | CARBON DIOXIDE CONVERSION | CARBON DIOXIDE REMOVAL | RELIABLE CARBON STORAGE AND TRANSPORT | DOMESTIC CRITICAL MINERALS PRODUCTION | METHANE MITIGATION

FOUR BLUEGEN SOLID OXIDE FUEL CELL (SOFC) STACKS BEGIN POWER PRODUCTION

Fuel cells are now supplying power to the NETL Morgantown site grid.

FUEL CELL PROJECT BY NETL RESEARCHERS AND ARIS RENEWABLE ENERGY IS PRODUCING 5.6 KW OF POWER

Four 1.5 kW BlueGEN solid oxide fuel cell (SOFC) stacks installed at NETL Morgantown were successfully brought online and are now **supplying 5.6 kW of power to the Morgantown site grid**.

Four Aris SOFC stacks in the test stand at Morgantown.

The stacks, manufactured by the European company SOLIDPower, were purchased by NETL as part of a **collaborative SOFC Program project** with Aris Renewable Energy aimed at demonstrating fuel cell resiliency and applications in small-scale commercial markets. Aris Renewable Energy is the American distributor for SOLIDPower.

The operation of the four 1.5 kW BlueGEN stacks under dynamic loading conditions at NETL Morgantown represents the first stage in the multi-year collaborative project.

Jay Liu monitoring Aris SOFC stacks.

LARGER DEPLOYMENTS TO FOLLOW

The knowledge gained from the stack tests at NETL Morgantown is **setting the stage for more and larger deployments** by addressing the potential scalability of these SOFC stacks. At least **27 kW** at a NASA facility in Fairmont, WV, along with up to **6 kW of additional capacity** installed in Morgantown, will be deployed later in the three-year project.

Aris SOFC stacks performance monitoring.

PARTNER

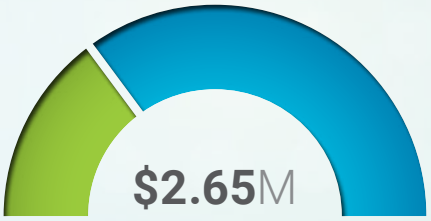
ARIS RENEWABLE ENERGY

AWARD NUMBER

FWP-1022474

PROJECT BUDGET

FY22 FUNDING



DOE $800,000
PARTNER $1,850,000

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FECM RDD&D PRIORITY

H_2 HYDROGEN WITH CARBON MANAGEMENT

CLICK HERE FOR MORE INFORMATION

NETL'S UNIQUE LASER DIAGNOSTIC CAPABILITY ENHANCES COMBUSTION CHARACTERIZATION

This specialized characterization tool developed by NETL researchers can analyze various chemical species across a broad range of applicable combustion conditions.

NOVEL CAPABILITY OVERCOMES CURRENT CHALLENGES

Advanced Instrumentation Meets Critical Research Needs

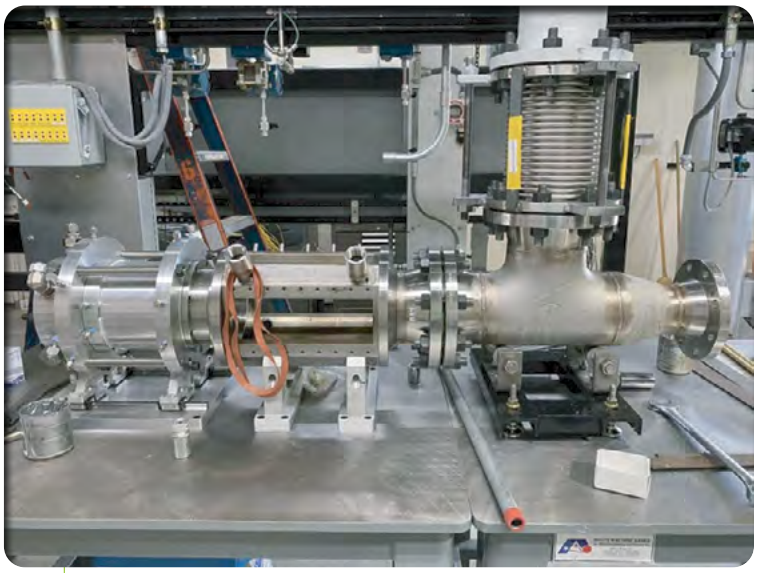
Identifying absorption features to enable effective high-speed temperature and pressure sensing has been a challenging aspect of tunable diode laser absorption spectroscopy, or TDLAS.

Improved accuracy in measurements of chemical species (including both fuel and by-products) in real-time during combustion is critical for assessing novel combustion technologies and developing more efficient combustion processes.

A new capability will **characterize absorption spectra for various gas species at relevant temperatures and pressures**, leading to novel sensing strategies in practical environments.

The combustion of a blend of a stoichiometric 50/50 mix of hydrogen/ammonia.

Recently Completed NETL Project Enables State-of-the-Art Characterization



Rotating detonation engine at NETL-Morgantown.

The Fundamental Combustion Laboratory at NETL-Pittsburgh completed construction on its Inconel gas cell for combustion characterization. Incorporating two 9-inch sapphire rod windows at either end allows the laser beam to pass through a hot, high-pressure gas mixture, while the window end seals can be located far from the heated zone.

NETL researchers will leverage this capability to **develop a NO/NO_2 sensing strategy for the NETL-Morgantown rotating detonation engine** to better manage emissions of pollutants formed during combustion.

This new experimental capability may be implemented more broadly, as its improvements can be applied to characterization efforts in various combustion research projects that operate under extreme environmental conditions.

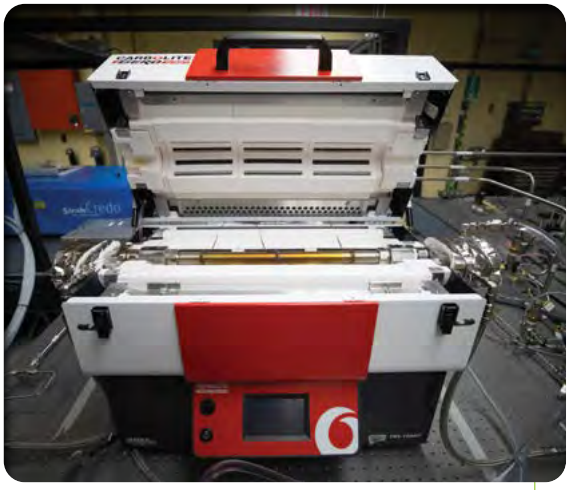
ENHANCED ANALYTICAL CAPABILITY

Operation Over a Broad Range of Relevant Conditions

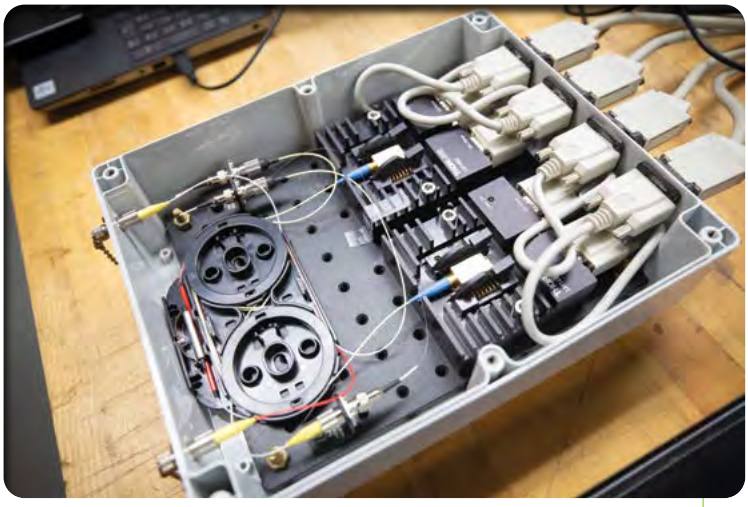
The system can utilize inert gas mixtures including methane, hydrogen, carbon monoxide, ammonia, nitrogen oxides, CO_2, and H_2O in a nitrogen bath gas.

The equipment operates at up to 440 PSIG and greater than 900 °C due to its water-cooled end caps protecting the seals of the sapphire rod windows.

The current TDLAS system includes two laser diodes targeting water vapor absorption. The lasers are combined into a single beam using a fiber multiplexer before being split into two outputs.



Inconel gas cell in a tube furnace enables high-temperature and high-pressure conditions to be replicated.



This equipment housing relays laser signals for specialized measurements.

One output is used to characterize the laser wavelength over time, while the other is directed to the gas of interest.

By modulating the laser current, the wavelength can be rapidly varied, enabling high-speed scanning across a given absorption feature to derive species concentration, temperature, and/or pressure.

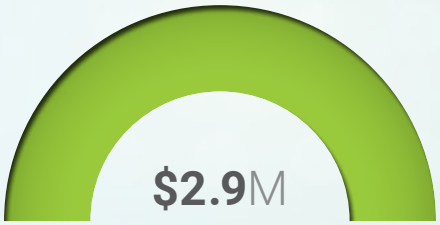
A second instrument — a Fourier-Transform-Infrared spectrometer — is also used in conjunction with the gas cell to generate high-resolution infrared spectra, enabling researchers to generate spectral data for new species of interest, as well as to inform the selection of new laser diodes.

AWARD NUMBER

FWP-1022408

PROJECT BUDGET

EY22 FUNDING



DOE $2,900,000

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FECM RDD&D PRIORITY

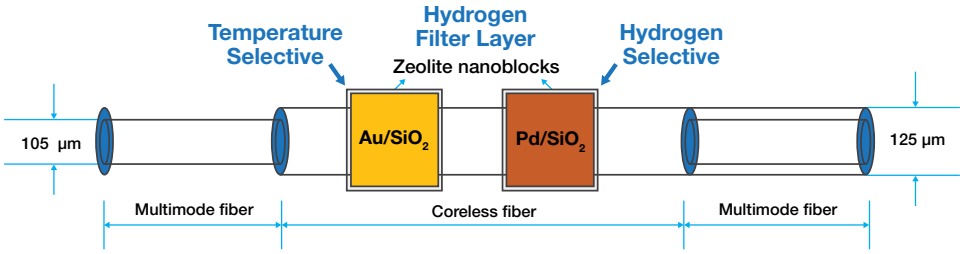
HYDROGEN WITH CARBON MANAGEMENT

PATENTED NETL SENSOR TECHNOLOGY SUPPORTS A SAFE HYDROGEN ECONOMY

NETL researchers were awarded a patent for an optical fiber sensor with multiple sensing layers for simultaneous hydrogen/gas and temperature sensing.

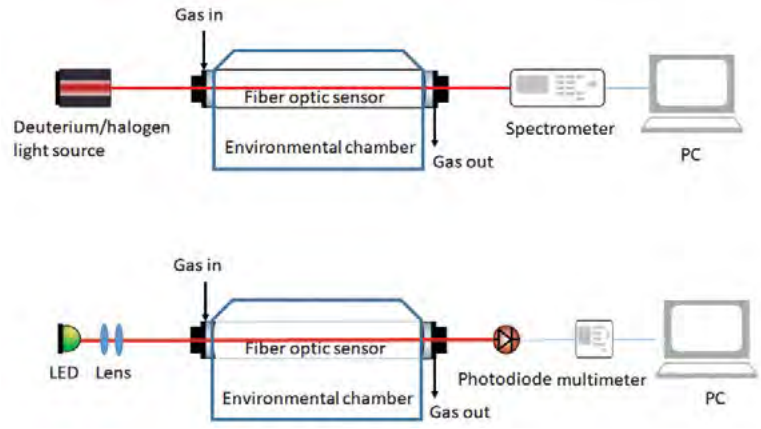
HYDROGEN GAS LEAK DETECTION

NETL's Patented Optical Fiber Sensor Technology

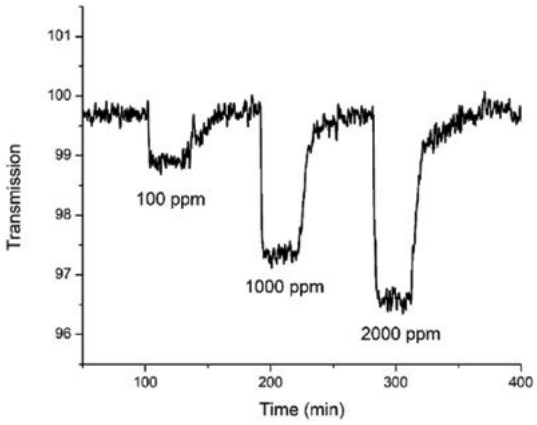


Schematic diagram of the sensor structure.

In March 2022, NETL researchers were awarded a patent for their optical fiber sensor that is functionalized with multiple sensing layers along a single fiber for simultaneous hydrogen/gas and temperature sensing. The patented technology, titled "**Low-cost Fiber Optic Sensor Array for Simultaneous Detection of Multiple Parameters**," enables hydrogen monitoring at the parts per million (ppm) level. Originally developed for transformer oil monitoring in support of the Grid Modernization Lab Consortium, this technology can be applied to hydrogen gas leak detection for hydrogen production, transportation, and storage.



Schematic diagram of the experimental setup.
Top: Conventional System; Bottom: Low-cost Prototype Device.

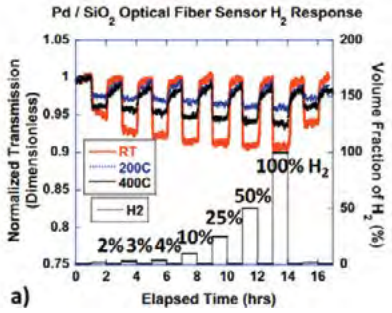


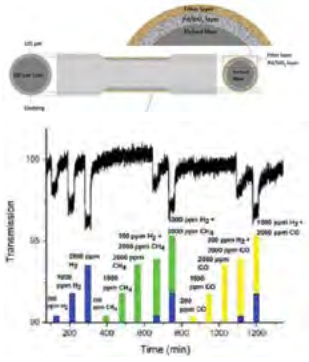
Hydrogen sensing responses and sensitivity at ppm level.

NETL researchers have discovered a system and method for a low-cost optical fiber sensor array that monitors multiple parameters using multi-wavelength interrogation combined with multiple sensor elements along a single optical fiber. The sensor array includes an optical fiber and nanocomposite thin films along portions of the optical fiber for interrogating parameters with different wavelengths. The NETL technology, using multiplexing capabilities of fiber optic sensors, enables monitoring of multiple sensing points with a single interrogation unit, saving money and time.

NETL HAS YEARS OF EXPERTISE IN HYDROGEN SENSOR TECHNOLOGIES

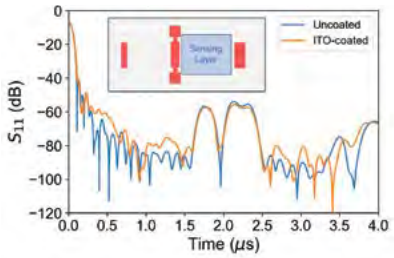
Fiber Optic-based Hydrogen Sensors

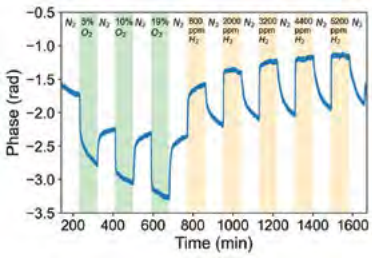




- Pd Nanoparticle Incorporated SiO_2 Thin Film-coated Optical Fiber Sensor was developed to monitor hydrogen from room temperature to 400 °C.
- Selective hydrogen sensing was achieved via a nano-filter layer.
- Issued Patent: "Palladium and Platinum-based Nanoparticle Functional Sensor Layers and Integration with Engineered Filter Layers for Selective H_2 Sensing" U.S. Patent No: US10,345,279; Issued: 07/09/2019.

Surface Acoustic Wave (SAW)-Based Hydrogen Sensors



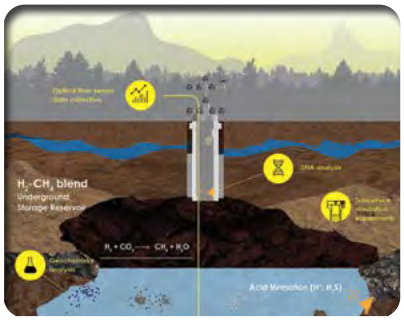


- Conducting oxide-coated SAW sensors have demonstrated hydrogen sensing at high temperatures.
- Developed in support of Advanced Sensors and Control Field Work Proposal (FWP).
- Issued Patent: "Conducting metal oxides integrated with the surface acoustic wave (SAW) sensor platform" U.S. Patent No: US10976287; Issued: 04/13/2021.

ENABLING A SAFE HYDROGEN ECONOMY

SHASTA
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

In support of the *Subsurface Hydrogen Assessment, Storage, and Technology Acceleration (SHASTA) Project*, in-situ optical fiber sensors are used for real-time monitoring of hydrogen, methane, and chemical parameters at subsurface hydrogen storage conditions. These advanced sensors will determine microbiological hydrogen consumption and geochemical pH change and identify well integrity risks.



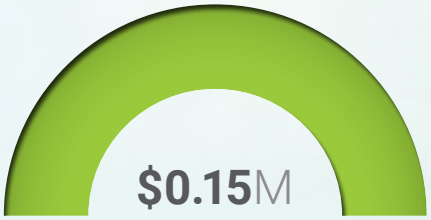
Other Related Projects

- Grid Modernization Lab Consortium.
- Advanced Sensors and Control FWP.
- Natural Gas Decarbonization and Hydrogen Technology FWP.
- H_2@Scale Cooperative Research and Development Agreement.

AWARD NUMBER
FWP-1022478

PROJECT BUDGET

EY22 FUNDING
SHASTA FWP, Task: Sensor Technology Development



DOE $150,000

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FECM RDD&D PRIORITY

HYDROGEN WITH CARBON MANAGEMENT

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SOLID OXIDE FUEL CELL (SOFC) WHITE PAPER BY NETL RESEARCHERS HIGHLIGHTS AI-BASED COMPUTER VISION TECHNIQUES IN MATERIAL SCIENCE

Innovation that facilitates commercial acceptance of SOFC technology.

NETL SHOWS HOW EMERGING COMPUTER VISION CONCEPT CAN BENEFIT MATERIALS SCIENCE

An NETL white paper highlights the substantial opportunities for using artificial intelligence (AI)-based computer vision techniques for **enhanced microstructural analysis of electrochemical cell electrodes**.

The paper posits **that computer vision using AI is a rapidly expanding field, ripe for application in materials science** even though the two fields have so far had little overlap.

Dr. Epting giving a presentation on electrode microstructure.

SELECTED FOR DEPARTMENT OF ENERGY'S AI@DOE ROUNDTABLE

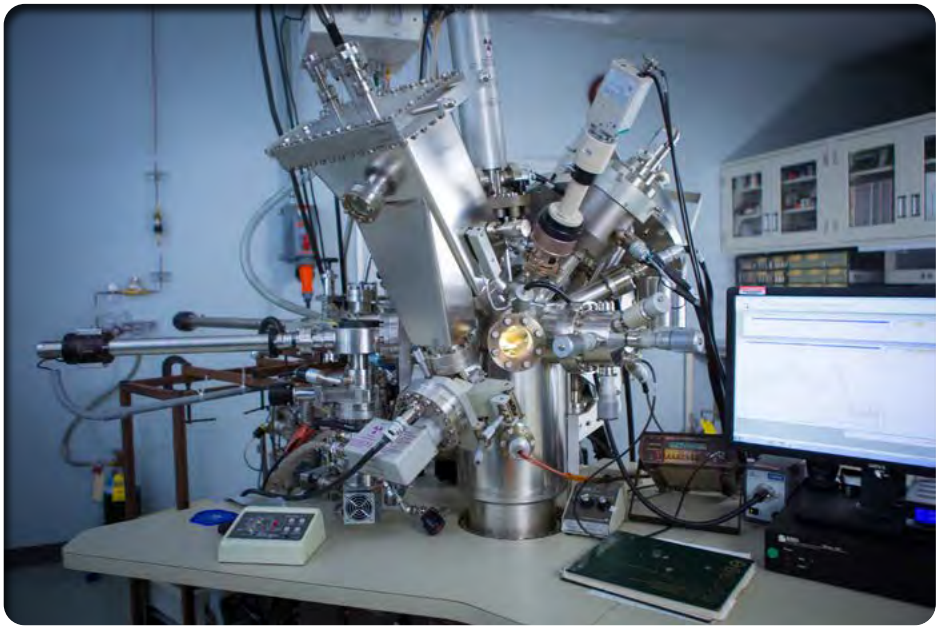
The Department of Energy's (DOE) **AI@DOE Roundtable committee selected the NETL white paper** by Dr. William Epting and co-authors Thomas Kalapos, Gregory Hackett, and Harry Abernathy entitled "Computer Vision for 3D Microstructures in Composite Electrochemical Electrodes" for an oral presentation at the invitation-only event held in December 2021.

Dr. Epting's white paper was one of 15 selected out of 170 submitted from across the DOE and the only white paper selected from NETL.

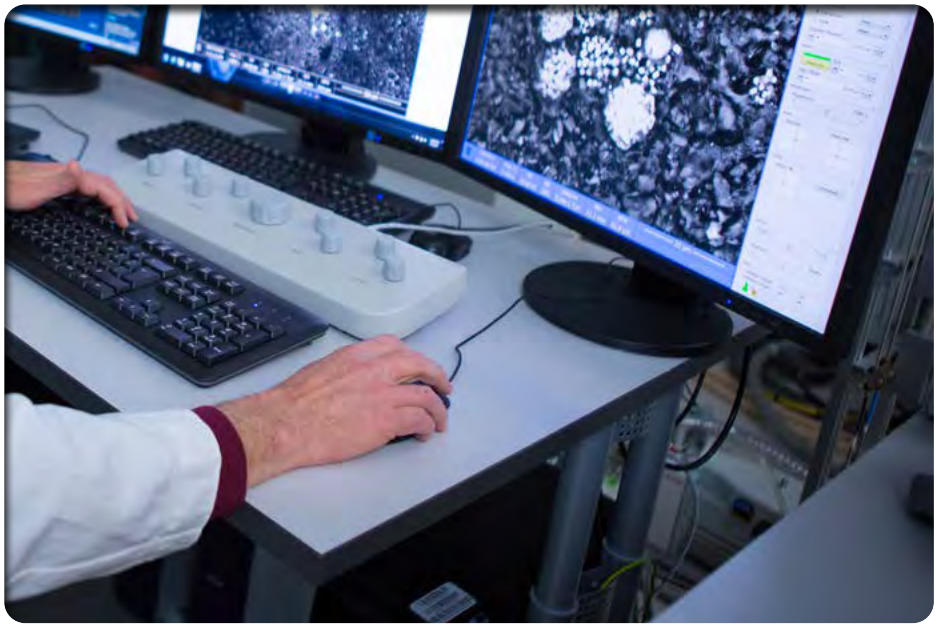
AI AND MACHINE LEARNING (ML) SHOW POTENTIAL TO ENHANCE ENERGY RESEARCH

Dr. Epting also made significant contributions to more general discussions at the roundtable event regarding DOE-wide ways in **which AI and ML could enhance energy research**.

For example, using AI and ML to characterize, analyze, and design better solid oxide fuel cells and solid oxide electrolysis cells is a **growing effort** within NETL.



NETL Materials Preparation Lab - Pittsburgh



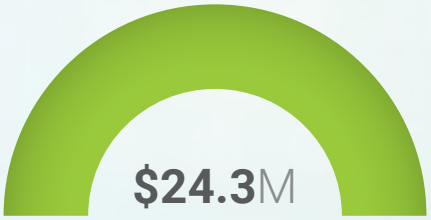
NETL-Pittsburgh Materials Lab

AWARD NUMBER

FWP-1022411

PROJECT BUDGET

TOTAL FWP FY22 FUNDING



DOE $24,348,183

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FECM RDD&D PRIORITY

HYDROGEN WITH CARBON MANAGEMENT

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CONSTRUCTION AT CONCRETE THERMAL ENERGY STORAGE PILOT TEST SITE

Concrete thermal energy storage can be integrated with any thermal power plant.

10 MWH-E PILOT PLANT AT PLANT GASTON COMPLETE

Electric Power Research Institute (EPRI) achieved mechanical completion of its concrete thermal energy storage system (CTES) located at Alabama Power's Plant Gaston in Wilsonville, AL, and the unit is ready for hot commissioning.

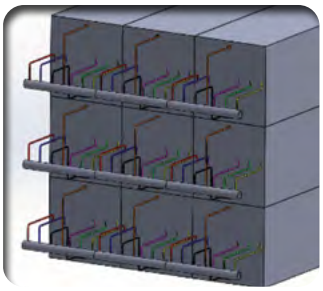
This is the largest CTES system ever constructed, and lessons learned from construction and operation will assist in evaluating the technical and economic feasibility of the technology at commercial scale.

Finalized, assembled CTES stack at Plant Gaston.

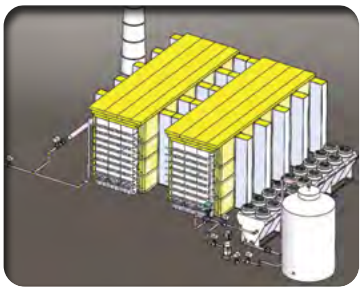
CTES HAS MANY ADVANTAGES

- **CTES provides a low-cost thermal energy storage system.**
- Concrete is a low-cost thermal medium, can easily be cast into any shape, and is highly durable.
- Concrete monoliths with embedded steam tubes allow for efficient conductive heat transfer, have no moving parts, and are modular, transportable, stackable, and scalable.

3-block, flue gas-heated testing modules.



Stackable and scalable.



10 MWh-e scale pilot concept.

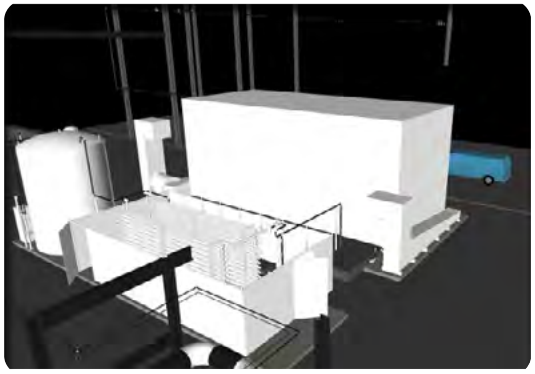
CTES MODULAR DESIGN DETAILS

10 megawatt-hours-electric (MWh-e) scale

[>30 megawatt-hours-thermal (MWh-th)]

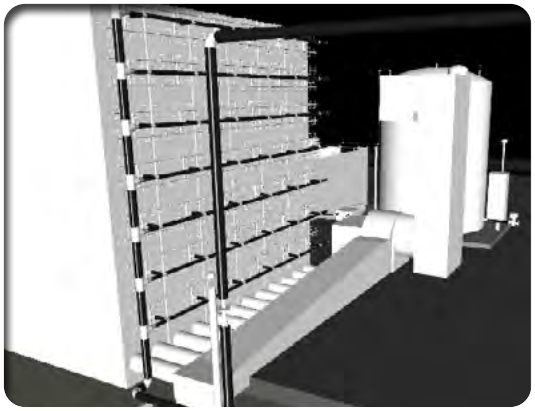
Modular Blocks

- 0.24 MWh-e each.
- Total of 42 blocks.
- 7 cubic meters, 20 tonnes.
- 30"x 36"x 41' (suitable for road/rail transport).



Thermal Energy Storage Assembly

- Arrangement: 7 modules high, 6 modules wide.
- Insulated: Cladding is like that of a heat recovery steam generator.
- Overall size 20' height, 22' width, 42' length.



THERMAL ENERGY STORAGE CONTRIBUTES TO ENERGY STORAGE GOALS

The Department of Energy's Energy Storage Grand Challenge is a comprehensive program to accelerate the development, commercialization, and utilization of next-generation energy storage technologies and sustain American global leadership in energy storage while achieving national net zero-emission goals.

Thermal energy storage technologies such as CTES play a critical role as part of a comprehensive set of solutions guided by an aggressive goal: to develop and domestically manufacture energy storage technologies that can meet all U.S. market demands by 2030.

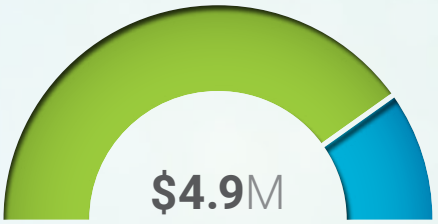
PARTNERS

EPRI · UNITED · Southern Company · STORWORKS POWER

AWARD NUMBER

FE0031761

PROJECT BUDGET



DOE $3,910,720
PARTNERS $977,680

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FECM RDD&D PRIORITY

H_2 HYDROGEN WITH CARBON MANAGEMENT

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DOE INVESTS $23.5 MILLION TO IMPROVE HYDROGEN TURBINE PERFORMANCE IN SUPPORT OF CARBON-FREE POWER

DOE awarded five research and development projects to various original engine manufacturers (OEMs) to address nitrogen oxide (NO_x) emissions from hydrogen combustion.

HYDROGEN COMBUSTION TURBINE PROJECTS FROM FOA 2400

Five Projects Valued at $34 Million Selected

Projects selected are from OEMs such as General Electric and research organizations, which include Raytheon and the Gas Technology Institute. Each project is designed to advance turbine combustor technology to utilize zero-carbon fuels such as hydrogen and/or ammonia, with at least three of the projects focusing on full combustion modules for larger (>100MW) turbines. These projects are carefully selected to bring these larger (F-Class) turbines up to par in terms of how much hydrogen they can use compared to their smaller counterparts. This is a crucial step in securing a place for gas turbines in the future hydrogen economy.

HYDROGEN NO_x EMISSIONS CAN MATCH THOSE OF NATURAL GAS

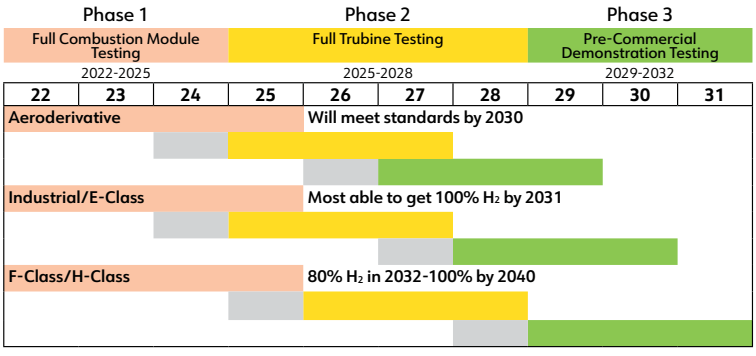
Selected Projects Advance Research Progress Toward This Goal

Hydrogen has several unique properties as a fuel, including a high flame speed, high flame temperature, wide flammability range, and low volumetric energy density, among others. Thus, the use of hydrogen as a fuel requires very special considerations when designing turbine combustors. It is possible to design high hydrogen combustion turbines that have the same or lower NO_x ratings as their natural gas counterparts, but further research and development (R&D) is needed. The five projects selected will push the current state-of-the-art forward by allowing larger combustors to safely accommodate hydrogen fuel.

FIRST STEPS TOWARD 100% HYDROGEN COMBUSTION

DOE Targets 2030–2031 Timeframe for First Pure Hydrogen Turbines

Currently, DOE projects that it will take at least two generations of gas turbine development for hydrogen to fully replace natural gas as the primary fuel of choice for all gas turbine classes. Smaller turbines, such as aeroderivatives and industrial turbines, already have high (30–50% by volume) hydrogen capabilities. These and F-Class turbines will be the first hydrogen turbines to achieve full commercialization, thus furthering the administration's goals of a decarbonized electricity sector, with H-Class turbines following suit by 2040.



HYDROGEN TURBINES WILL BE AN IMPORTANT PART OF ELECTRICITY GENERATION IN THE FUTURE

Gas Turbines Are Crucial for Carbon-Free Power

Gas turbine technology is the most mature, economical, and scalable technology for generating electricity in the world. No other form of power generation is as dispatchable, as energy dense, or as reliable. Keeping up with current energy demands while decarbonizing the electricity sector requires that gas turbines play a role in the generation process. If this electricity is to be carbon-free, adapting gas turbines to fuels such as hydrogen and ammonia is of paramount importance.

DEPARTMENT OF ENERGY TO RELEASE OFFICIAL POSITION ON THE FUTURE OF HYDROGEN TURBINE RESEARCH

Release of Advanced Turbines Program Record

The program record (PR) discusses the current state-of-the-art of hydrogen turbine technology and the results of a recent literature survey of past research efforts. The PR will serve to inform the general public of the challenges of using hydrogen fuels in gas turbines and the substantial progress that has been made by the DOE and others toward achieving 100% hydrogen combustion turbines. Major conclusions include (1) the need for specific New Source Performance Standards for hydrogen engines, (2) uniform adoption of appropriate NO_x measurement standards by industry, and (3) stronger R&D support with the goal of a 2030 product release date.

PARTNERS

Raytheon

GE Global Research

gti

GE Power

AWARD NUMBERS

FE0032169, FE0032170, FE0032171, FE0032172, FE0032173

PROJECT BUDGET

$34.2M

- TOTAL DOE $23,485,581
- TOTAL PARTNERS..... $10,763,069

DOE BREAKDOWN

- FE0032169 ..... $2,999,219
- FE0032170 ..... $6,999,923
- FE0032171 ..... $4,499,999
- FE0032172 ..... $3,000,000
- FE0032173 ..... $5,986,440

PARTNERS BREAKDOWN

- FE0032169 ..... $749.805
- FE0032170 ..... $1,749,981
- FE0032171 ..... $1,125,000
- FE0032172 ..... $1,176,189
- FE0032173 ..... $5,962,094

Note: Not included is a FY21 project from Solar Turbines, Inc. to develop an H_2-fueled combustor for industrial-scale turbines. The total award was $4.5 M with a 20% cost share.

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Angela Bosley (FE0032172)
Kelly Haught (FE0032173)

FECM RDD&D PRIORITY

HYDROGEN WITH CARBON MANAGEMENT

LOWER COSTS AND IMPROVED PERFORMANCE FOR SOLID OXIDE FUEL CELL SYSTEM ACHIEVED

2ND-GENERATION SOLID OXIDE FUEL CELL (SOFC) FEATURES LOW-COST AND SCALABLE PILOT MANUFACTURING EQUIPMENT AND PROCESSES

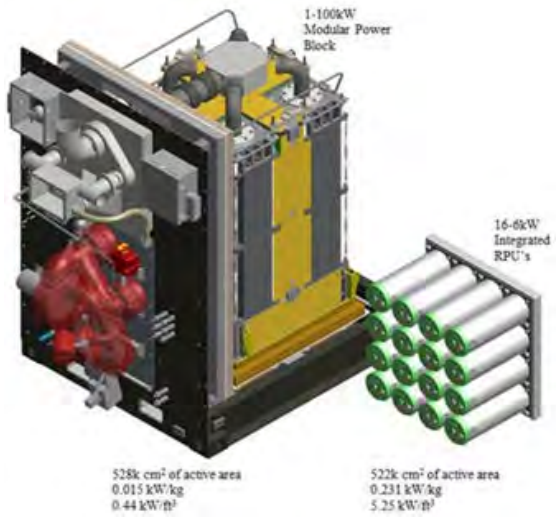
FuelCell Energy (FCE) has successfully developed its 2nd-generation SOFC power system cell and stack technology known as Compact Stack Architecture (CSA).

Costs are 61% lower compared to the 1st-generation and significantly lower than the U.S. Department of Energy [DOE] cost target of $225/kilowatt (kW) AC.

The cost is estimated at $87/kW AC at 1,000 megawatts (MW)/year high-volume production.

Performance improvements include:

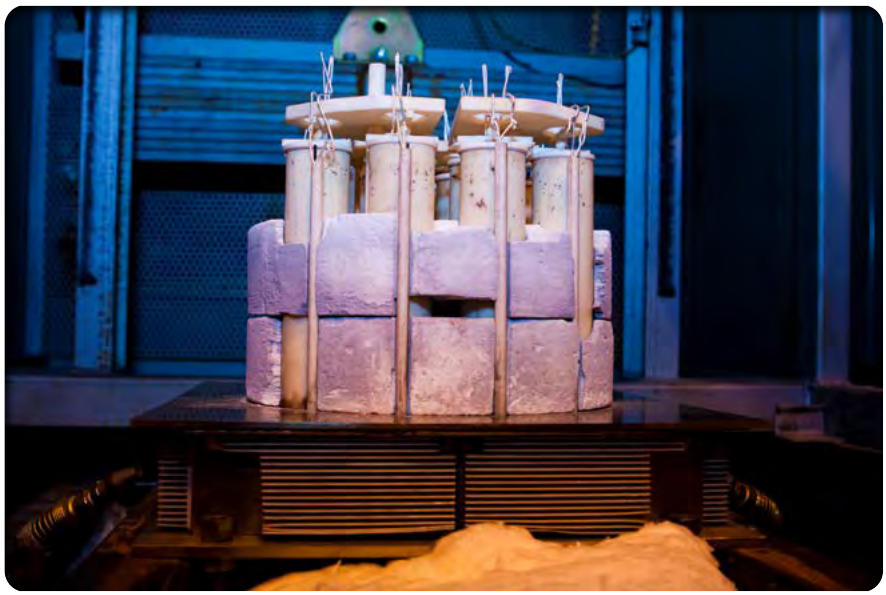
- 600% increase in watt/kg.
- 400% increase in watt/liter.
- Cell stack degradation rate of less than 1% per 1,000 hours.



Comparison of current FCE sofc and repeatable power unit concept at 100 kw scale.

FCE IS ADVANCING THE MATURITY OF SOFC POWER SYSTEMS

With the success of the 2nd-generation SOFC system, FCE is **advancing toward commercial deployment** of natural gas-fueled megawatt-electric (Mwe) -class distributed generation applications. FCE is currently developing the conceptual design of a MWe-class SOFC power system and has completed a techno-economic analysis.

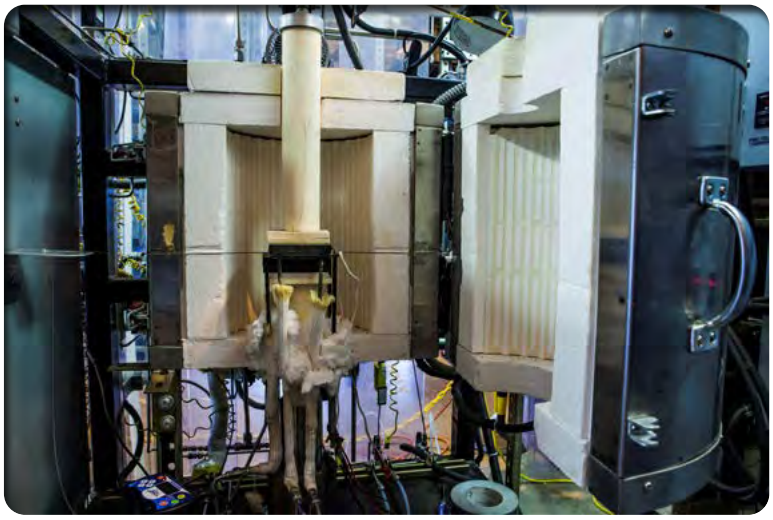


Example of an NETL Multi Cell Array under test.

FCE TECHNOLOGY ACHIEVING COMPETITIVE COST

FCE **has progressively demonstrated** CSA larger-system manufacturing and completed processes to **enable MWe-class production rates at a competitive cost**.

The techno-economic analysis of the MWe-class FCE SOFC systems showed a cost less than or equal to $6,000/kilowatt-electric (kWe).



Example of an NETL SOFC module after testing.

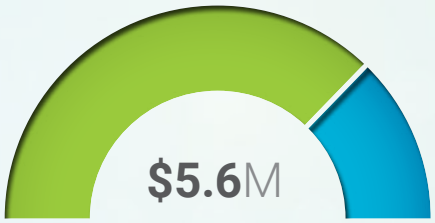
PARTNER

FuelCell Energy

AWARD NUMBERS

FE0027584
FE0031639

PROJECT BUDGET



DOE $4,500,000
PARTNERS..... $1,125,001

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FECM RDD&D PRIORITY

H_2 HYDROGEN WITH CARBON MANAGEMENT

CLICK HERE FOR MORE INFORMATION ON FE0027584

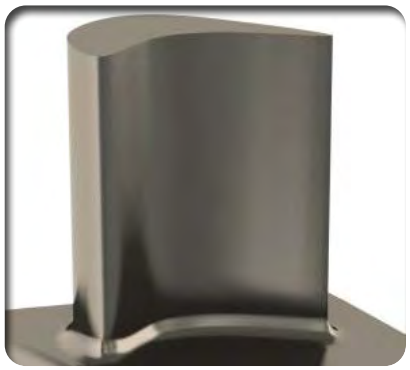
CLICK HERE FOR MORE INFORMATION ON FE0031639

NATIONAL EXPERIMENTAL TURBINE (NExT) DESIGN DELIVERED TO INDUSTRIAL PARTNERS

Full design of aeroderivative turbine blades delivered to original engine manufacturer (OEM) partners.

PENN STATE COMPLETED THE NExT DESIGN

Full Blade Designs and Test Data Package Created



Penn State University's Steady Thermal Aero Research Turbine (START) lab developed the key design parameters needed to predict the single-stage efficiency of the NExT blades.

A complete package of the results—including computer-aided design models and drawings for rig hardware—was delivered to OEM partners.

OEM partners will use the results of higher-level studies for analytical tool development, baseline case development, and optimization studies.

The NExT design will support current and future research for several other DOE-funded projects.

The first NExT hardware to be tested in the START rig will be additively manufactured turbine blades and vanes.

HIGH-LEVEL ANALYSIS OF BLADE CASTING TECHNIQUES

Multiple Sample Turbine Blades From Several Companies Analyzed

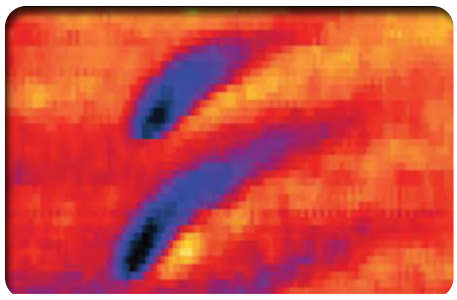
The START lab performed detailed evaluations of multiple blade casting and additive manufacturing companies.

Numerous parameters of each delivered sample blade—including surface finish/roughness, hole quality, and adherence to given tolerances—were analyzed.

The evaluations quantify the state-of-the-art manufacturing capabilities of the participating companies.

INNOVATIVE THERMAL IMAGING SCHEME

Can Measure Flow Properties on All Blades From a Single Point

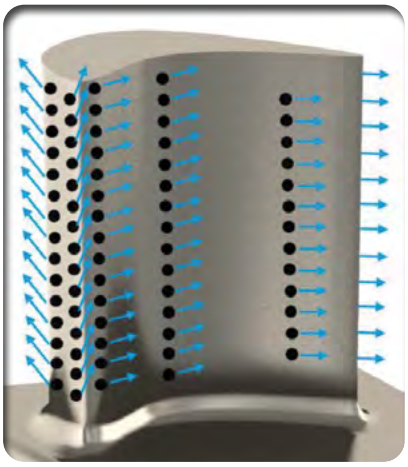


The START lab's innovative measurement techniques can measure various flow parameters around the turbine stage's entire circumference.

Thermal imaging tools can continuously measure temperature at a single location on the apparatus, and the results can be mapped onto individual blades to analyze various cooling schemes/techniques.

ADVANCED BLADE COOLING STUDIES

Complete Spatial Mapping of Temperature Profiles



Researchers at the START Lab evaluated nine blades at a nominal pressure ratio and examined various flow parameters and calculated overall cooling effectiveness.

The START test rig can examine the cooling effectiveness of various blade designs and hole patterns under actual turbine conditions.

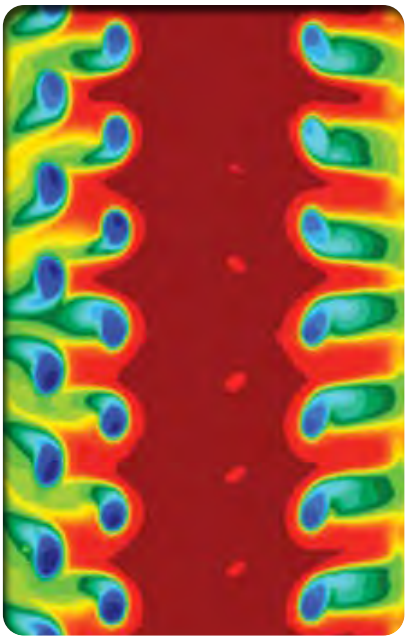
New cooled blades for DOE are currently being manufactured with delivery expected in the fourth quarter of 2022.

START LAB IS CONTINUOUSLY IMPROVING

Enhancing Equipment Measurement Accuracy

The operations of the START test rig have been significantly improved to enhance day-to-day repeatability of testing conditions.

Refinements have included developing accurate calibration methods for the camera as well as developing more accurate algorithms to map images onto blade surfaces.



PARTNERS

NExT

Solar® Turbines
A Caterpillar Company

SIEMENS energy

Pratt & Whitney — Dependable Engines

Honeywell
AEROSPACE

AGILIS
Revolutionary Insight

AWARD NUMBER
FE0025011

PROJECT BUDGET

DOE $8,226,916
PARTNERS..... $2,840,205

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FECM RDD&D PRIORITY

H_2 HYDROGEN WITH CARBON MANAGEMENT

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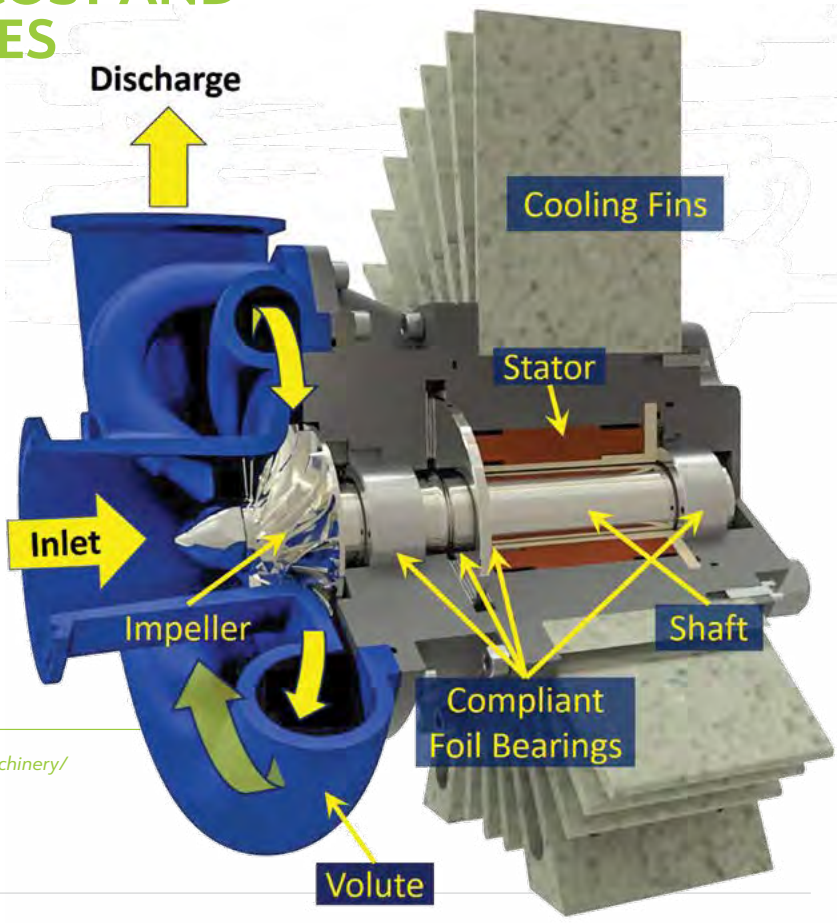
NEW ANODE RECYCLE BLOWER ENHANCES PERFORMANCE AND EFFICIENCY OF SOLID OXIDE FUEL CELL (SOFC) POWER PLANTS

An oil-free and high-temperature capable anode recycle blower was designed, fabricated, and tested.

ADVANCED ANODE RECYCLE BLOWER OVERCOMES CURRENT COST AND PERFORMANCE PENALTIES

Mohawk Innovative Technology, Inc. (MITI) **developed the modular oil-free and high-temperature anode recycle blower** (ARCB) to enhance the overall performance and efficiency of SOFC power plants by overcoming the limitations of lubricating oil and an external water supply. **The ARCB meets the needs of a 100-kilowatt SOFC power plant.**



MiTi® blowers, ranging from 5 HP to 200 HP, are designed to use high-efficiency, high-speed permanent magnet motor elements, MiTi® patented 6th Generation airfoil bearings, and advanced impellers and controllers for variable speed operation. The single integrated motor, impeller, and oil-free bearing system increases life and reduces maintenance costs and machine footprint. Wide operating speed range demands are achieved with sensorless variable frequency drives.

From the MiTi website: https://mohawkinnovative.com/oil-free-turbomachinery/

THE ADVANCED DESIGN ENABLES THE ARCB TO EXCEED THE DEPARTMENT OF ENERGY'S SOFC LIFETIME GOAL OF 40,000 HOURS

MITI's innovative oil-free ARCB was integrated into a module of FuelCell Energy's (FCE) 200 kWe SOFC demonstration system and **operated for more than 1,900 hours**. The ARCB was capable of fully tracking the SOFC's operating conditions and responding dynamically to load demands, thus completing system demonstration.

Following the qualification testing, **all critical components were intact and appeared in like-new condition**. The oil-free and encapsulated **design enables the ARCB to exceed DOE's SOFC lifetime goal of 40,000 hours**.

MINIMIZED DESIGN COMPLEXITY REDUCES COSTS

The complexity of the MITI ARCB hardware is minimized by using a single shaft system supported by compliant foil bearings, which use the process gas as a lubrication medium and require no maintenance due to their essentially frictionless operation.

The ARCB also addresses the need for a high-temperature recycle blower to help increase overall SOFC efficiency **by eliminating the need for an external water supply**.

MITI specializes in high-speed, high-temperature, oil-free rotating machinery technology.

FCE designs, manufactures, installs, operates, and services stationary fuel cell power plants.

Photo courtesy of FuelCell Energy

PARTNERS

MOHAWK INNOVATIVE TECHNOLOGY

FuelCell Energy

AWARD NUMBER

FE0027895

PROJECT BUDGET

DOE $2,098,408
PARTNERS $569,443

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FECM RDD&D PRIORITY

H_2 HYDROGEN WITH CARBON MANAGEMENT

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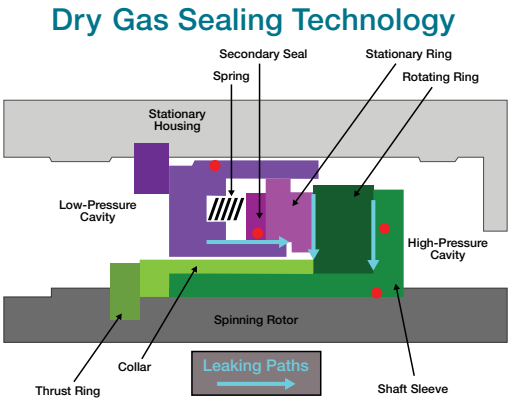
ROTATING TESTS OF 14-INCH DRY GAS SEALS FOR UTILITY-SCALE sCO_2 TURBO EXPANDERS SUCCESSFULLY COMPLETED

Effective seals for high-pressure supercritical carbon dioxide power cycles give this efficient and cost-effective technology a promising future.

EFFECTIVE SEALS ARE CRITICAL FOR HIGH-EFFICIENCY POWER SYSTEMS

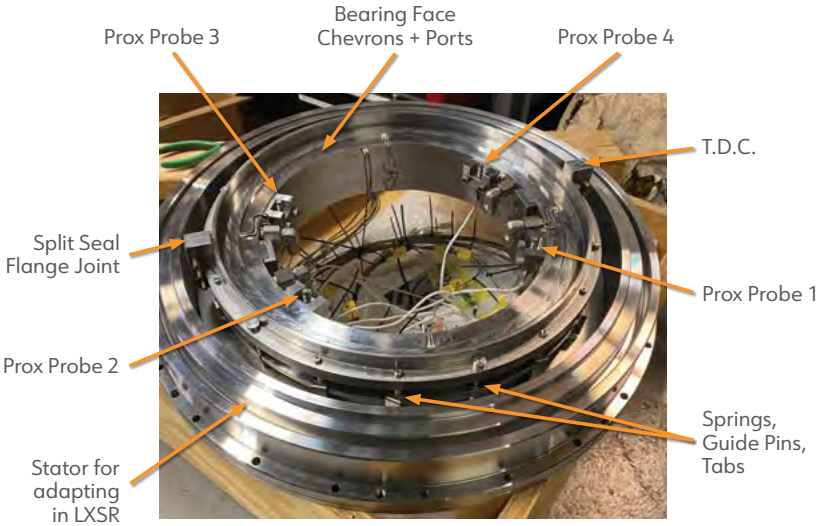
The New Seals Limit Pressure Losses

- Lower cost electricity production can be achieved through indirect supercritical carbon dioxide (sCO_2) power cycles with thermodynamic cycle efficiencies over 50%.
- However, achieving system-level objectives for sCO_2 cycles requires low-leakage, large-diameter and split-segment face seals.
- Such face seals are not presently available for use in the operating environments of utility-scale sCO_2 turbines.



ADVANCED DESIGN LEADS TO OPTIMAL MANUFACTURED SEALS

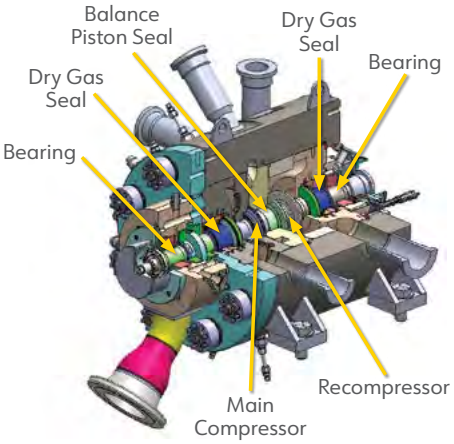
- Manufacturing processes were successfully developed to enable high-precision fabrication of split-segment face seals and the axial face of large-diameter rotors for testing.
- Research included a conceptual design of a custom machining tool to compensate for the limitations of the existing machining methods. This enabled adaption of high-precision face seals to large-scale turbine rotors.



14-inch face seal.

EXPECTED TECHNOLOGY BENEFITS

- Enables indirect sCO_2 power cycles with **thermodynamic cycle efficiencies of 50–52% or greater**.
- **Reduces water consumption** (no evaporator blow-down).
- **Reduces power block size** (smaller turbomachinery and condenser due to the higher density working fluid).
- **Provides better thermodynamic integration** with post-combustion CO_2 capture and compression equipment.



APPLIED TEST ACHIEVES BREAKTHROUGH PERFORMANCE

- The dry gas seal demonstrated stable operation at:
  - 5,200 rpm for 60 minutes.
  - 340 °F.
  - 1 mil film thickness.
- This is a **significant improvement over existing dry gas seal technology**, which currently operates with film thicknesses at least an order of magnitude greater.
- Operating at minimum film thicknesses **improves the sealing efficiency** and leakage rate, increasing turbine efficiency and the overall power cycle in power generation applications.

14-inch test rig.

ADVANCEMENT WILL HAVE WIDE-REACHING IMPACTS

This dry gas seal technology advancement will have wide-reaching impacts due to its **broad applications** for both power generation and aviation.

PARTNERS

GE imagination at work

SwRI®

AWARD NUMBER

FE0024007

PROJECT BUDGET

DOE $6,824,098
PARTNERS..... $1,793,304

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FECM RDD&D PRIORITY

H_2 HYDROGEN WITH CARBON MANAGEMENT

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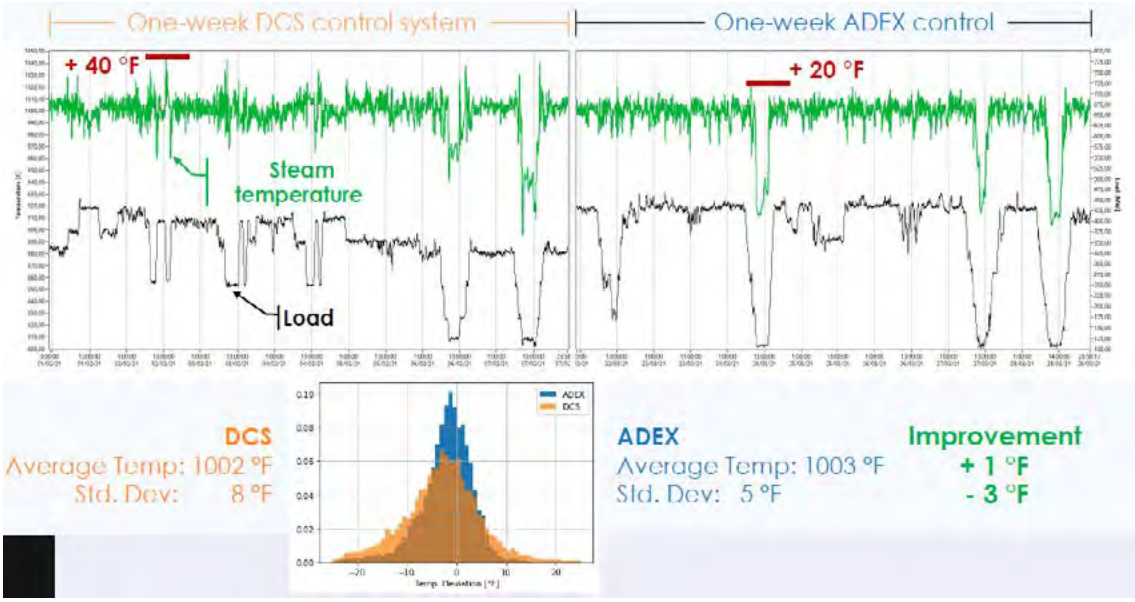
SENSOR NETWORK AND PREDICTIVE CONTROLS IMPROVE PERFORMANCE

An advanced sensor network, adaptive predictive controls, and neural network optimization software produced an immediate improvement in performance.

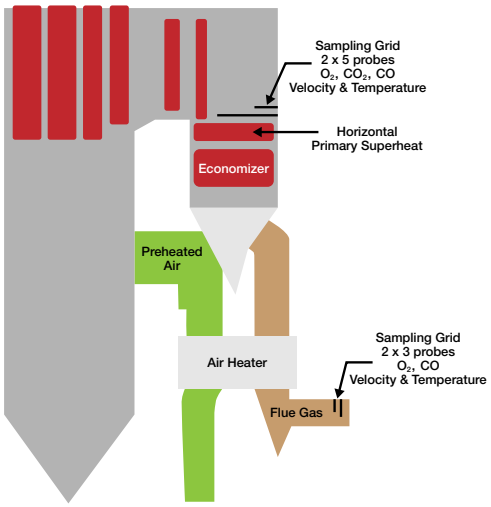
INTEGRATED SENSOR AND DYNAMIC NEURAL NETWORK OPTIMIZATION PROVIDE PERFORMANCE IMPROVEMENTS

The University of Utah and partners commissioned an integrated sensor/software system in Pacificorp's Hunter Power Plant coal-fired Unit 1 in Castle Dale, Utah. **The system produced an immediate improvement in plant operation.** Effective efficiency control at fossil energy plants with varying loads while integrated with renewables is critical for maintaining grid stabilization and avoiding curtailment of renewable power sources.



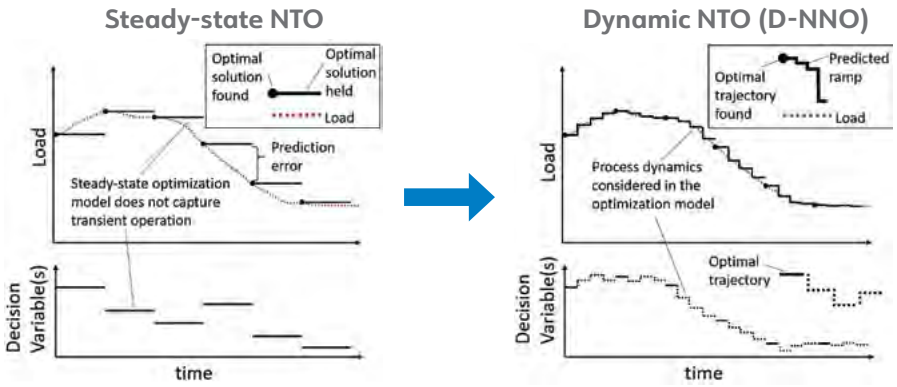
ADVANCED SENSOR NETWORK CALCULATES REAL-TIME NET UNIT HEAT RATE

The advanced sensor network installed through this project gives flow and composition data for use in calculating the net unit heat rate (NUHR) in real-time for PacifiCorp's Hunter Unit 1. **Real-time NUHR data are critical to the new predictive control system's ability to optimize plant operation at variable loads.** This allows the plant to perform optimally while adjusting to variable demand from the grid.

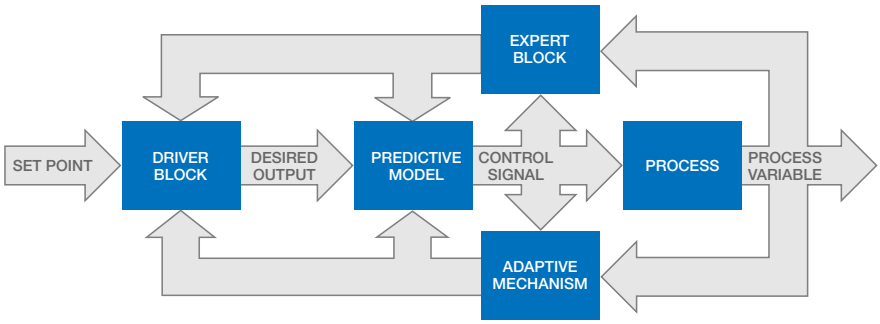


SENSOR NETWORK WITH PREDICTIVE CONTROLS CAN OPTIMIZE PERFORMANCE DURING TRANSIENT OPERATION

The system includes an advanced sensor network, adaptive predictive controls, and neural network optimization software. **Dynamic neural network optimization helps the plant perform optimally**, despite frequent ramping, by incorporating transient behavior into the plant and optimizing control move trajectories.



ADEX is a self-tuning artificial intelligence (AI) platform used to ensure real-time control precision. Self-tuning AI manages controllers for enhanced control over the full load range. A predictive model incorporates real-time model predictions. An expert block enables knowledge of process dynamics to influence control decisions within various operating domains and accounts for multi-variable interactions.



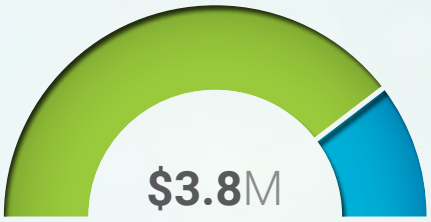
Project partners are now developing an optimal combination of dynamic machine learning modeling methods and an appropriate optimization algorithm to balance computational costs and provide effective, real-time closed-loop control for minimizing heat rate at a coal-fired power plant.

PARTNERS

THE UNIVERSITY OF UTAH®
GRIFFIN
BYU BRIGHAM YOUNG UNIVERSITY
PACIFICORP
ADEX
CHALMERS UNIVERSITY OF TECHNOLOGY

AWARD NUMBER
FE0031754

PROJECT BUDGET



DOE $2,992,781
PARTNERS..... $792,000

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FECM RDD&D PRIORITY

H_2 HYDROGEN WITH CARBON MANAGEMENT

CLICK HERE FOR MORE INFORMATION

U.S. AT THE FOREFRONT OF CUTTING-EDGE POWER CYCLE TECHNOLOGY AT THE STEP PILOT PLANT TEST FACILITY

The 10 MWe sCO_2 Pilot Plant Test Facility will demonstrate more efficient power generation at lower cost and enable the U.S. to lead in domestic and global power production.

PATH TO LOWER-COST DOMESTIC AND GLOBAL POWER GENERATION

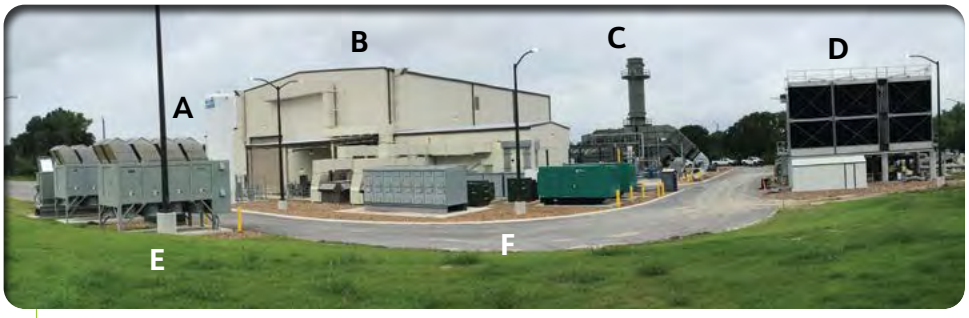
Supercritical carbon dioxide (sCO_2) power cycles offer potential for power generation with increased efficiency, lower cost of electricity, reduced customer costs, and reduced water consumption.

Quantified Performance Goals

- 2-5% point net plant efficiency improvement.
- 3-4% reduction in Levelized Cost of Electricity.
- Reduced emissions, fuel, and water usage.

STEP
SUPERCRITICAL
TRANSFORMATIONAL
ELECTRIC
POWER

PROVING A NOVEL POWER CYCLE USING A RECONFIGURABLE, FLEXIBLE STEP PILOT PLANT TEST FACILITY



A) supercritical carbon dioxide (sCO_2) inventory storage, B) test facility, C) sCO_2 heater, D) cooling towers, E) electrical load banks, F) electrical power and back-up generators.

The **STEP pilot plant** will demonstrate a fully integrated, functional, electricity-generating power plant using **sCO_2 technology**. This plant aims to show component performance and cycle operability over a wide range of operating conditions, as well as show progress toward a **lower cost of electricity**.

REDUCING BARRIERS AND RISKS TO COMMERCIALIZATION

Simple Cycle Commissioning at the STEP Pilot Facility Is Progressing

- A key step toward pilot testing and demonstration of the sCO_2 power cycle.
- DOE's investment in sCO_2 power cycle technology through the 10 MWe sCO_2 Pilot Plant Test Facility enables the U.S. to lead in developing and commercializing sCO_2 power cycle deployment for both domestic and global power generation.

sCO2 TECHNOLOGY

THE STEP PILOT IS THE WORLD'S LARGEST INDIRECT-FIRED sCO_2 POWER CYCLE TEST FACILITY

KEY EQUIPMENT AND PROCESS ADVANCEMENTS ACHIEVED IN FY22

- High-temperature recuperator delivered.

- Main compressor delivered and installed, commissioning ongoing.
- Piping mobilization 1 complete.

- Turbine rotor fabricated, final machining/coating ongoing.

- Low-temperature turbine stop valve delivered.
- High-temperature turbine stop valve shipped for RT inspection.

- Inventory management system installation complete.

- Turbine case fabricated, and inspection for simple cycle ongoing.

- Distributed Control System delivered.
- Heater Protection Valve manufactured.

PARTNERS

gti®

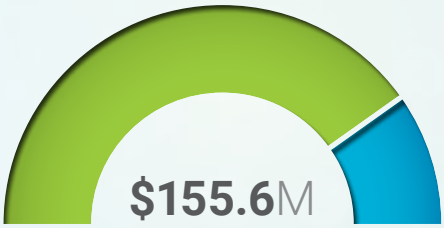
SwRI®

GE

AWARD NUMBER

FE0028979

PROJECT BUDGET



DOE $124,493,440
PARTNERS..... $31,123,394

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Raelynn Honkust

FECM RDD&D PRIORITY

HYDROGEN WITH CARBON MANAGEMENT

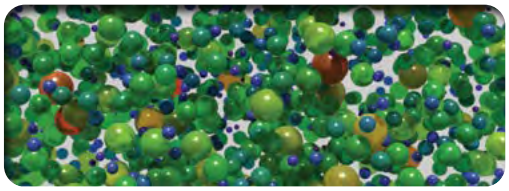
CLICK HERE FOR MORE INFORMATION

NETL MULTIPHASE FLOW WITH INTERPHASE EXCHANGES (MFiX) REACHES NEW MILESTONES

MFiX continued to provide exceptional value, receiving widespread recognition and enhancing the user experience with new modeling capabilities and user interface upgrades.

MFiX PROVIDES FLEXIBILITY TO TACKLE COMPLEX SIMULATIONS

MFiX provides a range of solution strategies to fit most modeling needs relevant to the Department of Energy Office of Fossil Energy and Carbon Management (DOE FECM). Recent additional modeling capabilities such as Particle in Cell polydispersity and collision damping modeling, and discrete element model rolling friction enable more accurate modeling of complex energy systems.



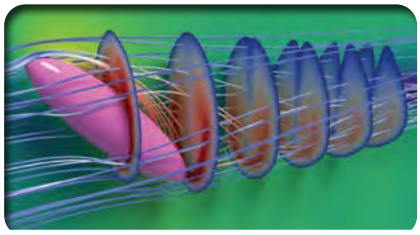
Polydisperse system.

Rolling friction.

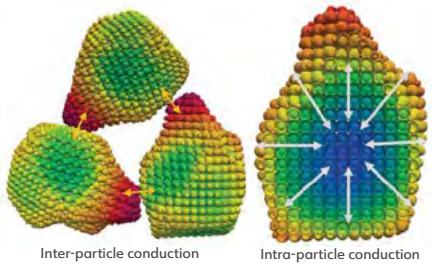
MFiX models.

DEVELOPING A NEXT-GENERATION DISCRETE ELEMENT METHOD

A wide range of feedstock particle shapes (coal, biomass, plastics, municipal solid waste) must be modeled to help DOE FECM achieve its mission of minimizing the environmental impacts of fossil fuels while working toward net-zero emissions. MFiX is developing multiple approaches to represent non-spherical particles using superquadrics and glued spheres.



Flow Over spheroid.



Glued spheres.

Wood pellet fluidized bed.

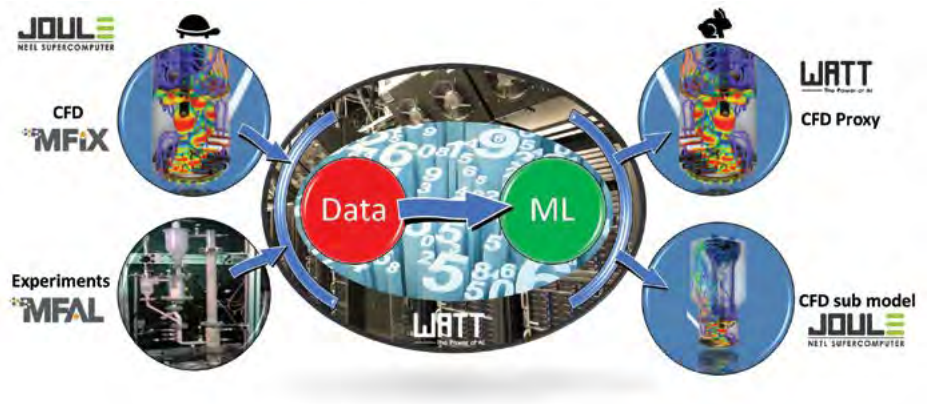
MFiX LEVERAGES NETL'S JOULE 2.0 SUPERCOMPUTER

MFiX uses the NETL Joule 2.0 supercomputer to study scale-up and performance optimization of coal-biomass circulating fluidized bed combustion systems designed for negative CO_2 emissions.

NETL's Joule supercomputer.

COUPLING MACHINE LEARNING WITH FLOW SOLVER

The MFiX development team is integrating machine learning methodologies to accelerate the flow solver and provide access to a range of submodels for improved accuracy.



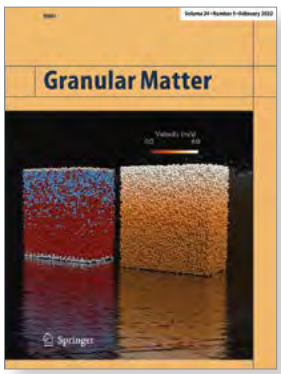
WORLDWIDE USER COMMUNITY

- 7,500+ total users.
- 4 releases per year.
- 3,800 downloads per year.
- 650 citations per year.

MFiX community location.

MFiX FEATURED ON JOURNAL COVERS

The MFiX software suite was featured on the covers of the journals *Granular Matter* (Feb. 2022) and *Particuology* (March 2022).



PARTNERS

UAF UNIVERSITY OF ALASKA FAIRBANKS

Natural Resources Canada

U.S. DEPARTMENT OF ENERGY
Fossil Energy and Carbon Management

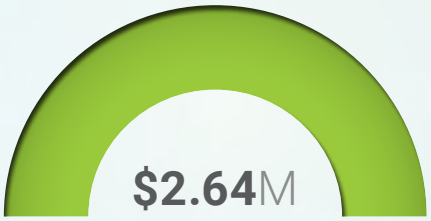
SOTACARBO
SUSTAINABLE ENERGY RESEARCH CENTRE

PARSONS

AWARD NUMBER
FWP-1022463

PROJECT BUDGET

EY22 FUNDING



DOE $2,643,000

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FECM RDD&D PRIORITIES

HYDROGEN WITH CARBON MANAGEMENT

POINT-SOURCE CARBON CAPTURE

CLICK HERE FOR MORE INFORMATION

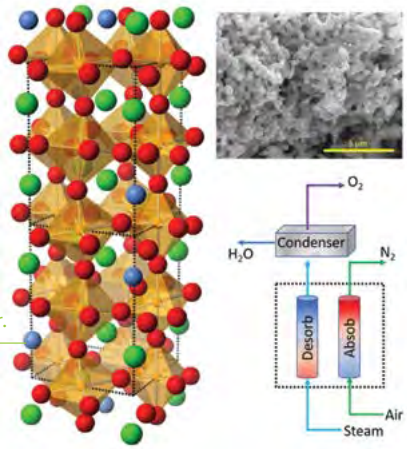
NOVEL OXYGEN SEPARATION TECHNOLOGIES ADVANCE TO PROTOTYPE AND DEMONSTRATION-SCALE READINESS

Synergy between NETL and national laboratory partners generates innovative advances in air separation methods.

RAPID ADVANCES IN NEW MODULAR AIR SEPARATION/ OXYGEN PRODUCTION TECHNOLOGIES

The National Energy Technology Laboratory (NETL) and multiple national laboratory partners are developing **a portfolio of small-scale advanced air separation technologies to supply oxygen to the flexible modular energy systems required for net-zero-carbon and net-negative-carbon energy systems**.

These small-scale (10–40 tons per day of pure oxygen) technologies must take different approaches than much larger conventional cryogenic air separation units that rely on economies of scale to reduce costs.



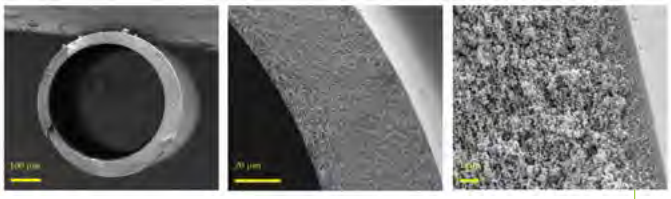
NETL's Perovskite Oxygen Carrier.

INNOVATIVE OXYGEN SEPARATION METHODS CAN RIVAL STATE-OF-THE-ART TECHNOLOGY

Sorbents, Membranes, and Non-Conventional Cryogenics

R&D is focused on sophisticated technological approaches:

- Membranes using unconventional materials such as carbon molecular sieves.
- High-temperature ceramic membranes using solid oxide fuel cell stack technology.
- Oxygen carriers.
- Unique magnetocaloric, solid-state refrigerant-based air liquefaction.

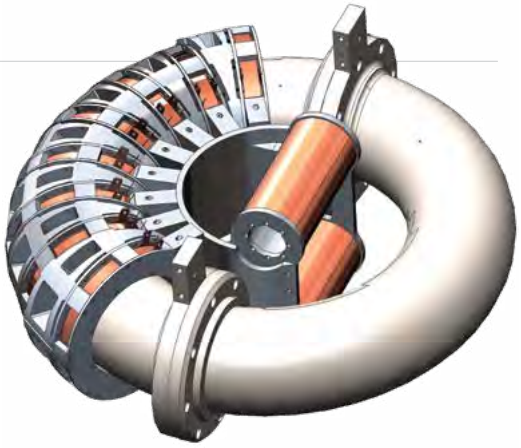


Carbon molecular sieve hollow fiber membrane.

TECHNOLOGIES READY FOR LARGE-SCALE PROTOTYPE TESTING

PNNL's Magnetocaloric Solid-State Air Liquefaction NETL's Oxygen Carrier and Reactor

- Technologies such as Pacific Northwest National Laboratory's (PNNL) Magnetocaloric Oxygen Liquefaction System and NETL's perovskite oxygen carrier/reactor are technologically matured to the point of readiness for small pilot/demonstration testing.
- Large-scale prototype testing would be a major step toward demonstrating the commercial feasibility of these new technologies.



Tokamak magnet around hermetic housing for active magnetic regenerative cycle.

MODULAR OXYGEN SEPARATION IS REQUIRED FOR NET-ZERO-CARBON AND NET-NEGATIVE-CARBON ENERGY SYSTEMS

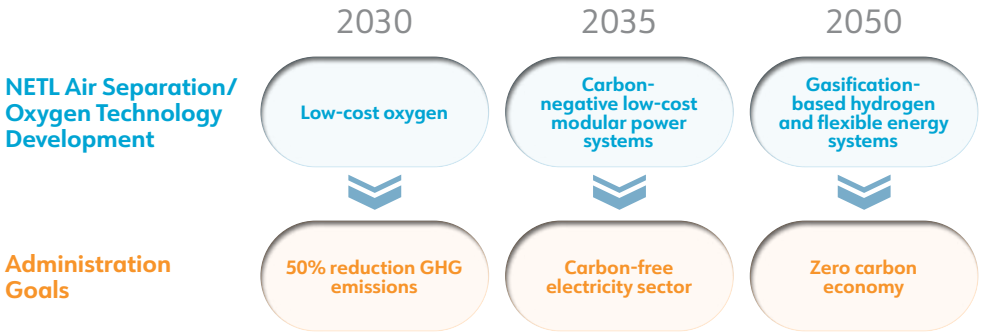
Supports Critical Hydrogen Production and Decarbonization

Supplying pure oxygen is essential for **enabling lowest cost carbon capture** in distributed, flexible, net-zero-carbon or net-negative-carbon energy systems such as oxygen-blown gasifiers.

Utilizing sustainable biomass and waste feedstocks in these decarbonized energy systems having the highest efficiency and environmental performance **provides critical support** for Office of Fossil Energy and Carbon Management (FECM) priorities **in advancing approaches toward deep decarbonization**.

FLEXIBLE, MODULAR OXYGEN PRODUCTION SUPPORTS NATIONAL EMISSIONS GOALS

Advanced oxygen production technologies target anticipated needs for flexible, distributed air separation technology solutions to support decarbonized energy systems and industries in the United States.



Decarbonized hydrogen may be crucial to the future U.S. energy economy, and flexible, modular oxygen production capabilities will strongly support net-zero and net-negative energy pathways.

PARTNERS

Pacific Northwest NATIONAL LABORATORY

Los Alamos NATIONAL LABORATORY

INL Idaho National Laboratory

Argonne NATIONAL LABORATORY

AWARD NUMBERS

FWP-FE-1049-18-FY19, FWP-B000-18-061, FWP-73143, FWP-73130, FWP-1022405

PROJECT BUDGET

2019–2022 FUNDING

- NETL $4,035,000
- PNNL $5,300,000
- LANL $2,650,000
- INL $2,000,000

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FECM RDD&D PRIORITIES

- HYDROGEN WITH CARBON MANAGEMENT
- POINT-SOURCE CARBON CAPTURE

CLICK HERE FOR MORE INFORMATION

PRELIMINARY DESIGN PACKAGE COMPLETED FOR WABASH HYDROGEN PLANT RETROFIT TO ACHIEVE NEGATIVE CARBON EMISSIONS

Plant design for gasification-based power and hydrogen co-production.

GROUNDBREAKING RETROFIT OF LARGE-SCALE GASIFICATION UNIT

Optimizing a Path To Achieve Net-zero or Negative Carbon Emissions

Wabash Valley Resources LLC (WVR) is converting the former Wabash River Integrated Gasification Combined Cycle power plant to a hydrogen co-production plant with carbon capture and sequestration capability. **The retrofit has significant potential for a gasification-based, clean hydrogen demonstration.**

WVR has determined the optimal path to achieve net-zero or negative carbon emissions for the Wabash Plant proposed retrofit using petroleum coke and biomass feedstocks.

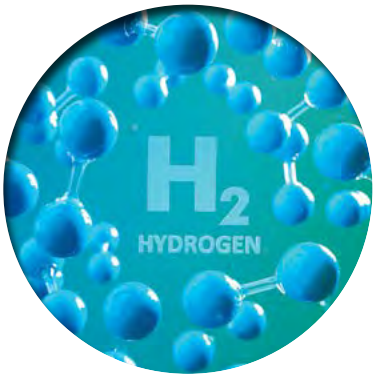
WVR also completed preliminary engineering studies for the gasification, hydrogen production, carbon sequestration, power generation, and hydrogen offtake processes. Essential economics were also defined in investment case and life-cycle analyses.

PRODUCING CARBON-NEGATIVE HYDROGEN WITH CARBON CAPTURE AND SEQUESTRATION

The retrofitted facility is expected to create hydrogen for many applications including transportation, power generation, chemical production, and refining. **1.5 million tons of CO_2 will be captured per year** following the WVR Wabash unit retrofit.

Wabash River Gasification Unit near West Terre Haute, Indiana.

ADVANCING POWER AND HYDROGEN PRODUCTION BEYOND TODAY'S STATE-OF-THE-ART



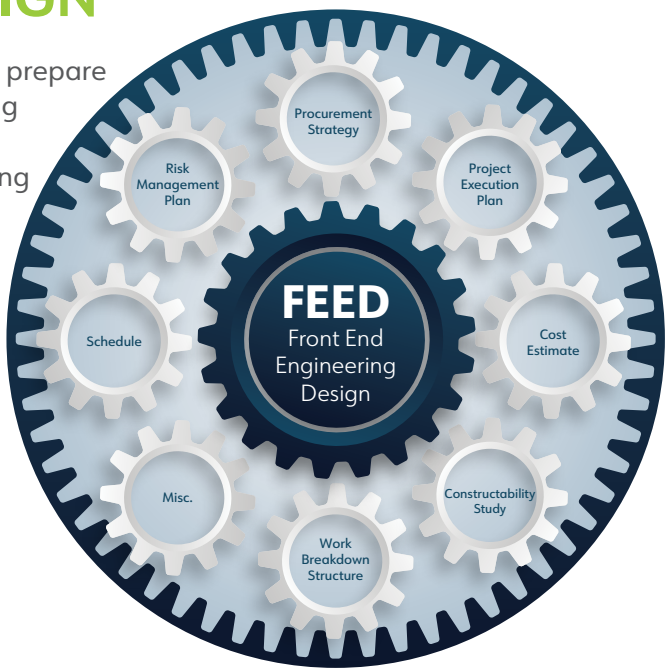
Department of Energy (DOE) 21st-Century Power Plant Initiative

The WVR retrofit project is part of DOE's 21st-Century Power Plant Initiative.

This DOE initiative seeks to advance power generation along with hydrogen production, making power plants more adaptive to the electrical grid with net-zero carbon emissions by 2035.

NEXT STEP: COMPREHENSIVE PLANT DESIGN

The next step will be to prepare a Front-End Engineering Design (FEED) study to redevelop WVR's existing coal gasification site into a prototype of a 21st-century power plant for gasification-based carbon-negative power and hydrogen co-production.



PARTNERS

GTI ENERGY
WABASH VALLEY RESOURCES
SIEMENS energy
Honeywell
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN
INL Idaho National Laboratory
NREL
FW FREITAG-WEINHARDT, INC.
Argonne NATIONAL LABORATORY
SAIPEM

AWARD NUMBER
FE0031994

PROJECT BUDGET

DOE $37,922,837
PARTNERS..... $9,599,347

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FECM RDD&D PRIORITIES

- HYDROGEN WITH CARBON MANAGEMENT
- POINT-SOURCE CARBON CAPTURE
- CARBON DIOXIDE REMOVAL

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NETL COMPUTATIONAL SCHEME PROVIDES RAPID SCREENING OF SOLVENTS FOR PRE-COMBUSTION CAPTURE

NETL researcher's computational method enables advanced screening capabilities for novel CO_2 pre-combustion solvents.

NETL-DEVELOPED COMPUTATIONAL SCREENING METHOD FOR CO_2 PRE-COMBUSTION CAPTURE SOLVENTS

A computational scheme was used to screen physical solvents for CO_2 pre-combustion capture by integrating the commercial National Institute of Standards and Technology (NIST) database, an in-house computational database, cheminformatics, and molecular modeling. A commercially available hydrophobic solvent possessing favorable physical properties and promising absorption performance for CO_2 separation from pre-combustion gas streams was identified.

ADVANCED METHODOLOGY ENABLES IDENTIFICATION OF NOVEL CO_2 SOLVENT MOLECULE

A unique hydrophobic solvent identified by NETL, CASSH-1 has proven to possess many promising properties including hydrophobicity, high CO_2 solubility, and high CO_2/H_2 solubility selectivity. The hydrophobic nature of this solvent means that pre-combustion capture can occur above room temperature, and the solvent can be regenerated using waste heat to reduce the cost of CO_2 capture at integrated gasification combined cycle powerplants. The research findings establish a better understanding of the technical needs and possibilities that can help decrease investment risk and encourage deployment of future novel technologies that can reduce the cost of carbon capture under pre-combustion conditions.

Computational Scheme

NIST Database ~27,000 pure compounds

Melting (Tm), boiling (Tb) temperatures, viscosity (m), Sat. Vapor Pres (Psat), surface tension (s), density (r)

Open Literature fills in missing properties from NIST Database

Flash point, safety, health, environment, price

In-house Computational Database: QM for gases – Chemical functional group interactions.

CO_2, CH_4, H_2, H_2O, H_2S, SO_2, O_2, N_2, etc.

~100-1,000 compounds

RDKit Chem-Informatics (logP), In-House Monte Carlo Molecular Simulation

Hydrophobicity, CO_2 solubility, CO_2/H_2 solubility, selectivity, heat of absorption

< 100 compounds

In-House Molecular Dynamics Simulation

Surface tension, heat capacity, viscosity, CO_2 diffusivity, density, vapor pressure, thermal conductivity

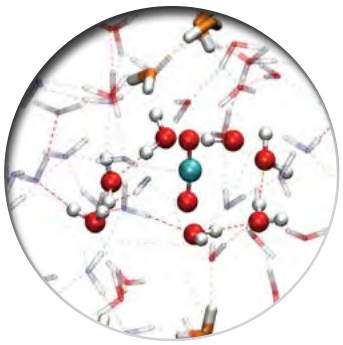
30-40 compounds

Experimental Testing and Economic Screening Analysis Best compound

U.S. Patent Demonstrates Novelty and Effectiveness of the Solvent Identified With Computational Method and Verified at Pilot Scale: Selective at Warm Temperatures

Hydrophobic Alkyl-Ester Physical Solvents for CO_2 Removal from H_2 Produced from Synthesis Gas; U.S. Provisional Patent Application Serial No. 63/223,422; DOE Ref. No. S-166,194

UNIQUE COMPUTATIONAL DATABASE CREATED TO CHARACTERIZE MOLECULAR INTERACTIONS



NETL researchers built a new computational database to characterize CO_2, H_2, N_2, and H_2O interactions with target molecules using 202 functional groups. Based on their CO_2 interaction energies, these functional groups could be classified as producing strong, intermediate, and weak interactions with CO_2.

Pilot-Scale Testing of CASSH-1 Was Conducted at UND EERC

NETL conducted the first pilot plant test for hydrophobic physical solvents for CO_2 and H_2S removal from coal-derived H_2-rich syngas. NETL's CASSH-1 solvent was compared against polyethylene glycol dimethyl ether (PEGDME), a hydrophilic physical solvent analog for the commercial process Selexol. Pilot plant testing at the University of North Dakota Energy & Environmental Research Center (UND EERC), demonstrated that CASSH-1 absorbed less water and showed comparable CO_2 absorption performance compared to the PEGDME, including at elevated absorption temperatures of up to 55 °C and during long-term operation. Both the limited water uptake and the low vapor pressure of tested solvents further alleviate concerns for scaled-up operations related to corrosion, water absorption, and solvent loss to evaporation.

NETL'S RESEARCH EFFORTS HIGHLIGHTED IN *THE JOURNAL OF PHYSICAL CHEMISTRY B*

NETL has published a peer-reviewed article demonstrating the proof-of-concept of this computational methodology. ***The Journal of Physical Chemistry B* editors were impressed with this research effort and requested that the NETL team contribute art for the cover of the journal.**

Citation: J. Phys. Chem. B 2021, 125, 13467−13481

CLICK HERE TO ACCESS THE FACT SHEET

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AWARD NUMBER

FWP-1022402

PROJECT BUDGET

FY20–FY21 FUNDING

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Janice A. Steckel

FECM RDD&D PRIORITIES

POINT-SOURCE CARBON CAPTURE

CLICK HERE FOR MORE INFORMATION

NETL COMPLETES SEVEN CARBON DIOXIDE CAPTURE FRONT-END ENGINEERING DESIGN STUDIES

DOE has invested heavily in developing advanced carbon capture technologies with high commercialization potential for fossil fuel-based power generation facilities.

MOVING TECHNOLOGY TOWARD COMMERCIALIZATION

Front-End Engineering Design (FEED) studies are a critical step in the progression of novel technologies from initial development to final deployment, ensuring that the design and costs of the project are accurate and feasible before the start of construction on major carbon capture retrofits to fossil fuel plants.

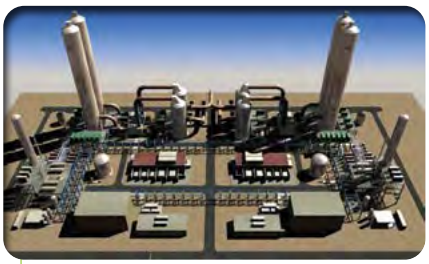
The real-world results and experiences gained from these large-scale FEED studies significantly push CO_2 capture technologies for fossil power sources toward commercialization, thus supporting the Bipartisan Infrastructure Law's goals for carbon capture technology deployment.

FEED STUDIES FOR NGCC POWER PLANTS COMPLETED

Elk Hills Power Plant (550 MWe)

Electric Power Research Institute (EPRI) completed a FEED study for the retrofit of California Resources Corporation's Elk Hills natural gas combined cycle (NGCC) power plant. The study used Fluor's Econamine FG+SM aqueous amine technology to capture at least 90% of the CO_2 in the flue gas. This promising technology's water minimization and hybrid air and water-cooled approaches have several advantages. *(FE0031842)*

Elk Hills Power Plant

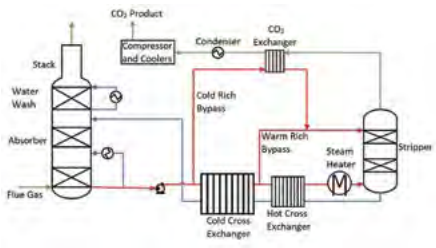


3-D model of Linde-BASF NGCC plant with carbon capture.

Plant Daniel Unit 4 (525 MWe)

Southern Company executed FEEDs at two NGCC host sites — Alabama Power Company's Plant Barry and Mississippi Power Company's Plant Daniel — to incorporate carbon capture technology capable of removing 90% of the plants' CO_2 emissions. Plant Daniel in Moss Point, MS, was selected as the optimal site to implement Linde-BASF's Post-Combustion Carbon Capture Technology that employs an optimized OASE® blue solvent with a longer solvent life and reduced solvent recirculation rates to lower capture costs. *(FE0031847)*

UT–Austin – Mustang Station (460 MWe) and Sherman Power Plant (758 MWe)



3-D model of Linde-BASF NGCC plant with carbon capture.

The University of Texas at Austin conducted a FEED study to assess the Piperazine Advanced Stripper (PZAS™) technology with NGCC flue gas at Golden Spread Electric Cooperative's Mustang Station in Denver City, TX. Bechtel evaluated a 35-weight% MEA solvent system for NGCC capture at Panda Power Funds' Sherman Power Plant in Sherman, TX. The studies determined that the costs were not favorable at these sites, but they did identify the challenges of variable load factors and major opportunities for enhanced performance and reduced cost. *(FE0031844, FE0031848)*

Panda Power Funds Sherman Energy Center

PROMISING DESIGNS FOR COAL PLANTS

Prairie State Generation Company (PSGC) (816 MWe)

PSGC Energy Campus

The **University of Illinois** completed a FEED study using Mitsubishi Heavy Industries' (MHI) advanced Kansai Mitsubishi Carbon Dioxide Recovery (KM-CDR) process with its new KS-21™ solvent. This process shows promise as its capture costs are near the $40/tonne CO_2 DOE goal for the coal-fired power plant in Marissa, IL. *(FE0031841)*

San Juan Generating Station

San Juan Generating Station (914 MWe)

Enchant Energy completed an assessment of the costs of implementing MHI's KM-CDR Process™ with its KS-1™ solvent. Costs were estimated near $45/tonne CO_2 for two coal-fired units at the plant in Waterflow, NM. *(FE0031843)*

MTR – Dry Fork Station (400 MWe)

Membrane Technology and Research Inc. completed a FEED study on its innovative high-performance Polaris™ membrane packaged in low-pressure-drop membrane modules. This low-cost capture system is projected to be below $40/tonne CO_2 at the Gillette, WY, coal-fired plant. *(FE0031846)*

Rendering and photograph of containerized membrane module stacks.

VALUABLE DATA FROM FEED STUDIES

FEED studies provide a rigorous analysis of realistic operating costs for the creation of new processes, validating several options for technologies that can achieve commercial success at various host sites.

Increased confidence in the accuracy of cost estimates makes partnering with commercial interests more favorable, enabling the eventual widespread implementation of carbon capture technologies.

PARTNERS

EPRI ELECTRIC POWER RESEARCH INSTITUTE · TEXAS The University of Texas at Austin · UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN · Southern Company · BECHTEL · ENCHANT ENERGY · MTR MEMBRANE TECHNOLOGY & RESEARCH

AWARD NUMBERS

FE0031841, FE0031842, FE0031843, FE0031844, FE0031846, FE0031847, FE0031848

PROJECT BUDGET

COMBINED FUNDING

$55.8M

DOE $44,617,246
PARTNERS $11,166,745

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Andrew O'Palko
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Naomi O'Neil

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FECM RDD&D PRIORITY

POINT-SOURCE CARBON CAPTURE

CLICK BUTTONS FOR MORE INFORMATION

FE0031841 · FE0031842 · FE0031843 · FE0031844 · FE0031846 · FE0031847 · FE0031848

NETL COMPLETES THREE ENGINEERING-SCALE FIELD TESTS AT TECHNOLOGY CENTRE MONGSTAD (TCM)

Post-combustion carbon capture technologies validated at world's largest industrial test facility to confirm readiness for commercial-scale deployment.

CARBON CAPTURE TECHNOLOGIES VALIDATED IN FIELD TESTS

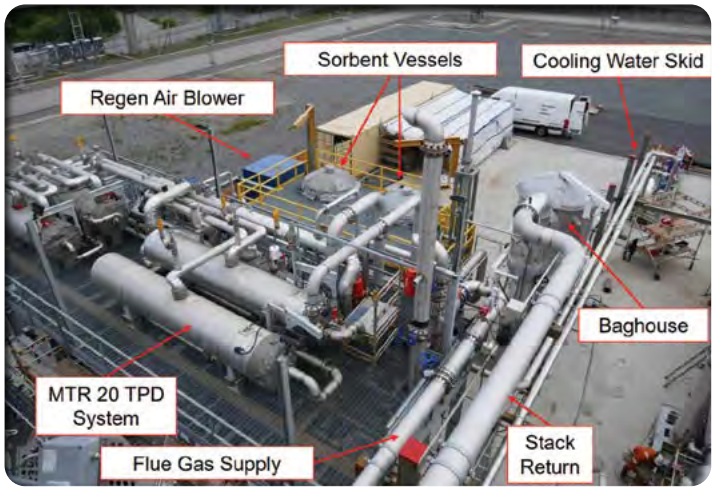
Three engineering-scale field tests of advanced carbon dioxide (CO_2) capture technologies matured by the U.S. Department of Energy (DOE) were completed at TCM in Norway. The completion of these engineering-scale field tests greatly enables the further scale-up and development of CO_2 capture technologies toward the ultimate goal of widespread commercial deployment.

PLATE-AND-FRAME MEMBRANE MODULE STACKS OPERATED IN CONTAINERIZED SKID

Membrane Technology and Research Inc. (MTR) tested a next-generation Polaris™ membrane housed in low-pressure drop modules for post-combustion carbon capture at 1 MWe-scale. The pilot system was tested over a range of CO_2 capture rates from 50% to >90%. MTR plans to continue advancing the modular membrane capture system by performing large-pilot (10 MWe) tests at the Wyoming Integrated Test Center. *(FE0031591)*

Planar module stacks with Gen-2 Polaris™ (2022 TCM field test).

TDA SORBENT COMBINED WITH MTR MEMBRANE TECHNOLOGY FOR HIGH CO_2 CAPTURE EFFICIENCY

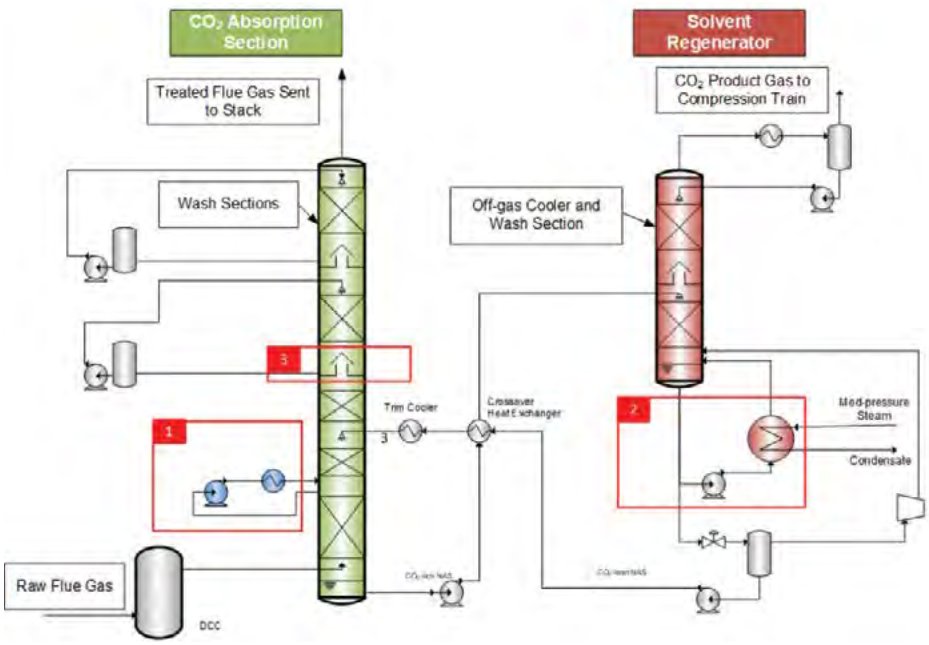


TDA Research operated an engineering-scale (1 MWe) hybrid post-combustion CO_2 capture system that combines a polymeric membrane and low-temperature physical absorbent. A 10-month test campaign was performed on the field unit at TCM using flue gas from the Residual Unit Catalytic Cracker at the adjacent Mongstad Refinery and flue gas from the Combined Heat and Power facility. The system processed ~1,890 tonnes of CO_2 with an overall capture efficiency of ~87.1% throughout the test campaign, with 1,789 hours of operation at a capture efficiency of ≥90% and 307 of those hours at ≥95% capture efficiency. *(FE0031603)*

RTI'S SOLVENT TECHNOLOGY ADVANCES TO LARGE PILOT-SCALE

RTI International has completed testing their transformational water-lean solvent for post-combustion CO_2 capture using the modified large pilot-scale (~12 MWe) plant at TCM. High-efficiency capture of >99% from natural gas combined cycle flue gas was achieved. The TCM test campaign validated that the RTI solvent exhibits a lower reboiler duty than monoethanolamine and negligible heat of vaporization, resulting in reduced thermal regeneration energy load. In addition, the amine emissions remained at <1 ppm during testing with use of the acid wash system. *(FE0031590)*

RTI INTERNATIONAL



TCM amine plant modifications.

PARTNERS

CCSI² Carbon Capture Simulation for Industry Impact
gti.
EPRI ELECTRIC POWER RESEARCH INSTITUTE
TECHNOLOGY CENTRE MONGSTAD
DRESSER-RAND A Siemens Business
SINTEF
WorleyParsons resources & energy
TRIMERIC CORPORATION
TEXAS The University of Texas at Austin
UNIVERSITY OF OSLO
PRESSURA
UCI University of California, Irvine

AWARD NUMBER
FE0031591
PROJECT BUDGET
$10.6M
DOE $8,166,304
PARTNERS..... $2,493,181

CLICK HERE FOR MORE INFORMATION ON FE0031591

AWARD NUMBER
FE0031603
PROJECT BUDGET
$11.5M
DOE $9,198,799
PARTNERS..... $2,299,725

CLICK HERE FOR MORE INFORMATION ON FE0031603

AWARD NUMBER
FE0031590
PROJECT BUDGET
$17.4M
DOE $10,013,513
PARTNERS..... $7,371,000

CLICK HERE FOR MORE INFORMATION ON FE0031590

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FECM RDD&D PRIORITY

POINT-SOURCE CARBON CAPTURE

NETL DRIVES THE ADVANCEMENT OF CRYOGENIC CARBON CAPTURE TECHNOLOGIES

NETL supported the development of this transformational carbon capture technology that has advanced from small pilot testing to integrated, pilot-scale testing.

TESTING SUCCESS AT THE SMALL PILOT SCALE

Transformational Capture Technology

Sustainable Energy Solutions (SES) developed its **cryogenic carbon capture (CCC) technology for efficient carbon capture** with small pilot testing in earlier projects.

SES **successfully met its goals and achieved greater than 90% carbon capture** at a cement plant, which was subsequently utilized in concrete production.

CCC small pilot.

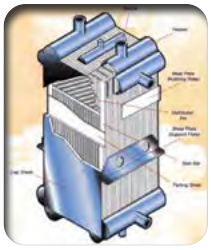
Concrete use with CarbonCure.

TECHNOLOGY ACQUIRED FOR COMMERCIAL DEPLOYMENT

Chart Industries' Experience Provides Additional Expertise

SES was acquired by Chart Industries in 2020, allowing for a **smooth transition due to the high degree of overlap** in equipment used for the CCC process.

The process can incorporate some of **Chart's complementary technologies**, including their "cold box" equipment, a bolt-on natural gas liquids recovery module, and their IPSMR® liquefaction process.



Schematic and photograph of examples of Chart Industries' relevant equipment.

LARGE PILOT PROJECT BEGINS

Sugar Creek Cement Plant Will Host

The next phase of the advancement of this technology will be a **30-tonne per day (TPD) CCC pilot design** based on the field-tested 1 TPD unit at an operating cement plant.

The skid-based design can be built mostly off site with limited field construction.

This project will demonstrate:

- The ability to cool the gas to at least minus 117 C.
- Complete continuous testing for a minimum of two months.
- 95% capture with 95% CO_2 purity at 30 TPD CO_2.
- Full-scale techno-economic analysis showing energy of CO_2 captured less than 0.83 MJe/kg CO_2.

The project began in early 2022 and is expected to complete testing by the end of 2024.

3-D model of a proposed site including the CCC skid.

Photo of a constructed CCC skid.

COMMERCIAL POTENTIAL OF CCC

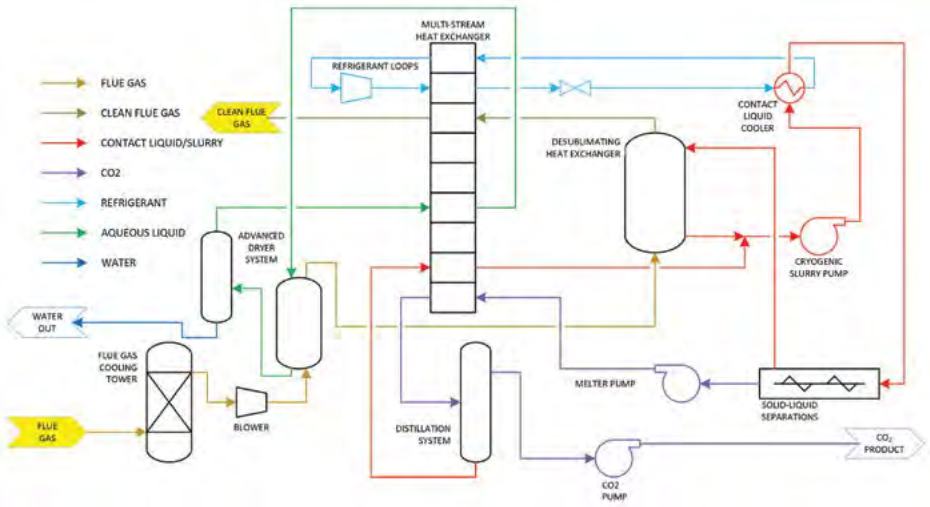
An Efficient Cryogenic Approach To Carbon Capture

CCC technology can be applied to post-combustion flue gases and uses **multi-stream heat exchangers to optimize energy use for its intense cooling**.

The process works by first cooling the flue gas to extremely low temperatures, followed by a separation of light gases from the solidified CO_2.

The dry ice form of CO_2 is then melted and prepared for transport, while the light gases are released back into the atmosphere.

Carbon dioxide in its solid form.



Simplified process flow diagram of CCC technology.

Potential advantages of the CCC process include:

- Low energy and low-cost technology.
- Easy retrofit carbon capture system.
- Robust to pollutants and captures most criteria pollutants.
- Produces high-purity liquid CO_2.
- Very high capture rates (99+%).

The successful maturation of CCC technology up to commercial deployment **establishes a precedent for future promising NETL-supported carbon capture technologies**.

PARTNERS

SES INNOVATION

CHART

FLSmidth

Eagle Materials

Sargent & Lundy

AWARD NUMBER

FE0032148

PROJECT BUDGET

DOE $4,999,849
PARTNERS..... $10,350,226

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FECM RDD&D PRIORITY

POINT-SOURCE CARBON CAPTURE

CLICK HERE FOR MORE INFORMATION

SOLVENT ACHIEVES 98% CAPTURE EFFICIENCY ON NATURAL GAS FLUE GAS

Advanced water-lean solvent technology with enhanced CO_2 capture efficiency and exceptional solvent stability.

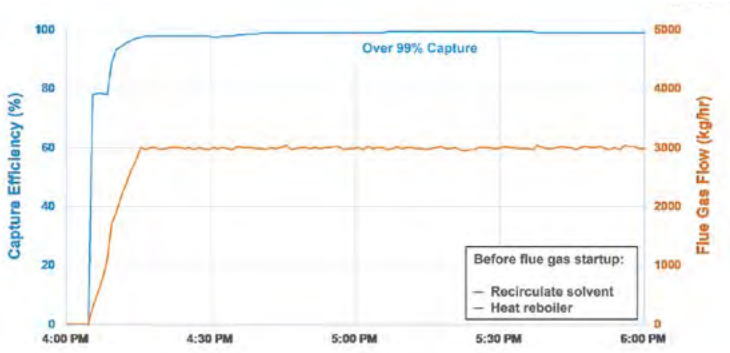
SOLVENT PERFORMANCE VALIDATED AT PILOT-SCALE

ION Clean Energy (ION) successfully completed a six-month testing campaign of its third-generation solvent technology, ICE-31, at the National Carbon Capture Center (NCCC) in Wilsonville, Alabama. The campaign at NCCC operated for more than 4,000 hours and included parametric and long-term steady-state testing on flue gas from a natural gas steam boiler unit (4.4 - 8% CO_2) and actual coal-fired flue gas (13% CO_2).

Continuous steady-state operation of the solvent technology in the 0.6 MWe Pilot Solvent Test Unit for 1,500+ hours resulted in 95%+ CO_2 capture from natural gas boiler flue gas.

Parametric tests validated a lower specific reboiler duty compared to commercial monoethanolamine (MEA) solvent; specifically, 3.0 GJ/tonne CO_2 was achieved on 4% CO_2 natural gas-fired flue gas at 95% capture, and 2.5 GJ/tonne CO_2 on 13% CO_2 coal-fired flue gas at 91% CO_2 capture. In addition, the solvent **achieved 98% CO_2 capture efficiency with minimal specific energy increase (relative to 95% capture) on natural gas flue gas**. CO_2 capture ramp rates to 98%+ were also exhibited within minutes from warm start-up, indicating flexibility for dynamic operations necessary in load-following commercial environments.

Long-term steady-state operation.



Capture-ready warm start-up.

ICE-31 Solvent Development Path

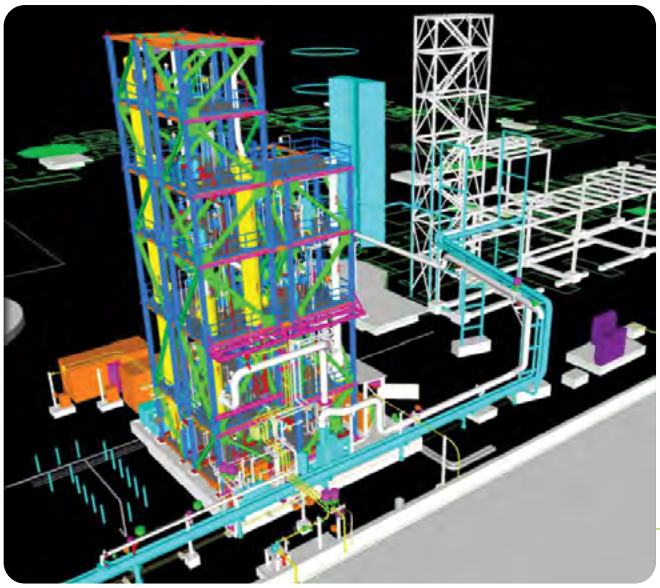
SOLVENT TECHNOLOGY ADVANCES THROUGH LONG-TERM FIELD TESTING WITH ACTUAL FLUE GAS

ION will field test ICE-31 on a 1 MWe slipstream of flue gas from Calpine's Los Medanos Energy Center (LMEC), a commercially dispatched natural gas combined cycle (NGCC) power plant.

The kinetic performance and solvent stability of ICE-31 for CO_2 absorption from NGCC flue gas will be validated against baseline test results for ICE-21 (second-generation) and MEA solvents.

ION is utilizing a **modular design and fabrication approach** for the engineering-scale system combined with **process intensification** improvements, which will result in a smaller physical plant, reduced energy requirements, less solvent degradation, lower emissions, lower water usage, less maintenance, and lower capital costs.

The testing will further validate this technology's expected suitability for future commercial-scale deployment to enable **deep decarbonization of NGCC power plants**.



Modular pilot system design for field test at LMEC.

ION CLEAN ENERGY

PARTNERS

OGT Optimized Gas Treating, Inc.

Koch Modular

CSIRO

NC NATIONAL CARBON CAPTURE CENTER

Hellman & ASSOCIATES BUILDING PARTNERSHIPS FOR A SAFER WORKPLACE

Sargent & Lundy

CALPINE

AWARD NUMBER
FE0031727

PROJECT BUDGET
$3.7M

- DOE $2,999,998
- PARTNERS $750,000

CLICK HERE FOR MORE INFORMATION

AWARD NUMBER
FE0031950

PROJECT BUDGET
$25.1M

- DOE $19,008,203
- PARTNERS $6,086,414

CLICK HERE FOR MORE INFORMATION

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FECM RDD&D PRIORITY

POINT-SOURCE CARBON CAPTURE

NETL CATALYSTS PRODUCE COST-COMPETITIVE CHEMICALS WITH MASSIVE CARBON SAVINGS

Microwave catalysts developed by NETL researchers reduce associated CO_2 emissions by nearly 200% compared to state-of-the-art methods.

NETL'S MICROWAVE CATALYST ANTICIPATED TO PRODUCE COST-COMPETITIVE METHANOL FROM CO_2

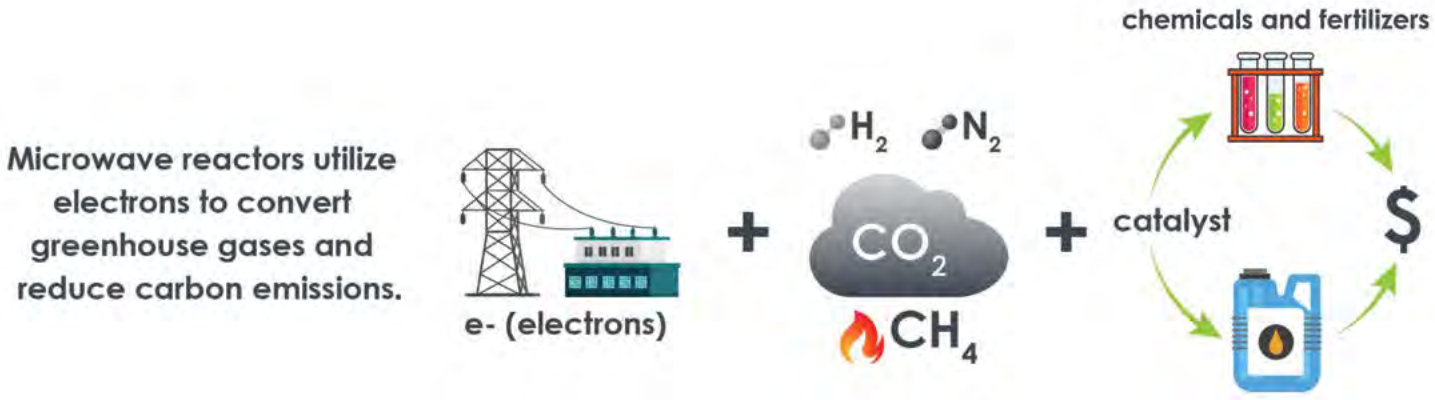
NETL's microwave catalysts can convert a mixture of CO_2 and methane into methanol at a levelized production cost of $1–2 dollars per gallon.

- Conventional, fossil-derived methanol production cost is approximately $1/gallon.
- Preliminary economic analysis suggests NETL's process can achieve cost-parity with fossil-based methanol with further optimization.

This process would produce a sustainable, cost-competitive chemical with a **200% reduction in CO_2 emissions**!

MICROWAVE-ASSISTED CO_2-DERIVED METHANOL PROCESSES

NETL uses microwaves to convert CO_2 and methane into the chemical feedstocks needed to produce high-volume industrial chemicals such as methanol. NETL's process is anticipated to drastically reduce carbon emissions and generate revenue. The project's combination of applied research and economic analysis exemplifies the ability of early-stage research to identify, evaluate, and demonstrate emerging carbon conversion strategies.

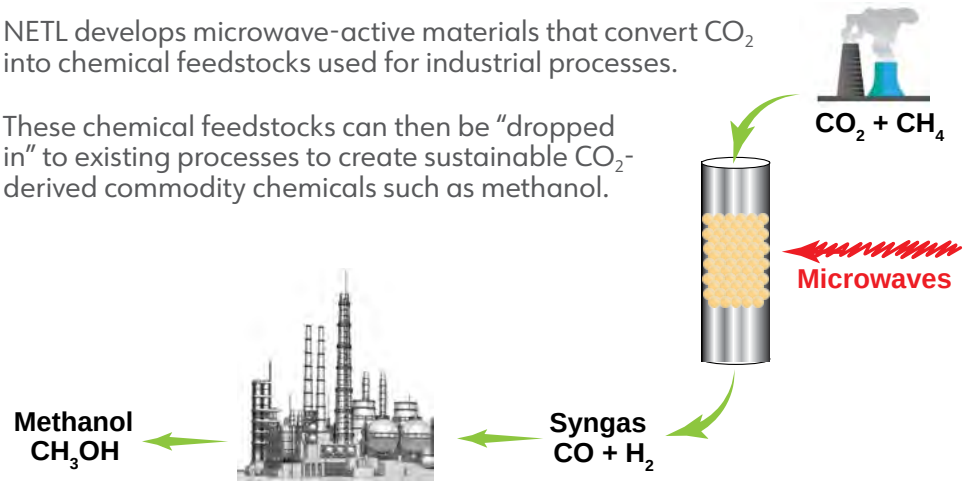


MICROWAVE SYSTEMS CAN OPERATE USING EXCESS CARBON-NEUTRAL ELECTRICITY

Microwave reactors can operate using excess carbon-neutral electricity to efficiently produce chemicals.

NETL develops microwave-active materials that convert CO_2 into chemical feedstocks used for industrial processes.

These chemical feedstocks can then be "dropped in" to existing processes to create sustainable CO_2-derived commodity chemicals such as methanol.



U.S. PATENTS ARE PENDING, AND ENGAGEMENT OF INDUSTRIAL PARTNERS IS UNDERWAY

NETL has filed patents and published many peer-reviewed articles demonstrating proof-of-concept of this technology.

PARTNER

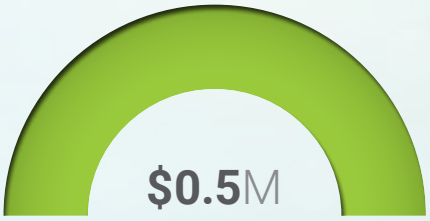
NU:IONIC TECHNOLOGIES

AWARD NUMBERS

FWP-1022426
FWP tasks 2.4, 5.2.4, and 6

PROJECT BUDGET

EY22 FUNDING



DOE $500,000

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FECM RDD&D PRIORITIES

CARBON DIOXIDE CONVERSION

CLICK HERE FOR MORE INFORMATION

NETL ESTIMATES THE COST OF PERFORMING SOLVENT AND SORBENT-BASED DIRECT AIR CAPTURE (DAC)

Analysis addresses a critical need for an independent assessment of the cost of DAC.

NETL'S INDEPENDENT COST ASSESSMENT SHOWS COST OF DAC CO_2 CAPTURE CAN LIKELY BE REDUCED TO LESS THAN $300/TONNE ON A NET CO_2 REMOVED BASIS

Generic Solvent-based DAC System Case Overview

Analysis considers three unique DAC system cases.

- **Case 1:** The DAC system captures a gross 909,225 tonne/yr CO_2 and net 903,970 tonne CO_2/yr (1 million ton/yr) when the NGCC power source is equipped with 187,131 tonne/yr CO_2 capture and when 314,926 tonne/yr CO_2 is captured from an oxy-fired calciner.
- **Case 1 CPU:** Essentially the same as Case 1 but incorporates a CO_2 compression and purification unit. Additionally, any excess electricity from the on-site combustion and stream turbines is sold for $60/MWh.
- **Case 1A:** Essentially the same as Case 1 but with a smaller net CO_2 removal scale of 100,000 tonne/yr.

Generic Sorbent-based DAC System Case Overview

Analysis considers two unique DAC system cases described in the table below, in which a net 100,000 tonne/yr of CO_2 is removed from the atmosphere in each case.

Case	Sorbent Configuration	Power Source	CO_2 Captured from Power Source, tonne/yr	CO_2 Captured from DAC, tonne/yr
OB	Monolith	NGCC with 90% CCS	125,090	113,900
OB-EB		Carbon free electricity (purchased at $60/MWh)	N/A	100,000

NETL STUDY USES "NET CO_2 REMOVED" COST BASIS

Cost estimates by solvent and sorbent technology developers to remove CO_2 from the atmosphere via solvent or sorbent technologies span a range of $95–$600/tonne.

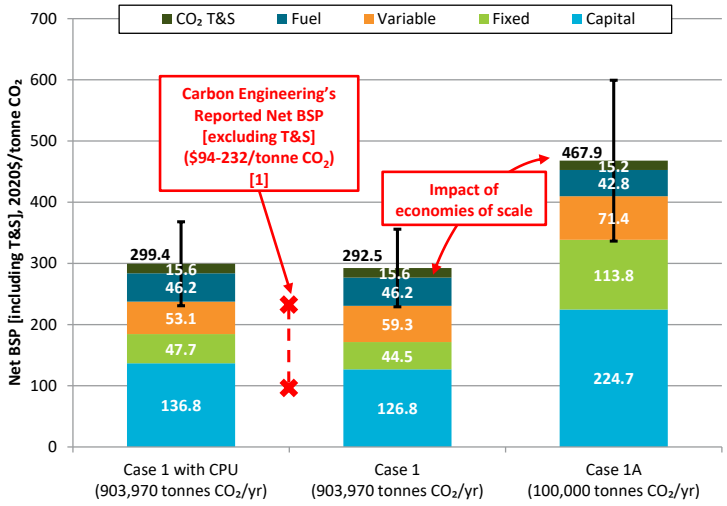
- However, some lower-cost estimates do not account for the CO_2 emissions from the source of power used by DAC— **a critical consideration**.
- Estimates such as those produced by NETL use a "Net CO_2 Removed" basis where the DAC cost of CO_2 removal is divided by the **net** amount of CO_2 removed — including DAC power source emissions.
- **While the estimated cost of DAC can be significantly higher, the "Net CO_2 Removed" basis is a more informative metric.**

DAC Type	Electric /Thermal Energy Source	Capture Costs ($/tonne CO_2)	Net CO_2 Removed (Mt/yr)	Net CO_2 Removed Costs ($/tonne CO_2)
Generic Solid Sorbent	Solar /solar	88-228	0.892-0.992	89-256
	Nuclear /nuclear	88-228	0.91-0.994	89-250
	Solar /natural gas	88-228	0.70-0.78	113-326
	Wind / Natural Gas	88-228	0.56-0.71	113-326
	Natural gas / natural gas	88-228	0.56-0.71	124-407
	Coal / coal	88-228	0.26-0.53	166-877

Cost Basis Matters

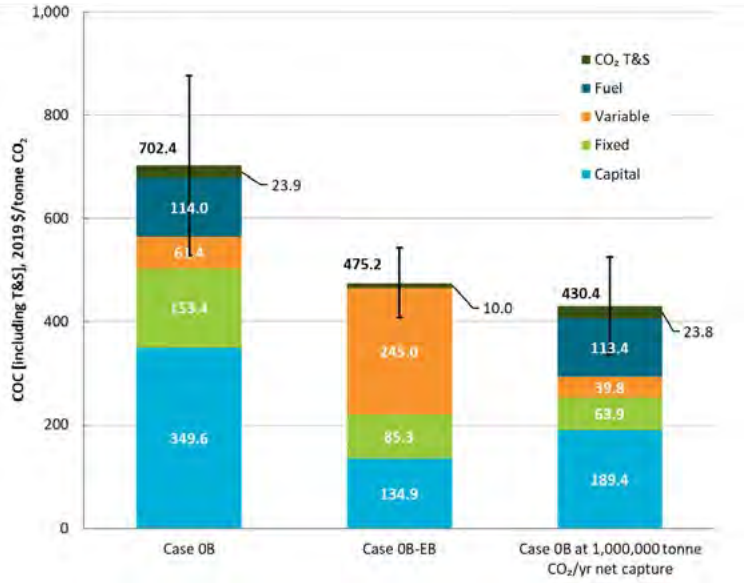
Table adapted from NAS study: The National Academy of Sciences, Engineering, and Medicine, "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda," Washington, DC, 2016.

SOLVENT-BASED DAC CO_2 REMOVAL COSTS



- **Case 1 CPU** (903,970 tonne/yr scale): $299.4/tonne net CO_2 removed.
- **Case 1** (903,970 tonne/yr scale): $292.5/tonne net CO_2 removed.
- **Case 1 A** (100,000 tonne/yr scale): $467.9/tonne net CO_2 removed.

SORBENT-BASED DAC CO_2 REMOVAL COSTS



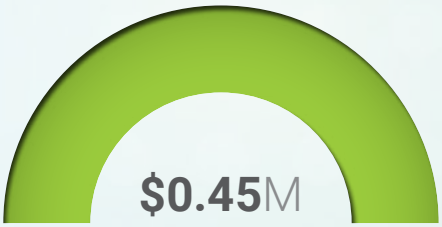
- **Case 0B** (100,000 tonne/yr scale): $702.4/tonne net CO_2 removed.
- **Case 0B-EB** (100,000 tonne/yr scale): $475.2/tonne net CO_2 removed.
- **Case 0B** (1,000,000 tonne/yr scale): $430.4/tonne net CO_2 removed.

AWARD NUMBER

FWP-1022402

PROJECT BUDGET

EY22 FUNDING



DOE $450,000

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PRINCIPAL INVESTIGATOR
Timothy Fout

FECM RDD&D PRIORITY

CARBON DIOXIDE REMOVAL

CLICK HERE FOR MORE INFORMATION

NETL RELEASES 2022 COMPENDIUM OF CARBON CAPTURE TECHNOLOGY

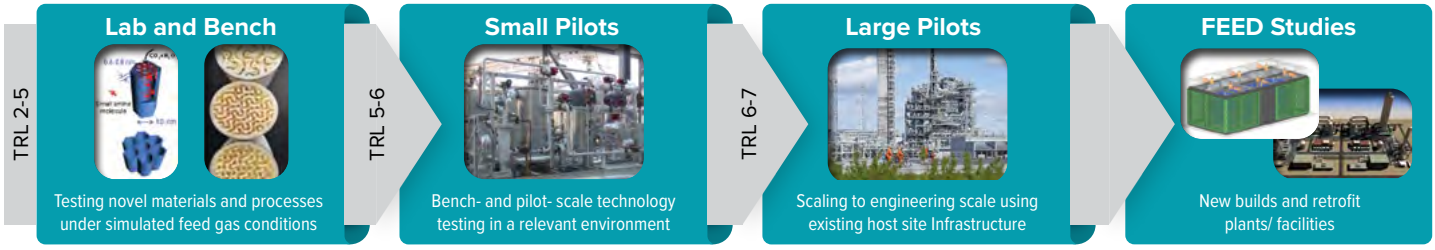
Comprehensive document featuring descriptions of NETL's carbon capture and removal R&D efforts.

COMPILATION OF NETL-SPONSORED CARBON CAPTURE AND REMOVAL R&D PROJECTS

The Compendium provides a technical summary of 124 carbon dioxide (CO_2) capture and removal technology research and development (R&D) projects implemented by the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) Point-Source Capture (PSC) and Carbon Dioxide Removal (CDR) Programs into a single document. All projects within the 2022 Compendium were active at some point between October 1, 2019, and October 1, 2021.

CARBON CAPTURE TECHNOLOGY R&D AT VARIOUS SCALES

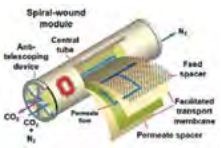
The Compendium includes R&D performed at a range of scales, from front-end engineering design (FEED) and pre-FEED, to large- and small-scale pilot testing (Technology Readiness Level [TRL] 6–7), to conceptual engineering and materials design at bench and laboratory scale (TRL 2–5).



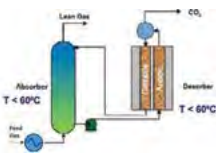
R&D efforts featured in the 2022 Compendium include the development of advanced solvents, sorbents, membranes, hybrid approaches, novel concepts, and key enabling technologies.

Solvents

Sorbents



Membranes



Novel Concepts

Hybrids

Enabling Technologies

MULTI-PRONGED APPROACH FOR CARBON MANAGEMENT

DOE's Office of Fossil Energy and Carbon Management (FECM) is developing both PSC and CDR technologies as part of its multi-pronged approach to support the U.S. in achieving its goals for a greenhouse gas (GHG)-neutral economy by 2050, a carbon-pollution-free power sector by 2035, and a 50% reduction from 2005 levels in economy-wide net GHG pollution by 2030.

The Compendium includes carbon management technologies with a broad range of applications:

- PSC (pre-combustion and post-combustion capture from fossil fuel-based power generation and industrial sources).
- CDR (e.g., direct air capture, biomass carbon removal and storage, and enhanced mineralization technologies).

PSC for Power Generation and Industrial Sectors


Power Plants


Cement Plants


Ethanol Plants


Steel Plants


Hydrogen Plants


Petrochemical Plants

CDR from Air


Direct Air Capture


Enhanced Mineralization


Bioenergy Carbon Removal and Storage (BiCRS)

The success of the research highlighted in the 2022 Compendium of Carbon Capture Technology will enable cost-effective implementation of carbon capture and removal technologies to help decarbonize the power generation and industrial sectors, remove CO_2 from the atmosphere, and mitigate the environmental impacts of fossil fuel production and use.

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Andrew Jones

FECM RDD&D PRIORITIES

CARBON DIOXIDE REMOVAL

POINT-SOURCE CARBON CAPTURE

CLICK HERE FOR MORE INFORMATION

OCSS: OFFSHORE CO_2 SALINE STORAGE METHODOLOGY AND CALCULATOR

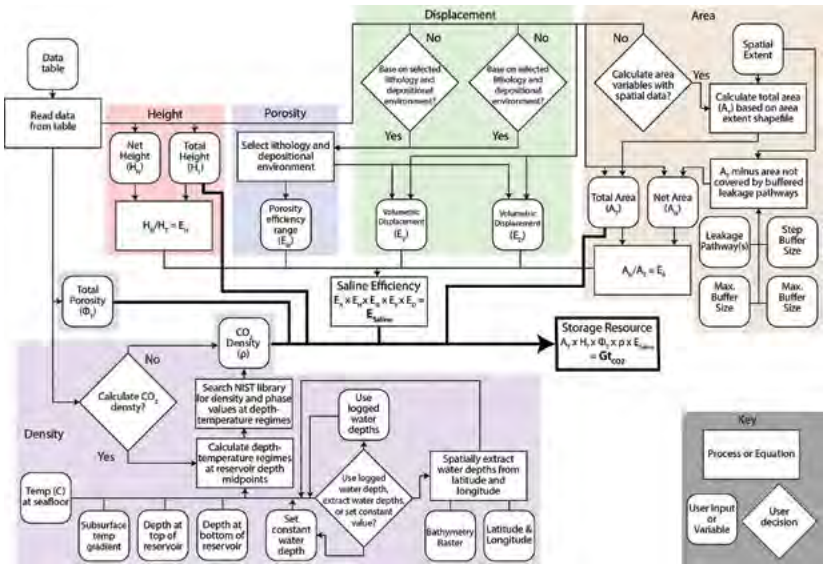
NETL researchers provide timely insights into offshore saline carbon storage potential assessment and risk reduction.

OFFSHORE SALINE RESERVOIRS: POTENTIAL CARBON STORAGE (CS) RESOURCE OPPORTUNITIES

The U.S. Department of Energy's (DOE) NETL published a **data-science-informed methodology and tool** for evaluating, characterizing, and quantifying CS potential in offshore saline reservoirs to **advance understanding** of offshore saline systems.

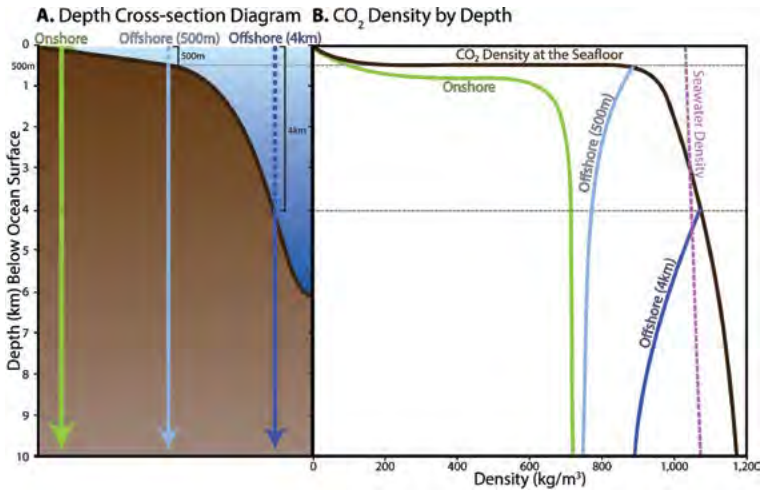
The methodology incorporates data, tools, and models from **NETL's R&D 100 award-winning Offshore Risk Modeling Suite** to support safe injection site selection strategies.

Remotely located below marine environments, saline reservoirs are potential resources that could serve as long-term, high-capacity storage for CO_2.



Framework of the Offshore CO_2 Saline Storage Calculator's logic. Background colors represent how different variables are handled (e.g., height, porosity). Figure from Romeo et al., 2022.

PUBLISHED THE SCIENCE-BASED METHODOLOGY IN THE HIGH IMPACT *INTERNATIONAL JOURNAL OF GREENHOUSE GAS CONTROL*.



(A.) Cross-section of onshore to offshore seafloor and injection points at depth below the ocean surface (0 m, 500 m, and 4 km).

(B.) Diagram showing CO_2 density values at the seafloor, injection points (as shown in diagram A), and the density of seawater. Diagram B shares a depth axis with the cross-section in diagram A.

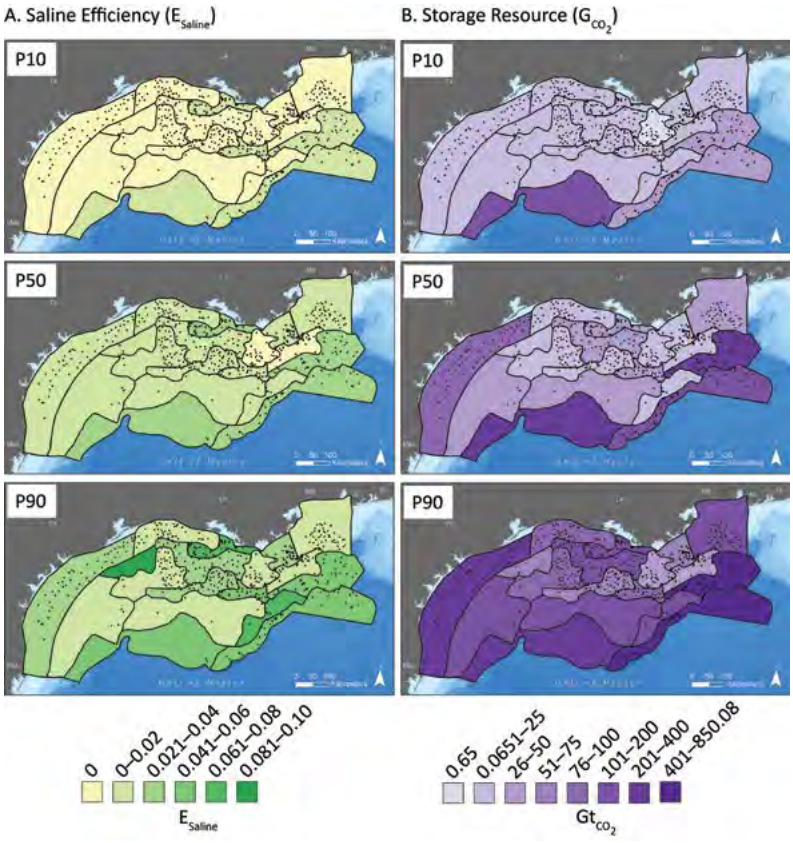
This big data-science-informed methodology and tool support DOE's carbon-negative goals and aligns with regulatory and commercial decision support requirements to responsibly unlock the potential of offshore CS.

This improves resource estimates, mitigates risks, and assesses reservoir and infrastructure reuse potential.

The adapted DOE-NETL methodology coincides with ongoing rule making by the U.S. Department of Interior charged with establishing the first set of regulations and rules for offshore CS in federal waters under the 2021 Bipartisan Infrastructure Law.

PROSPECTIVE STORAGE RESOURCE ESTIMATES FOR AREAS THROUGHOUT THE GULF OF MEXICO

Filling the niche prior to site-specific, temporally dynamic analytics, the OCSS Calculator estimates prospective reservoir volumes for CS. Demonstrable applications of the OCCS Calculator, as featured in the paper, include estimates for 18 geologically distinct domains, which were spatially defined by NETL's Subsurface Trend Analysis™ (*Rose et al., 2020*). Applications relied on spatial data, information from literature, and two to 50 interpreted petrophysical well logs per domain, which defined variables including porosity, sealing shales, and thickness. Results showed CO_2 to be in the liquid or supercritical phase at reservoir depth, with storage estimates ranging from 0.5 to more than 10,000 gigatons of CO_2. The calculator and relevant data are available for download on EDX®.



Calculated 10th, 50th, and 90th percentiles of (A) saline efficiency (E_{Saline}) values and (B) gigatons of CO_2 by geologic domain.

KEY RESOURCES

CLICK HERE TO ACCESS THE OCSS CALCULATOR

CLICK HERE TO VIEW THE JOURNAL PUBLICATION

AWARD NUMBER

FWP-1022465

PROJECT BUDGET

EY22 FUNDING

$0.25M

DOE $250,000

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FECM RDD&D PRIORITIES

RELIABLE CARBON STORAGE AND TRANSPORT

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PROOF-OF-CONCEPT DEMONSTRATED FOR SCIENCE-INFORMED MACHINE LEARNING TO ACCELERATE REAL-TIME (SMART) SUBSURFACE APPLICATIONS

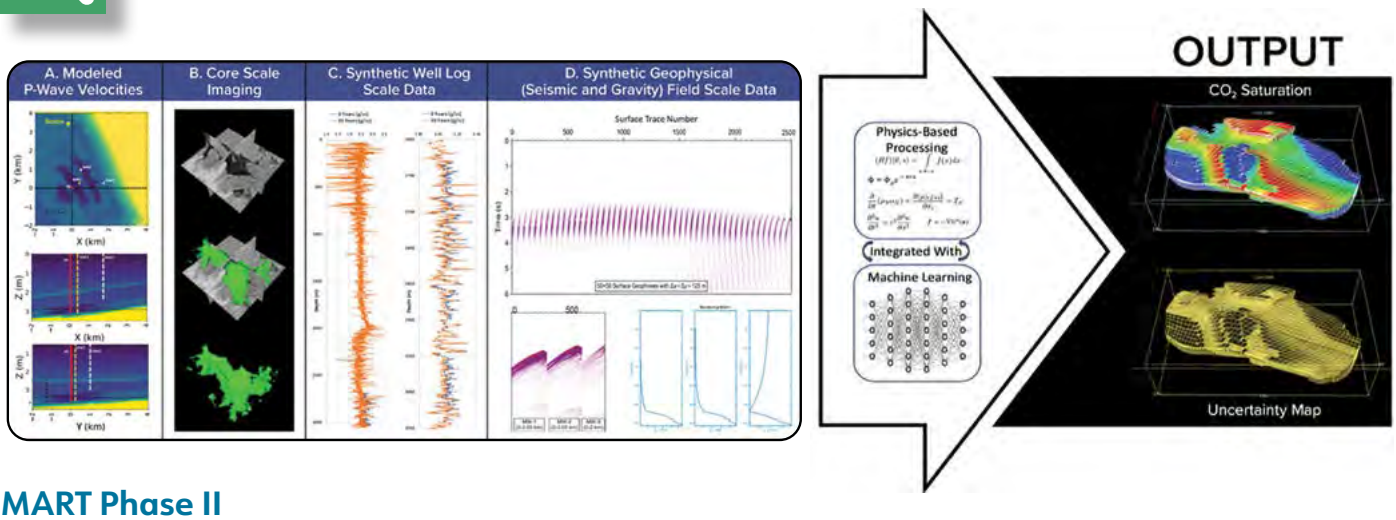
NETL researchers advance SMART Phase II Development and Validation after proof-of-concept was demonstrated through machine learning-based workflows and platforms.

PROOF-OF-CONCEPT ADVANCES DEVELOPMENT AND VALIDATION

Evaluated existing state-of-the-art technologies for incorporating multiple types of data to provide CO_2 saturation images and quantify uncertainty in real-time.

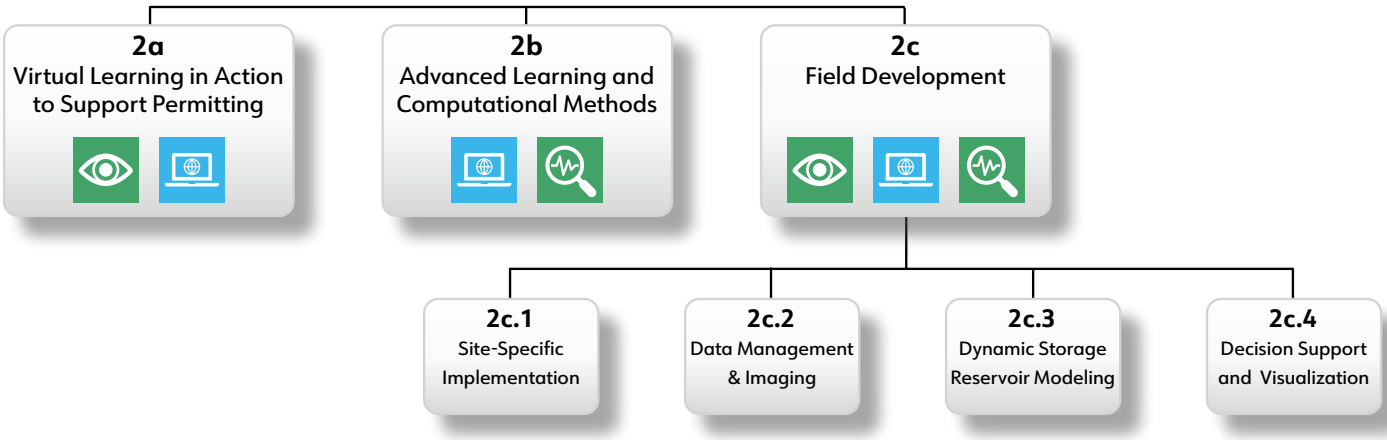
Developed a prototype, demonstrating that an interactive platform using machine learning-based models can be built.

Evaluated existing state-of-the-art machine learning approaches to integrate into a workflow for rapid CO_2 and pressure plume forecasting.



SMART Phase II

- Demonstrate virtual learning in action to support regulators and stakeholders during permitting (Task 2a).
- Develop advanced learning computational methods (Task 2b).
- Apply machine learning-assisted workflows from Phase I for field deployment (Task 2c).



TRANSFORMING DECISIONS THROUGH CLEAR VISION OF THE PRESENT AND FUTURE SUBSURFACE

SMART objectives are to provide added value for decision making and to develop tools for rapid deployment of carbon storage projects. Key research areas:

SMART

Real-Time Visualization

"CT" for the Subsurface

Real-Time Visualization of Key Subsurface Features and Flows

Enable dramatic improvements in the visualization of key subsurface features and flows by exploiting machine learning to improve speed and enhance detail.

Rapid Prediction

Virtual Learning

Virtual Learning for Rapid Prediction of Reservoir Behavior

Perform rapid analysis of real-time data to inform operational decisions and transform reservoir management.

Real-Time Forecasting

"Advanced Control Room"

Real-Time Forecasting of Actively Managed Carbon Storage Systems

Develop a computer-based experiential learning environment to improve field development and monitoring strategies.

PARTNERS

Bureau of Economic Geology · The University of Utah · PennState · Pacific Northwest National Laboratory · Texas A&M · Carnegie Mellon University · Colorado School of Mines · Lawrence Livermore National Laboratory · Battelle · EERC · Los Alamos National Laboratory · Oak Ridge National Laboratory · Berkeley Lab · FACT · University of North Dakota · Illinois · Sandia National Laboratories · West Virginia University

AWARD NUMBER

FWP-1025011

PROJECT BUDGET

DOE $8,749,999
PARTNERS $6,248,767

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RELIABLE CARBON STORAGE AND TRANSPORT

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CARBONSAFE STORAGE EFFORTS ADVANCE UNDERSTANDING OF LARGE-SCALE STORAGE AT SIX SITES

CarbonSAFE Phase III projects are catalyzing the growth of commercial dedicated storage sites and hubs.

COMPLETED CHARACTERIZATION OF SIX STORAGE COMPLEXES

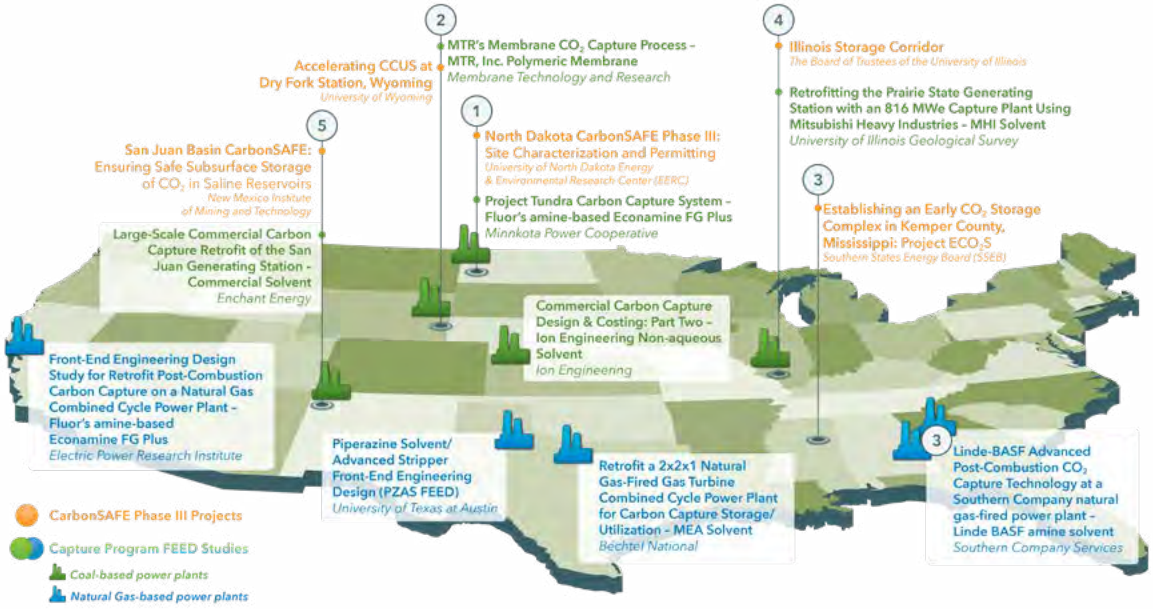
Dedicated Storage that can safely store >50MMT of CO_2 over a 30-yr period.

Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Phase III projects have characterized six storage complexes (two in Illinois, one in North Dakota, one in New Mexico, one in Mississippi, and one in Wyoming) collectively capable of storing at least **975 million metric tons (MMT) of CO_2 over 20 years**. Characterization has included drilling **15 wells, 303.6 total linear miles of 2-D seismic lines (24 lines), and 136.5 square miles of 3-D seismic**. At least **20 MMT of CO_2 is produced per year** by the sources that will feed the storage sites.

The alignment of these projects with five of the nine sites for the DOE Carbon Capture Program's front-end engineering and design (FEED) studies represents an integrated strategy as the foundation for regional CO_2 hubs anchored by these CarbonSAFE facilities.

These projects will apply for at least seven Underground Injection Control (UIC) Class VI permits. Once these sites acquire Class VI permits, they will represent 950 MMT of commercial storage capacity in the United States ready for storage operations.

CarbonSAFE projects are integrated with five capture FEED studies.



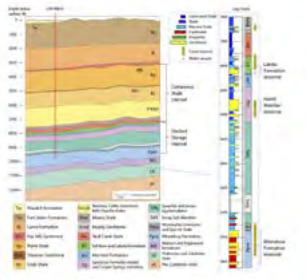
Key	Plant(s) (MMT/yr CO_2)	Storage Location by County	Prospective CO_2 Storage (MMT of CO_2)	Charac. Wells	2D seismic lines	3D seismic
1	Milton R. Young Unite 2, ND (4)	Hensler, ND	80	4 (3 fed-funded)	26 mi. collected	18.5 sq. miles
2	Basic Electric Dry Fork Station, WY (2)	Gillette, WY	>50	2	56.6 mi. collected	9 sq. miles
3	Plant Daniels 3&4, MS Or Plant Barry 6&7, AL (>1.7)	Kemper County, MS	500-1,800	7 (6 deep wells, 1 USDW well)	92 mi. acquired	none
4	Prairie State Generating Co: One Earth Energy, IL (1 to 8)	Gibson City, IL Marissa, IL	64 (site 1) 162 (site 2)	2 (1 at each site)	129 mi. collected (2 sites)	9 sq. miles (1 site)
5	San Juan Generation Station, NM (6 to 7)	San Juan County, NM	120	0 (1 planned)	none	100 sq. miles

1 Two Class VI UIC permits to construct obtained.

- Near Minnkota's Milton R. Young Station 455-megawatt (MW) Unit 2.
- Less than 4 MMT/yr of CO_2.
- Two Class VI UIC permits to construct injection wells were signed on Jan. 21, 2022.

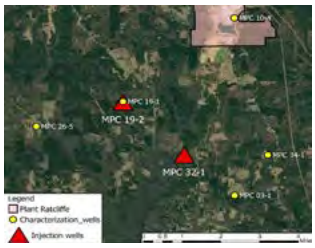
2 Two wells completed to Class VI standards.

- Campbell County, Wyoming, at Basin Electric's Dry Fork Station.
- 2.2 MMT CO_2/yr.
- Two wells were completed to Class VI standards, facilitating their use as project monitoring wells.
- Between nine and twelve Class VI permit applications will be submitted.



3 One Class VI UIC permit to construct submitted.

- Two-to-three gas-fired power plants and possibly a few industrial sources.
- Less than 900 MMT of CO_2 over a 30,000-acre area.
- Two Class VI UIC permit applications ongoing. First submitted to EPA Region 4 in August 2022.

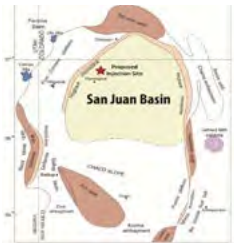


4 Two Class VI UIC permits to construct in progress.

- Prairie State Generation Company, 1,600 MW.
  - Six million tons per acre (MTPA) of CO_2.
  - Class VI permit writing currently in progress.
- One Earth Energy ethanol plant, 450,000 tons CO_2/yr.
  - 0.5 to 1.7 MTPA CO_2.
  - Class VI permit writing currently in progress.

5 90% of documentation for permit complete.

- San Juan Generating Station, 847-MW.
- Six-to-seven MMT CO_2/yr.
- Currently completed approximately 90% of the required documentation for a UIC Class VI permit.



CARBONSAFE LEADS

ILLINOIS
Illinois State Geological Survey

New Mexico Tech
Energetic Materials Research and Testing Center

EERC
Energy & Environmental Research Center®

University of Wyoming

Southern States Energy Board

AWARD NUMBERS

FE0031891, FE0031890, FE0031889, FE0031892, FE0031888

PROJECT BUDGET

COMBINED FUNDING

DOE $89,827,651
PARTNERS $31,210,354

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FECM RDD&D PRIORITY

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FIELD-SCALE FAULT REACTIVATION EXPERIMENTS BRIDGE LABORATORY-SCALE INVESTIGATIONS

Field experiments provide testing and observation in real-world scenarios.

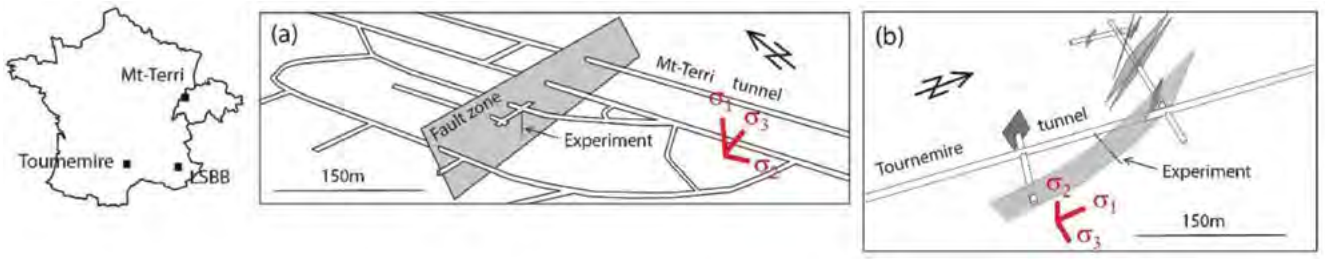
PREDICTING THE BEHAVIOR OF PRESSURIZED CAPROCKS IS CRITICAL FOR SUCCESSFUL LONG-TERM STORAGE OF CO_2

Small-scale field experiments provide important new insights.

Fault reactivation experiments were performed in the Opalinus Clay in the Mont Terri Underground Research Laboratory (URL) in Switzerland and in the Tournemire Clay in France to test fault behavior under pressurized conditions.These tens-of-meter-scale experiments, few of which have been conducted to date, enable high-resolution, real-time observation of complex faults and tracking of fault slip and induced seismicity.

Results imply that shale faults ruptured by local fluid pressure increases could cause significant leakage.

However, because such shale faults may not trigger significant seismic activity, **seismicity may not be a reliable predictor of loss of caprock integrity in these rocks**.



(a) Mont Terri URL Main Fault experiment at 350m depth; (b) Tournemire URL experiment at 250m depth

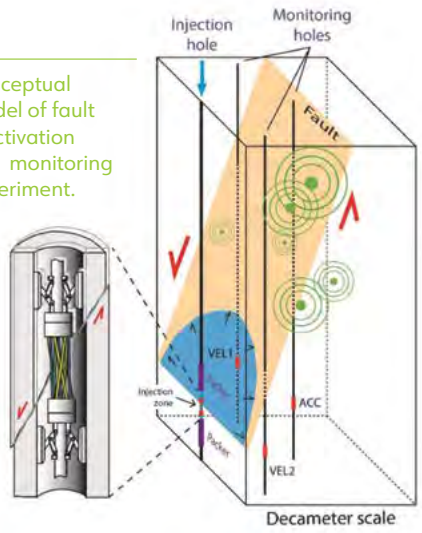
Experiment: Sealed sections of boreholes were pressurized with fluid to trigger millimeter-scale slip. The monitoring boreholes were equipped with a step-rate injection monitoring of fracture in-situ properties (SIMFIP) tool and multiple types of seismic sensors, which enabled continuous monitoring of three-dimensional displacements of the fault simultaneously with injection pressure and flowrate.

Drilling and coring at Mont Terri with 52mm ID casing.

NEW MONITORING METHODS TO ASSESS AND MITIGATE RISKS

These experiments will be further refined to assess the wide variety of rock types under consideration for storage by:

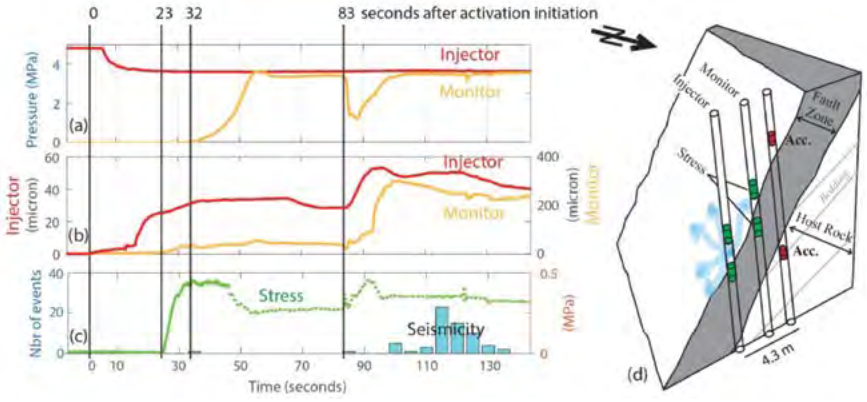
- Monitoring effects from minutes to days.
- Examining different injection protocols from pressure-controlled to flow-rate-controlled types.
- Monitoring fault displacement, pore pressure, and micro-seismicity in the nearfield of the injection source.



Conceptual model of fault reactivation and monitoring experiment.

RESULTS VALIDATE GEOMECHANICAL SIMULATIONS FOR FAULT REACTIVATIONS

- Significant leakage was observed when shale faults were reactivated by local fluid pressure increases.
- Rupture was associated with significant aseismic slip.
- Only small-magnitude seismicity (Mw < -2.5) was observed outside the pressurized leakage patch.
- After activation, the shale faults clamped to almost zero permeability, although not to a complete seal.



PARTNERS

swisstopo, IRSN Institut de Radioprotection et de Sûreté Nucléaire, Shell, Chevron, BGR, CO2 Capture Project, JAEA, ETH zürich, Mont Terri Project, Berkeley Lab, Total

AWARD NUMBER

FWP-FP00007630

PROJECT BUDGET

DOE $1,550,000

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FECM RDD&D PRIORITY

RELIABLE CARBON STORAGE AND TRANSPORT

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LIFE-CYCLE ANALYSIS (LCA) PERFORMED FOR MIDWEST CARBON STORAGE SCENARIOS DEMONSTRATES NET CO_2 STORAGE

Greenhouse gas emissions life-cycle analysis helps illustrate the net benefits of carbon capture and storage.

LCA FACILITATES CLIMATE RESILIENCE IN KEY INDUSTRIAL CORRIDORS IN MIDWEST-NORTHEAST U.S. REGION

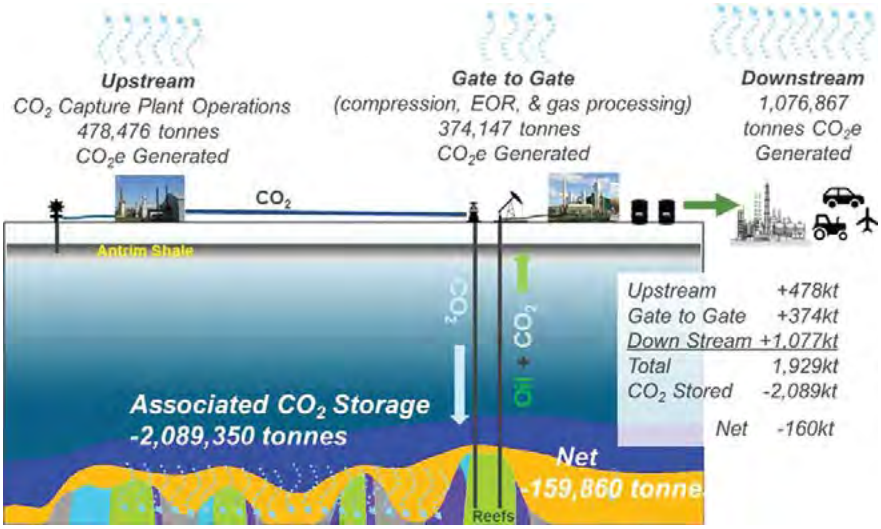


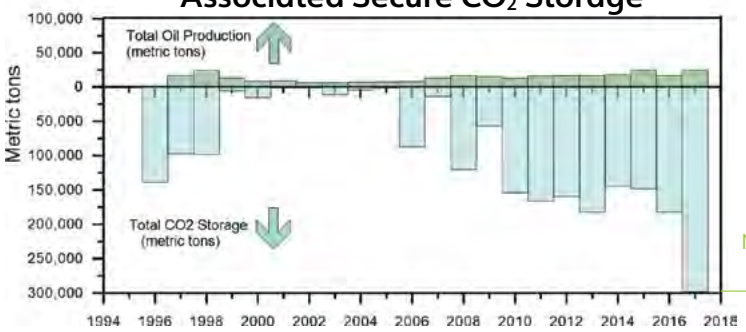
Diagram illustrating the CO_2-EOR process at the Niagaran Reef complex.

Life-cycle analysis of net CO_2 storage is needed to assess the most impactful carbon capture and storage (CCS) projects in the twenty states of the Midwest Regional Carbon Initiative (MRCI) to mitigate emissions from CCS operations such as capture, compression, and injection that can offset the CO_2 stored in geological formations.

Study Objectives

- Quantify greenhouse gases (GHGs) generated for CCS facilities in the MRCI region.
- Assess "cradle to grave" CO_2 equivalent (CO_2e) emissions for carbon capture, transport, and storage operations in relation to the volume of CO_2 stored underground.
- Integrate MRCI-specific factors into analysis of CO_2 sources, geology, and geographic location.

Enhanced Oil Recovery (EOR) and Associated Secure CO_2 Storage

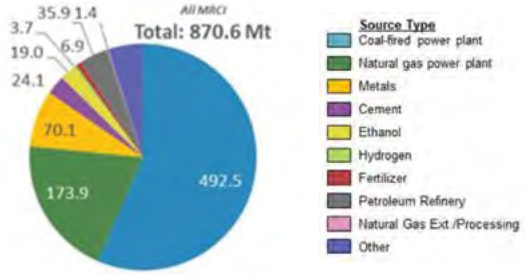


Annual oil production and CO_2-associated storage, illustrating the variations in Niagaran Reef CO_2-EOR operations over time.

End Product

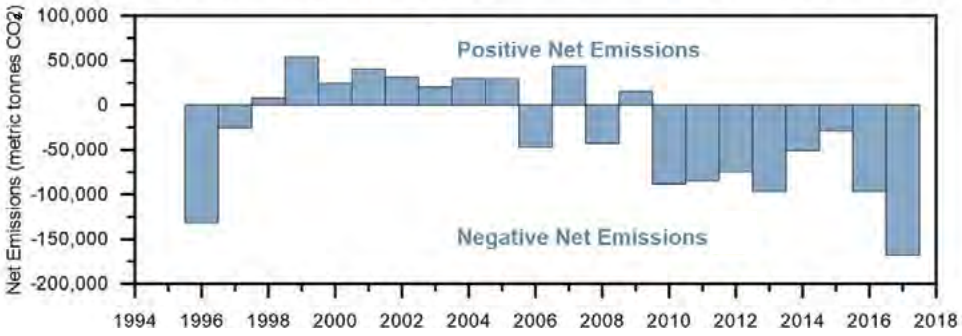
- GHG life-cycle guidance for developing CCS in the MRCI region in terms of maximizing net CO_2 storage effectiveness. Optimizing decarbonization of these large point sources will facilitate climate resilience in this key industrial corridor of the U.S.

Annual CO_2e Emissions for MRCI Region



LCA DEPICTS THE NET BENEFITS OF CCS

- Eight scenarios were assessed: Ethanol Plant, Natural Gas Power Plant, Direct Air Capture Plant, CO_2 Enhanced Oil Recovery, Hydrogen Plant, Petroleum Refinery, Cement Plant, and Fertilizer/Ammonia Plant.
- The analysis integrated the following specific factors for CCS: geologic storage setting, geographic location, CO_2 emissions details, capture requirements, compression needs, CO_2 transport possibilities, and CO_2 injection. Combustion of fuel products and displaced electricity were not included.
- The analysis included the following key inputs: source size (based on existing sources in MRCI), energy for capture, compression requirements, pipeline transport distances, and fugitive emissions. Scenarios were evaluated for low, average, and high source emissions. The life-cycle model includes more than 200 other input parameters from MRCI data.



Graph illustrating annual trends considering gate-to-gate, downstream, and CO_2 storage net emissions.

Results

- Historical analyses of net CO_2 stored vs. emissions from the CCS process included the following: capture, compression, transport, injection, and economies of scale.
- There are many opportunities for CCS in the MRCI region.
- Sources that integrate capture and compression achieve the highest net storage percentages.
- CCS LCA emissions are likely to change over time as operations are optimized to reduce emissions.

PARTNERS

MRCI Midwest Regional Carbon Initiative

BATTELLE

AWARD NUMBER

FE0031836

PROJECT BUDGET

DOE $14,849,641
PARTNERS..... $8,819,554

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POINT-SOURCE CARBON CAPTURE

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STUDY DETERMINES TECHNICAL AND ECONOMIC REQUIREMENTS FOR CARBON TRANSPORT AND STORAGE

The Wabash Valley Resources facility proves capable of storing a large volume of CO_2 while remaining economically viable.

DEVELOPING A WORLD-CLASS CO_2 CAPTURE FACILITY

Projected to Store 60 Million Tonnes of CO_2 Over 30 Years

The University of Illinois evaluated the technical and economic feasibility of transporting CO_2 from dozens of regional point sources (ethanol plants and hydrogen production facilities) to a potential commercial-scale geologic storage complex beneath the Wabash Valley Resources (WVR) facility near Terre Haute, IN, where planned hydrogen production is expected to produce CO_2 that will be stored on-site. **This work supports the transition to a low-carbon economy by assessing the technical and economic requirements for large-scale carbon transport and storage facilities and regional hubs**.

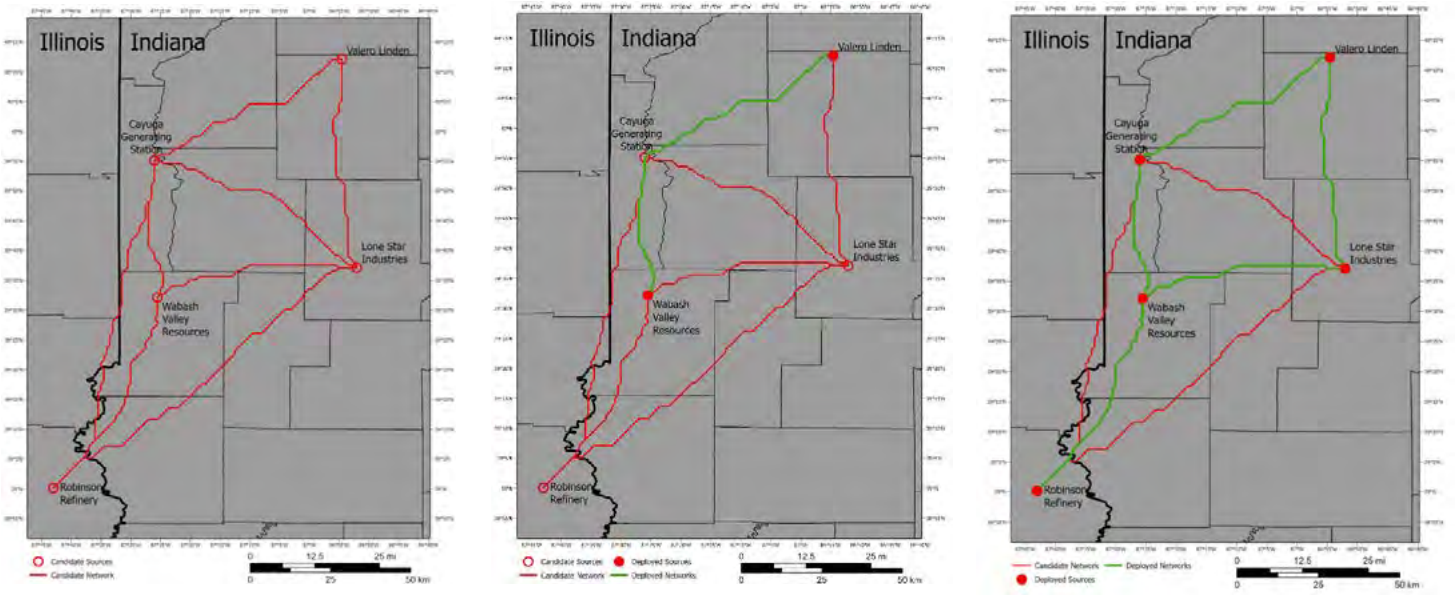
Two cases were assessed based on the assumed maximum injection rates of the WVR storage facility.

The first case assumes the maximum injection rate of the storage facility at WVR is 2.0 Mtonnes per year (MMTA) using two wells, each injecting 1.0 MMTA. Scenarios with total capture amounts ranging from 0.5 to 2.0 MMTA in increments of 0.1 MMTA were created.

The second case assumes the maximum injection rate of the storage facility can equal the total capturable CO_2 of all six sources, for a total of 8.23 MMTA, using wells at an injection rate of 1.0 MMTA.

WVR FACILITY IS PROJECTED TO STORE CO_2 FROM ALL NEARBY SOURCES

Both cases only consider the WVR and Valero Linden Plant (VLP) for capture facilities. The VLP is considered economically advantageous at low- and average-cost scenarios; however, it has a low annual capturable amount of 0.36 MMTA, requiring WVR to be deployed for all annual capture rates.



Left: Candidate sources and pipeline network for SimCCS Gateway simulations. The storage facility is located at WVR and stores all captured CO_2 of all scenarios. Cayuga Generating Station Units 1 and 2 coincide. Center: All capture facilities and pipeline networks deployed throughout the Case 1 scenarios. Right: All capture facilities and pipeline networks deployed throughout the Case 2 scenarios.

Reference: https://www.sciencedirect.com/science/article/abs/pii/S1364815218300185

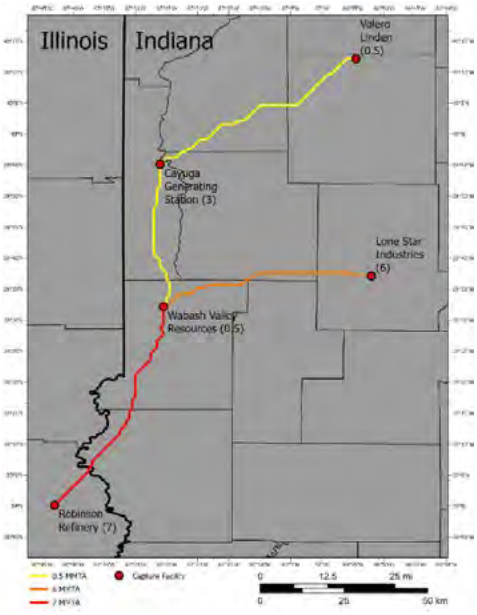
OPTIMAL HUB LOCATION IDENTIFIED

Both cases were analyzed for a carbon capture and storage hub at WVR. Both cases assume a 30-year project period and a 0.1 capital recovery factor. They also use the same six capture facilities, candidate pipeline networks, and costs associated with each respective capture facility. Each scenario considered a **low, average, and high capture cost** that was applied to all capture facilities.

Capture Facility	Sector	Total Emissions (MMTA)	Capturable Emissions (MMTA)	Capture Cost ($/tCO$_2$)		
				Low	Average	High
Wabash Valley Resources	Hydrogen	1.82	1.82	25	26	27
Cayuga Generating Station – Unit 1	Power Generation - Coal	1.91	1.72	46	56	60
Cayuga Generating Station – Unit 2	Power Generation - Coal	2.19	1.97	46	56	60
Lone Star Industries	Cement	1.01	0.91	40	56	75
Robinson Refinery	Refineries	1.63	1.47	43	56	68
Valero Linden Plant	Ethanol	0.36	0.36	12	17	33

Summary of capture facility input parameters for simulations.

OPTIMAL HUB LOCATION



Order of deployment of capture facilities and pipeline network for high capture cost scenarios. Number in parentheses next to capture facility names denotes the lowest annual project capture amount where the respective facility is utilized. The value provided at Cayuga Generation Station is for Unit 1; Unit 2 is utilized beginning at 4 Mtonnes per year. Color of pipeline networks denotes the lowest annual project capture amount where the respective pipeline is utilized.

Yellow: 0.5 MMTPA
Orange: 3 MMTPA
Red: 4 MMTPA

The WVR site was shown to be an ideal storage hub after optimizing pipeline networks and deployment scenarios for carbon capture and storage using SimCCS Gateway. This simulation suggests a total unit cost to capture, transport, and store CO_2 of $22.20 to $58.44 per tonne of CO_2 depending on capture costs and injection rates.

PARTNERS

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Projeo
WABASH VALLEY RESOURCES
Pacific Northwest NATIONAL LABORATORY
GEOSTOCK SANDIA ENTREPOSE
INDIANA GEOLOGICAL & WATER SURVEY INDIANA UNIVERSITY
INDIANA UNIVERSITY
BYU BRIGHAM YOUNG UNIVERSITY

AWARD NUMBER
FE0031626

PROJECT BUDGET

DOE $11,140,875
PARTNERS $8,110,652

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Angela Bosley

FECM RDD&D PRIORITIES

RELIABLE CARBON STORAGE AND TRANSPORT

POINT-SOURCE CARBON CAPTURE

CLICK HERE FOR MORE INFORMATION

COAL-DERIVED BUILDING MATERIALS SHOW VERY PROMISING RESULTS

Coal-derived building materials have performance characteristics that exceed those of commercial brick and concrete block.

INITIAL PERFORMANCE TESTING OF FIVE COAL-DERIVED BUILDING MATERIALS REVEALS HIGH-PERFORMANCE CHARACTERISTICS

Initial performance testing of coal-derived building materials (CDBM)—including X-BLOX, X-BRIX, X-PANEL, X-MATRIX, and X-TILES—exhibited several exciting **high-performance** characteristics:

- **Five times** the flexure strength of the best commercial brick.
- More than **twice** the compressive strength of construction-grade concrete block.
- **Lower** density than comparable material.
- Improved mechanical **durability** and abrasion resistance.
- Very **high temperature stability**.
- **Resistance** to chemicals, acids, salts, and water.

ADVANCING THE UTILITY OF COAL-DERIVED BUILDING MATERIALS

X-MAT, in collaboration with their production partner the Center for Applied Research and Technology, Inc., has **steadily improved several CDBM products**. The XMAT CDBM components contain at least 55% coal by weight and 71% carbon by weight.

Based on their **favorable testing results**, X-MAT is currently working on a **market-worthy design** for a CDBM structure that will meet insurance standards (seismic, fire, wind resistance) and the International Building Code.

Coal-based bricks (X-BRIX) and blocks (X-BLOX).

Examples of various colors and coatings for the ceramic tiles.

CDBM USE RESULTS IN ECONOMIC AND ENVIRONMENTAL JUSTICE BENEFITS

CDBM can **reduce the cost of building construction** for targeted markets, create employment in disadvantaged coal communities and the CDBM industry, and remediate legacy waste by utilizing existing coal waste as feedstock for CDBM.

Artist's conception of coal building proof-of-concept design.

PARTNERS

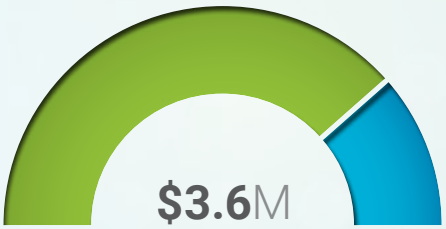
August Brown
EERC
Semplastics
CART Center for Applied Research and Technology, Inc.
Lignite Energy Council
X-MAT Reimagining high performance materials

AWARD NUMBER

FE0031985

PROJECT BUDGET

FY20 & FY21 FUNDING



DOE $2,746,286
PARTNERS $826,000

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Sue Miltenberger

FECM RDD&D PRIORITY

DOMESTIC CRITICAL MINERALS PRODUCTION

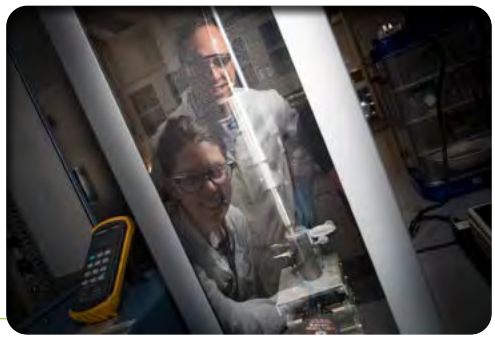
CLICK HERE FOR MORE INFORMATION

COLLABORATIONS ADVANCE CRITICAL MINERALS AND MATERIALS PROGRAM

Collaboration presents a growing opportunity to diversify the global supply of critical minerals and materials.

NETL IS DEVELOPING AND UTILIZING UNIQUE COLLABORATIONS TO ADVANCE RESEARCH IN MISSION-CRITICAL PROGRAMS

NETL collaborations reach across the U.S. Department of Energy (DOE) and other entities **comprising personnel from national labs, academia, state and national geological societies, and tribal and local government**.

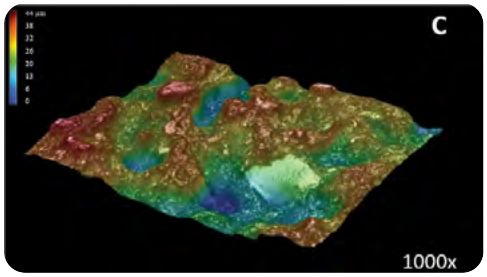


NETL REE research.

LANL LIBS Raman Sensor. Courtesy of LANL.

RECENT COLLABORATIVE EFFORTS

NETL researchers are advancing rare earth elements separation technology developed at NETL in partnership with the University of Wyoming.



Strategic collaborations with Ramaco Carbon, the U.S. Geological Survey, Duke University, UCLA, Oak Ridge National Laboratory, the West Virginia Geological and Economic Survey, and the University of Wyoming **were instrumental in developing a predictive REE model**.

Three working groups are advancing common inter-basinal objectives by facilitating open communication and information-sharing among a portfolio of external projects covering 13 coal basins across the United States via the Carbon Ore, Rare Earths, and Critical Mineral (CORE-CM) Initiative.

- The Resource Characterization Working Group focuses on pathways to identify and assess the quality and quantities of critical minerals and carbon ore for production.
- The Environmental Justice and Social Responsibility Working Group **addresses the environmental and social implications** of building out a CMM supply chain in each of the 13 basins.
- The Infrastructure Working Group addresses all **aspects of infrastructure** in each basin.

COLLABORATIONS HAVE DEMONSTRATED WORLD-CLASS REE PROGRESS

NETL **collaborations have demonstrated world-class** concentrations of REEs in U.S. unconventional geologic media and have been instrumental in conducting preliminary assessments and evaluations of two U.S. geologic basins.

As these technologies mature and **external collaborations help to increase the use and visibility of project models and methods**, there exists a growing opportunity to diversify the global supply of CMM critical for meeting clean energy goals, realizing environmental and social benefits, and democratizing access to these resources.

REE research team at NETL.

PARTNERS

WVGES GEOLOGY UNDERLIES IT ALL

RAMACO CARBON

USGS science for a changing world

Duke UNIVERSITY

UCLA

OAK RIDGE National Laboratory

UNIVERSITY OF WYOMING

SUCCESSFUL CRITICAL MINERALS & MATERIALS COLLABORATIONS REPRESENT MULTIPLE NETL AND EXTERNAL PROJECTS AND PARTNERS ACROSS A BROAD RANGE OF INITIATIVES.

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PRINCIPAL INVESTIGATOR
Various Investigators

FECM RDD&D PRIORITY

DOMESTIC CRITICAL MINERALS PRODUCTION

CLICK HERE FOR MORE INFORMATION

FEASIBILITY STUDIES FOR PROCESSING RARE EARTH ELEMENTS FROM COAL BYPRODUCTS COMPLETED

DOE's Critical Minerals and Materials Program has demonstrated the technical feasibility of extracting rare earth elements from coal-based resources.

EIGHT DOWN-SELECTED PROJECTS COMPLETED PRE-FRONT-END ENGINEERING DESIGN (PRE-FEED) FEASIBILITY STUDIES

Initiated in FY21 as a group of 13 concept studies, **eight down-selected projects completed pre-FEED feasibility studies** in support of a 1-3-tonne per day mixed rare earth oxide/mixed rare earth salt (MREO/MRES) engineering-scale rare earth element (REE) processing facility.

REEs are used in many advanced energy, defense, and high-tech applications and industries.

R&D HAS PROGRESSED FROM BENCH/PILOT-SCALE TO ENGINEERING-SCALE PROTOTYPES

Research has **progressed from bench/pilot-scale to engineering-scale prototype materials processing** to address scale-up challenges for future opportunities.

The eight feasibility studies were required to use coal or coal byproduct feedstocks for a minimum operating life of five years.

The projects considered the processing of the REEs or critical minerals from intermediate products (MREO/MRES) through to commercial rare earth metals, alloys, or other products.

Projects also considered other byproducts that would improve the economics of each facility.

Processing coal byproducts to extract MREO/MRES.

SEVERAL FACILITIES PROPOSED PRODUCTION BEYOND MREO OR MRES

Notably, some of the eight completed pre-feed studies **elected to extend their proposed facilities further** to refined metals, alloys, or other products, which further accelerates technology development.

The feasibility studies help to de-risk a potential future engineering-scale REE facility by using Association of Cost Engineering Class 4 estimates on the conceptual facilities.

Rare earth elements and critical minerals needed for clean energy, economic security, defense, and national security.

NATIONAL ENERGY TECHNOLOGY LABORATORY AWARDED MORE THAN $19 MILLION ($19,138,598)

Cumulatively, more than **$19 million in federal funding was awarded** for the eight feasibility studies, which were managed by DOE's National Energy Technology Laboratory.

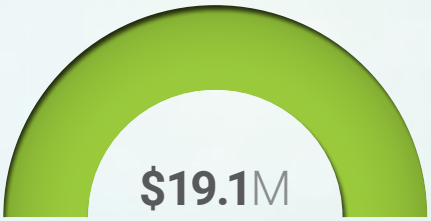
PARTNERS

ENERGY FUELS
MATERIA
MP MATERIALS
TETRA TECH
EERC Energy & Environmental Research Center
TMR TEXAS MINERAL RESOURCES CORP.
West Virginia University RESEARCH OFFICE
WinnerWater SERVICES

AWARD NUMBERS

Multiple

PROJECT BUDGET



DOE $19,138,598

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PRINCIPAL INVESTIGATOR
Multiple

FECM RDD&D PRIORITY

DOMESTIC CRITICAL MINERALS PRODUCTION

INNOVATIVE INTEGRATED INSTRUMENT FOR CHARACTERIZING RARE EARTH ELEMENTS BUILT AND TESTED

The instrument is anticipated to be a breakthrough in the rapid in situ detection of rare earth elements in coal and in a myriad of other REE-related applications.

INNOVATIVE PORTABLE INSTRUMENT ENABLES FIELD ANALYSIS OF RARE EARTH ELEMENTS (REE) IN COAL-RELATED MATERIALS

Applying their expertise in integrated laser induced breakdown spectroscopy (LIBS) and Raman spectroscopy instruments (e.g., 2020 Mars Rover), Los Alamos National Laboratory (LANL) has completed the assembly and testing **of a prototype field-portable LIBS and Raman spectroscopy backpack instrument**. This device is capable of **simultaneous chemical and mineralogical analysis** of REE in coal-related materials **in the field**.

Left: The field-portable LIBS and Raman (backpack) prototype unit undergoing field testing. Right: Close-up of the field-portable unit.

ALL RESEARCH AND DEVELOPMENT OBJECTIVES SUCCESSFULLY ACHIEVED

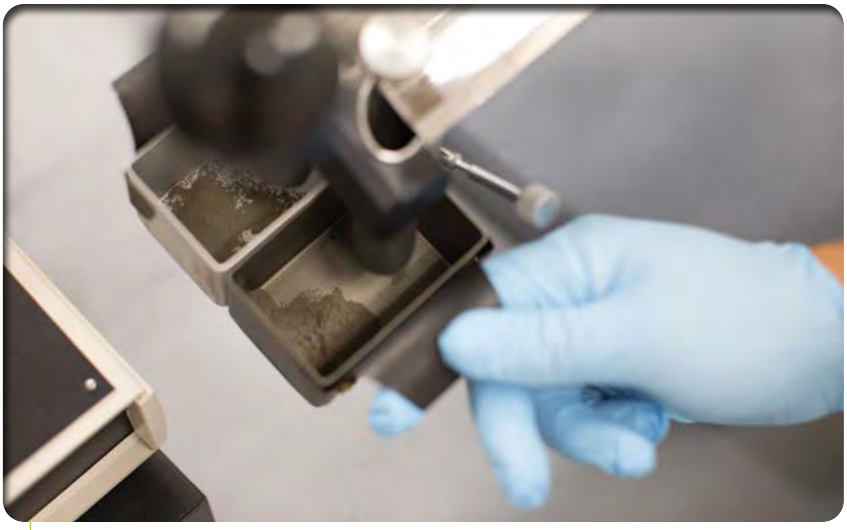
The **primary objectives** of this research and development effort were to:

1. **Develop and test** analytical protocols for analyzing the concentration and mineralogy of REE in coal-related materials using LIBS and Raman spectroscopy.
2. **Develop a prototype field-portable system** for LIBS and Raman analysis of REE in coal-related materials.
3. **Analyze the chemistry and mineralogy of REE** in a variety of coal-related materials, principally from New Mexico coal deposits.

INSTRUMENT TECHNOLOGY METHODOLOGY VALIDATED

LANL **successfully developed** a method using fluoroboric acid to digest coal, coal fly ash, and geological samples for REE analysis using inductively coupled plasma mass spectrometry (ICP-MS).

Fluoroboric acid preparation and ICP-MS analysis were validated against reference materials and shown to be very accurate. End-to-end performance and functional testing of the device, as well as field testing, were completed.



Sensor technology is anticipated to have applications in REE processing.

SENSOR PACKAGE IS ANTICIPATED TO HAVE BROAD USE BEYOND THE PROJECT OBJECTIVES

Sensor packages such as this will be useful in many applications besides REE detection in coal including:

- **Monitoring** of REE content in process streams.
- **Detection** of upsets during industrial processing.
- **Rapid testing and validation** of new extraction or separations techniques.

PARTNER

Los Alamos NATIONAL LABORATORY

AWARD NUMBER

FWP-FE-781-16-FY17

PROJECT BUDGET

DOE $1,000,000

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Sam Clegg

FECM RDD&D PRIORITY

DOMESTIC CRITICAL MINERALS PRODUCTION

CLICK HERE FOR MORE INFORMATION

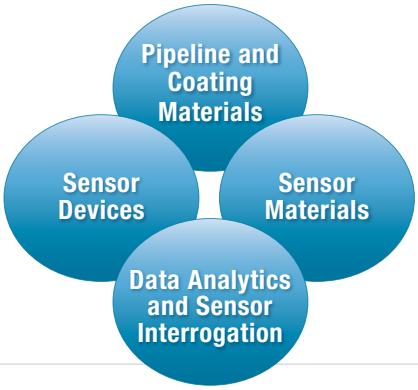
NETL ADVANCES SENSOR TECHNOLOGIES FOR NATURAL GAS PIPELINE RELIABILITY, RESILIENCY, AND METHANE EMISSION REDUCTION

Advanced sensor technologies are developed by NETL researchers and collaborators for natural gas pipeline monitoring to ensure safety and mitigate global warming.

IMPROVING RELIABILITY OF THE NATION'S NATURAL GAS INFRASTRUCTURE AND REDUCING METHANE EMISSIONS

NETL aims to **strengthen natural gas pipeline reliability** and **reduce greenhouse gas (GHG) emissions** using advanced sensor technology to address the reliability, public safety, operational efficiency, and flexibility of the Nation's aging natural gas infrastructure.

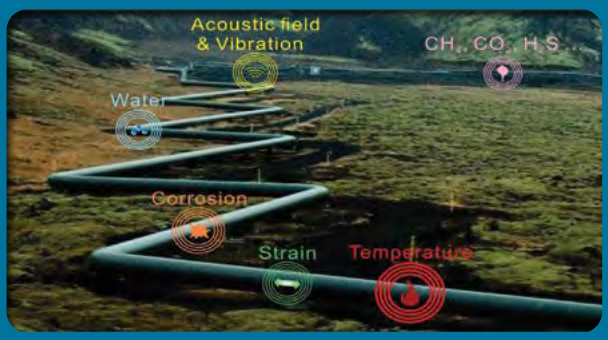
NETL develops sensor tools and materials to quantify and mitigate emissions from natural gas infrastructure, including sensor technologies for low-cost, low-maintenance monitoring of pipeline corrosion rates, gas leaks, and gas stream chemistry.



MULTIPLE ADVANCED SENSOR TECHNOLOGIES

NETL and collaborators are developing three synergistic sensor platforms with complementary cost, performance, and geospatial characteristics that emphasize corrosion and gas monitoring. NETL recommends sensor technologies based on performance and projected costs for more intelligent pipeline systems with continuous monitoring for improved reliability and safety.

TYPES OF SENSORS



A real-time, multi-parameter, distributed sensor network for >100 km interrogation.

Distributed Optical Fiber Sensor

Passive Wireless Surface Acoustic Wave Sensor

Advanced Electrochemical Sensor

This research aims to:

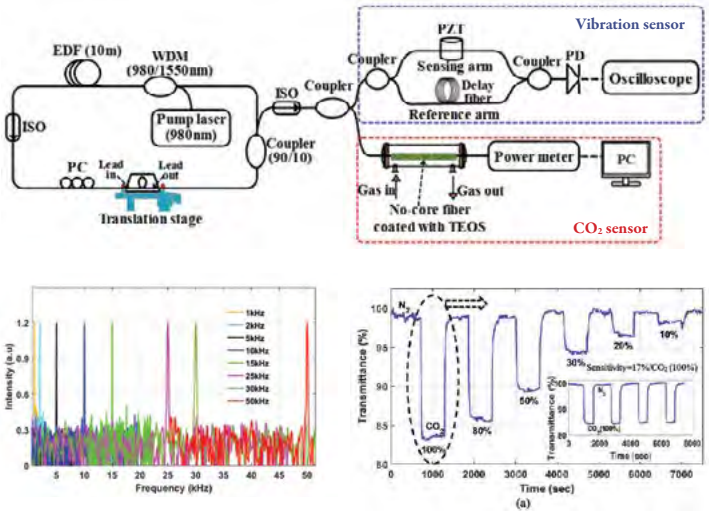
1. Develop sensor technologies for early corrosion onset detection before catastrophic failures occur and for early methane leak detection to inform timely maintenance and repairs.
2. Develop optical fiber sensors for long-distance, spatially distributed, and real-time monitoring (>100 km).
3. Develop passive wireless sensors for remote, low-cost, and multi-parameter monitoring over a large area.
4. Develop advanced electrochemical sensors compatible with natural gas applications and with a longer lifespan.
5. Develop artificial intelligence/machine learning enhanced sensor network for intelligent monitoring and control.

PATENTS FILED ACROSS THREE CLASSES OF ADVANCED SENSOR PLATFORMS

NETL's advancements in sensor technologies (optical fiber-based sensors, passive wireless surface acoustic wave (SAW) sensors, and electrochemical sensors) benefit **long-distance pipelines for natural gas and hydrogen transportation**.

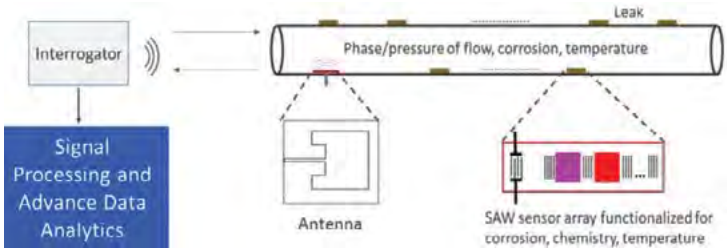
Patents filed include:

- Simultaneous Ultrasonic Vibration and Gas Sensing Based on a Tunable Fiber Ring Laser.
- Performance Improvement of Phase-Optical Time Domain Reflectometry (Φ-OTDR) Based on Wavelength Diversity Technique.
- Low-Cost Acoustic Emission Monitoring Based on Multiplexed Single-Mode–No-Core–Single-Mode (SNS) Fiber Sensors.
- Increasing the Lifespan of Reference Electrodes by Increasing the Diffusion Length.
- Distributed Fiber-Optic Sensor Network for Sensing the Corrosion Onset and Quantification.
- Distributed Multi-Parameter Sensor for Simultaneous Monitoring of Corrosion and Humidity.
- Microwave Diagnostics and Passive Sensors for Pipeline, Well-Bore and Boiler-Tube Monitoring.
- Gas Sensor and Method of Optimizing an Array of Gas Sensors.



Simultaneous ultrasonic vibrations and gas sensing based on a tunable fiber ring laser.

Simultaneous ultrasonic vibrations and gas sensing based on a tunable fiber ring laser.



Microwave diagnostics and passive sensors for pipeline, well-bore and boiler-tube monitoring.

PARTNERS

University of Pittsburgh

PennState

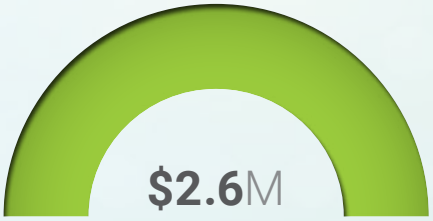
AWARD NUMBER

FWP-1022424

PROJECT BUDGET

EY22 FUNDING

Natural Gas Infrastructure FWP
Task: Pipeline Sensor Technologies



DOE $2,600,000

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FECM RDD&D PRIORITY

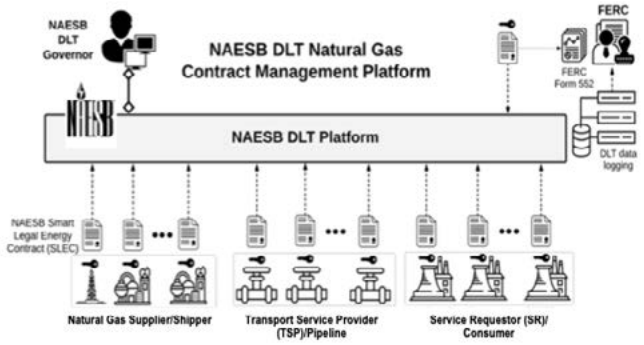
CH_4 METHANE MITIGATION

DISTRIBUTED LEDGER TECHNOLOGY SUPPORTS INCREASED EFFICIENCY AND IMPROVED CYBERSECURITY

A distributed ledger technology was developed to evaluate cybersecurity, efficiency, and operational improvements to current processes used to settle natural gas trades.

WHAT IS DISTRIBUTED LEDGER TECHNOLOGY (DLT)?

DLT is a digital system for recording asset transactions in which transactions are recorded in multiple places simultaneously, **enabling secure and accurate storage of information**.

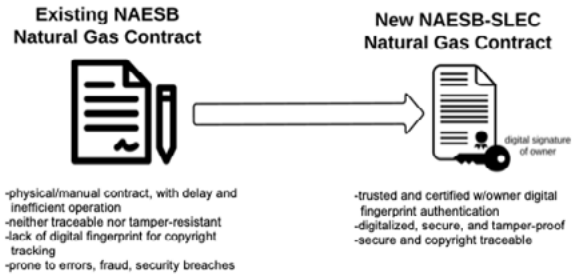


NAESB DLT platform reference architecture.

CURRENT NATURAL GAS TRADING PROCESS

Trades are currently executed and settled **without automation or digitalization**, relying instead on the exchange of physical documents.

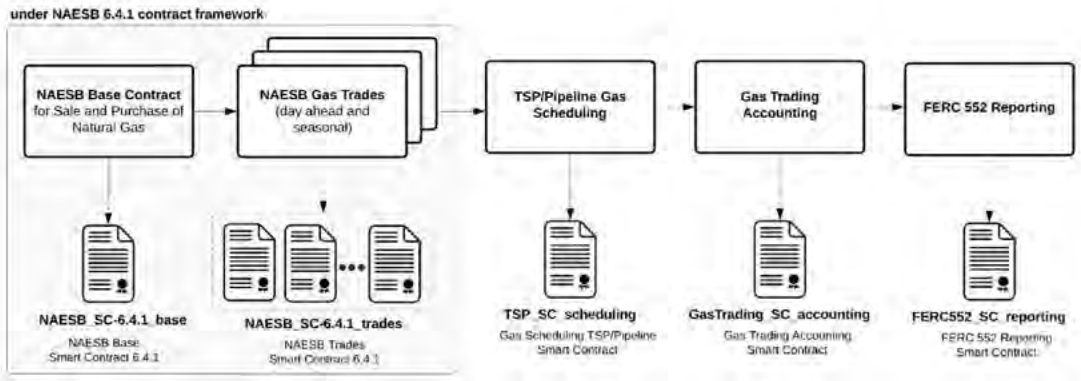
This can lead to delays, higher transactional costs, and inefficiencies associated with human error, while also **increasing the risk of fraud** and **cybersecurity/data privacy breaches**.



Digitally certified NAESB-SLEC natural gas contract with main benefits compared to traditional ones.

DLT PROVIDES SECURE AND EFFICIENT NATURAL GAS TRANSACTIONS

DLT can lead to more cost-effective and secure methods of completing natural gas trades, thereby **improving the efficiency, transparency, and cybersecurity of transactions**. DLT can also reduce **potential credit risk and late payments** during transactions.



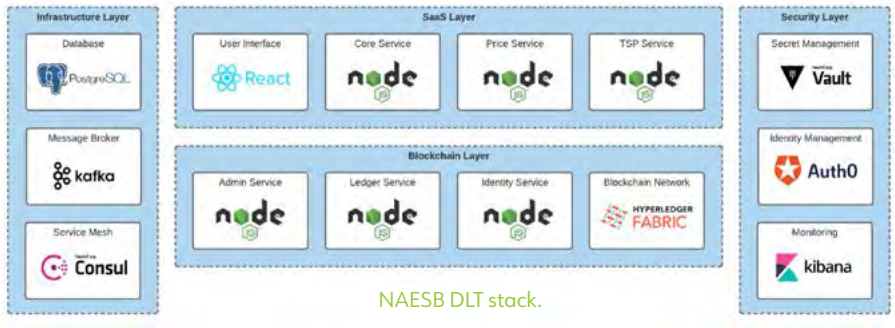
NAESB-SLEC dataset business process framework using DLT method for initial contract negotiation.

NORTH AMERICAN ENERGY STANDARDS BOARD (NAESB) DLT

Consistent, dependable, and transparent record-keeping improves the traceability of all natural gas transactions, creating a digital footprint of these traceable events.

The NAESB DLT Platform is a web-based trade process lifecycle platform built on top of a modular distributed ledger network that **optimizes ease-of-use, security, scalability, and extensibility**.

The platform places information, updates data fields, and queries the DLT database. All data input and logs are registered in immutable records for auditing while placing data in a decentralized location, improving the reconciliation process between parties.



NAESB DLT stack.

STUDY RESULTS SHOW DLT GREATLY IMPROVES CYBERSECURITY

More than **100,000** transactions were processed through the DLT Platform. Results showed that cybersecurity in the settlement process was greatly improved through enhanced encryption techniques.

Exposure to ransomware attacks **decreased**, while the ability to ensure consistent use of current standards throughout the supply chain was achieved.

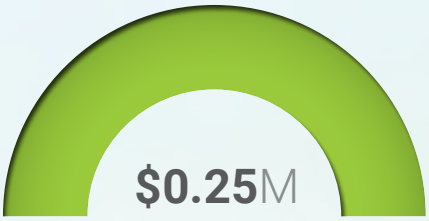
There was also **substantial improvement** to the current **credit risk and payment procedures**.

PARTNERS

NAESB · BIG DATA ENERGY SERVICES · TVA TENNESSEE VALLEY AUTHORITY · SPIRE MARKETING

PROJECT BUDGET

FY22 FUNDING



DOE $253,750

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FECM RDD&D PRIORITY

CH_4 METHANE MITIGATION

DRONE-MOUNTED, AUTONOMOUS, SMART METHANE EMISSION DETECTION SYSTEM REDUCES FALSE POSITIVES

Technology for improved detection of methane emissions employs machine learning.

AUTONOMOUS, REAL-TIME METHANE LEAK DETECTION

The Smart Methane Emission Detection System (SLED/M)

Southwest Research Institute has developed a system to **reliably, accurately, and autonomously identify methane leaks** at critical midstream sections of the natural gas transmission network in **real-time** for the purpose of mitigating methane emissions.

SLED/M utilizes machine learning techniques and commercial-off-the-shelf optical sensors for early detection of methane emissions.

This work further advanced the technology to perform autonomously from drones for commercial aerial inspections.

Drone with the Optical Gas Imaging (OGI) camera for data collection.

TIMELY, ACCURATE, AND COST-EFFECTIVE LEAK DETECTION

Reducing False Positives and Identifying Methane Leaks

Left: Ronin Gimbal outfitted with an OGI camera; the Gimbal allows for controlled omnidirectional pointing of the camera

Conventional detection systems, designed to locate larger leaks, suffer from false positives and missed detections, which hamper effectiveness and utilization by industry.

Southwest Research Institute designed SLED/M to **identify methane leaks along pipelines and in storage facilities that typically go unnoticed**.

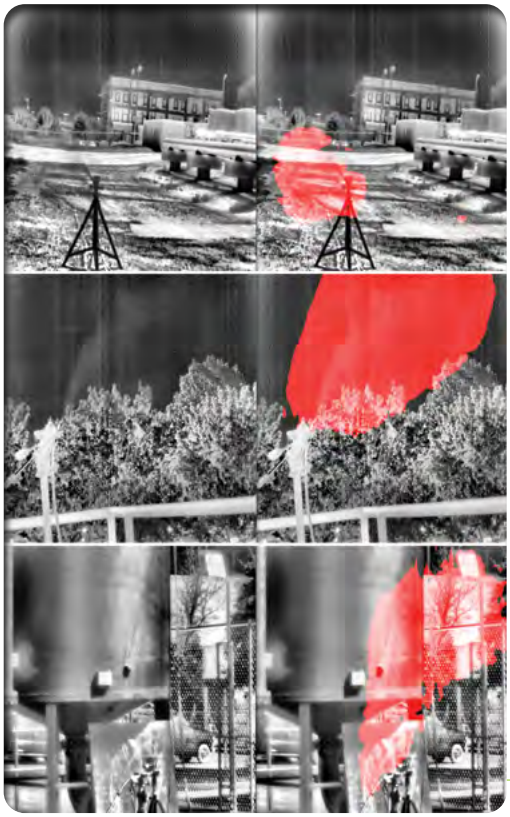
By optimizing algorithms to reliably detect leaks under a variety of environmental conditions, this technology **substantially reduces false positives (<2.25%; number of events classified as leaks)**.

CAN YOU SPOT THE METHANE?

The system detects and pinpoints methane leaks, known as fugitive emissions, by pairing passive optical sensing data with artificial intelligence algorithms.

The integration of SLED/M into an autonomous drone has generated a more precise and efficiently deployed leak detection method.

By optimizing and enhancing the algorithms and inspection method, the technology is expected to lead **to reduced methane emissions and a reduction in the environmental impact** of natural gas transportation.



Optical sensing data and artificial intelligence are utilized to create a negative-colored image.

SLED/M can detect methane leaks as low as **three standard cubic feet per hour with a precision of 96.6% and a false positive rate of 2.22%**. Additionally, SLED/M is capable of **estimating methane flow rate and concentration to within 12.3%** of ground truth flow rate.

PARTNERS

SIERRA-OLYMPIC Technologies Inc.

IRCameras

Falcon Inspection & Services

FLIR

SwRI

AWARD NUMBER

FE0029020

PROJECT BUDGET

DOE $1,811,107
PARTNERS..... $453,057

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Keith Carrington

FECM RDD&D PRIORITY

CH_4 METHANE MITIGATION

CLICK HERE FOR MORE INFORMATION

NEW LINER REFRACTURING TECHNIQUE OPTIMIZES PRODUCTION WHILE MINIMIZING ENVIRONMENTAL IMPACTS FROM EXISTING WELLS

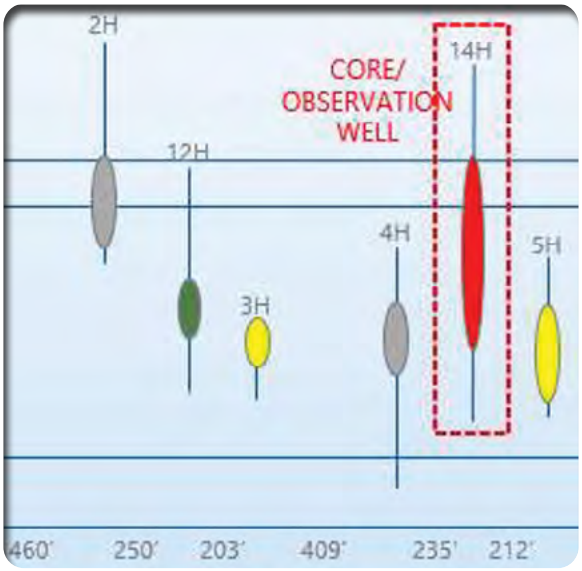
Recompletion technology recovers additional resources from existing wells.

LEGACY WELL RECOMPLETION – INFILL STIMULATION PROJECT IN THE EAGLE FORD SHALE

GTI Energy and Devon Energy, as part of the third phase of the Hydraulic Fracturing Test Site project, demonstrated a recompletion strategy to **optimize hydraulic fracturing** in the Eagle Ford formation.

The test site comprises **nine legacy horizontal wells that were drilled in 2013**, two of which **were re-completed with a cemented liner and used for infill stimulation testing**.

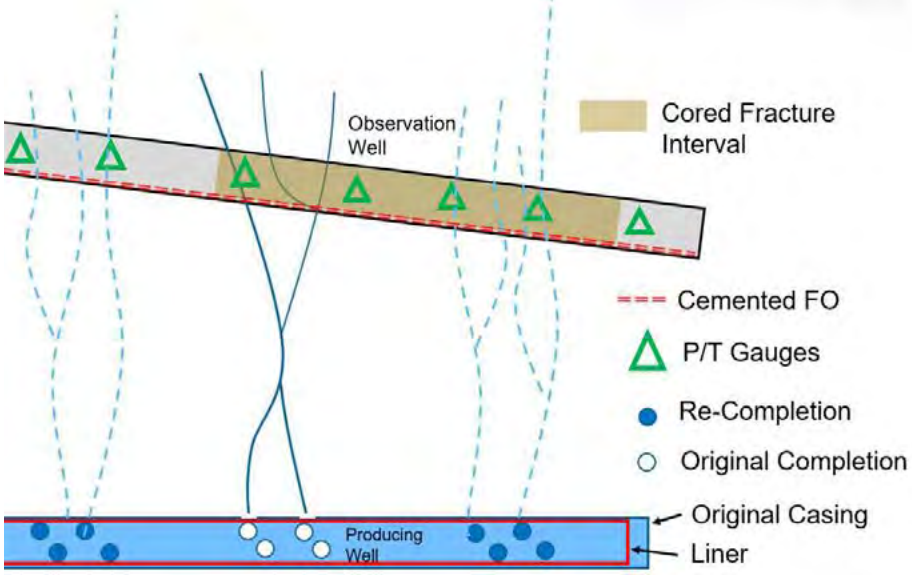
A recompletion strategy is utilized to refracture and restimulate a well to improve production. The strategy is based on the **initial fracturing design and information gained from the fracturing and stimulation of wells within the same formation**.



Locations of core and observation well (red), refractured wells (yellow), and production infill well (green).

DATA COLLECTION, CONTINUOUS MONITORING, AND STAGE DESIGN

- A total of **420 feet of whole core was collected** between the two re-completed wells.
- Fiber optics and pressure/temperature gauges were installed within adjacent horizontal wells and the slant core well to **monitor fracturing progress during the 68 total fracture stages pumped** in the two re-completed wells.
- The re-completed wells were placed into their production phase, and **oil samples were collected for time-lapse geochemical analysis while well conditions were monitored with fiber optics**.

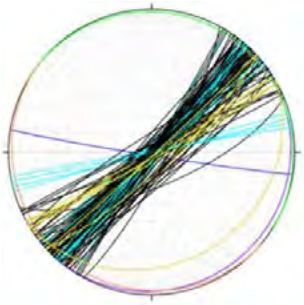


Plan view of proposed observation/core well and the liner re-completion.

PHASE 3 KEY FINDINGS AND LEARNINGS

Key Findings

- Prior to recompletion, the wells were producing approximately 20 barrels of oil per day (bopd). After recompletion, **each well initially produced at a rate of more than 1,000 bopd**.
- **Significant Estimated Ultimate Recovery uplift** from liner recompletions.
  - **Captures stranded reserves** from less effective early completions, which leave significant fracture voids.
  - Leaves a much **smaller environmental footprint** than drilling new wells and can be more economical as well.



Core analysis of hydraulic fracture orientation after refracturing operations is consistent, even with liner infill stimulation.

Lessons Learned

- Multiple diagnostics **confirm fractures from initial completions and fracture corridors from liner recompletions**.
- **High perforation friction low cluster designs show the highest efficiency** in both near field (perforation imaging) and far field (cross-well strain).
- Mud-return proppant-log can **quantify proppant and identify stimulated areas of the reservoir**.

Proppant embedded in hydraulic fracture created through liner infill stimulation.

PARTNERS

gti, Discovery Natural Resources, EnCana, Core Lab, Total, OXY, University of Pittsburgh, ConocoPhillips, Energen, SM Energy, Pioneer Natural Resources, Laredo Petroleum, devon, Halliburton, Shell, Chevron, ExxonMobil

AWARD NUMBER

FE0024292

PROJECT BUDGET

DOE $21,460,000
PARTNERS..... $22,740,000

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FECM RDD&D PRIORITY

METHANE MITIGATION

CLICK HERE FOR MORE INFORMATION

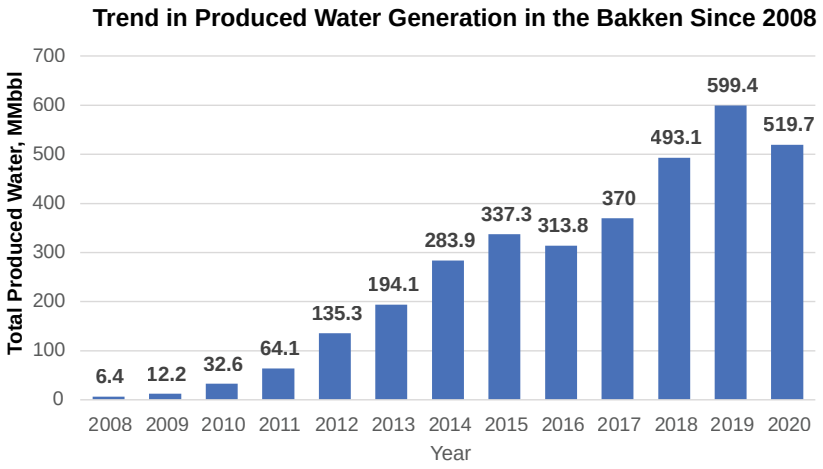
PRODUCED WATER MANAGEMENT THROUGH GEOLOGIC HOMOGENIZATION, CONDITIONING, AND REUSE (GHCR)

Technology for managing water produced from oil and gas operations.

PRODUCED WATER IN THE WILLISTON BASIN, NORTH DAKOTA EXPECTED TO DOUBLE OVER THE NEXT DECADE

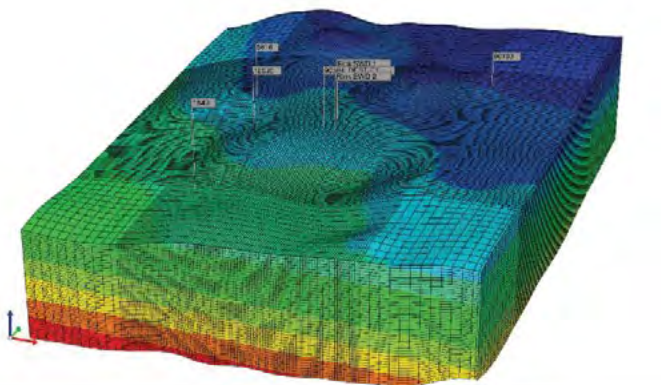
Produced water is the water that is generated, along with a target hydrocarbon such as oil or natural gas. Produced water is a mixture of returned fracture fluid and natural formation water. The quality of the produced water is dependent on local and target formation properties. Regardless of their source or quality, these produced waters must be managed.

Water volumes for hydraulic fracturing are **averaging 200,000 barrels per well** for a single well stimulation. Within North Dakota, low costs for acquiring fresh water sources inhibit the reuse of produced water for hydraulic fracturing resulting in nearly 100% of all produced water being disposed of in saltwater disposal (SWD) formations.



Increasing volumes of produced water and SWD in North Dakota.

GHCR – A VIABLE APPROACH FOR NORTH DAKOTA'S WATER MANAGEMENT



The Inyan Kara geomodel used in the evaluation of the GHCR concept was provided from other DOE-funded projects' geologic modeling efforts and included history-matching using field data.

GHCR is defined as Geologic Homogenization, Conditioning, and Reuse as it is applied to produced water.

Laboratory testing of core samples and field numerical modeling indicate that **GHCR can be a viable approach to water management** in North Dakota.

The GHCR concept addresses challenges that hinder the more traditional approaches to recycling in the industry such as **large-volume transport and large-scale temporary surface storage of fluids with a high concentration of total dissolved solids**.

The model used showed **good agreement with the salinity values from the samples analyzed in the laboratory**.

TECHNICAL EVALUATION OF GHCR EFFECTIVENESS

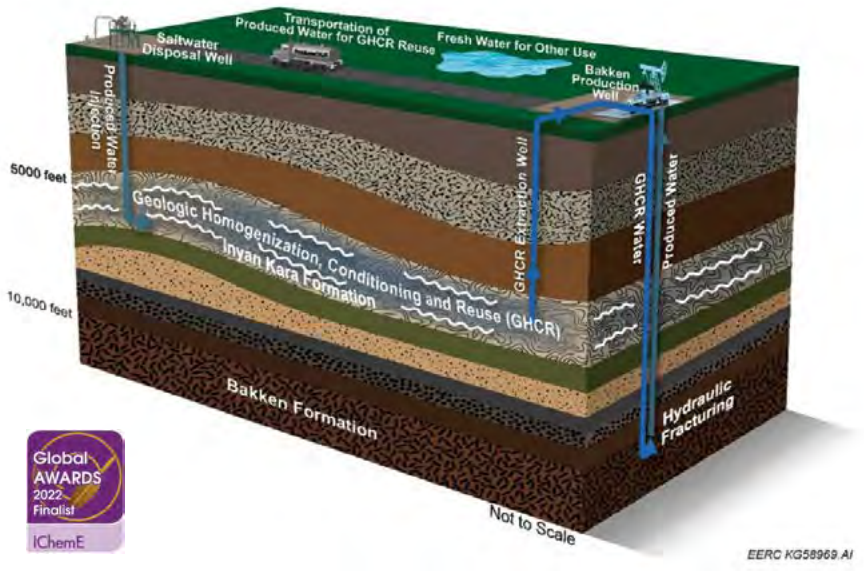
The technical evaluation of the GHCR concept consisted of **laboratory column flow-through testing, field sampling at a commercial SWD location** that has a water production well targeting the same SWD formation, and geologic modeling and numerical simulations.

The GHCR concept **appears capable of providing fluid storage, homogenization, and some conditioning for fluid volumes that are typical of hydraulic fracturing operations in the Bakken formation**.

Implementing the GHCR concept could **reduce SWD formation pressure at the drill spacing unit level**.

It appears that **GHCR could be a competitive or even lower-cost option compared to conventional water management approaches for some sites**.

The GHCR concept aims to use a subsurface geologic formation as a natural medium for managing produced water recycling and reuse. GHCR involves the addition of an extraction well and utilizing the extracted water as hydraulic fracturing makeup water for Bakken wells.



Global AWARDS 2022 Finalist IChemE

Finalist in the Oil and Gas category of the 2022 Institution of Chemical Engineers (IChemE) Global Awards.

PARTNERS

EERC

Nuverra Environmental Solutions

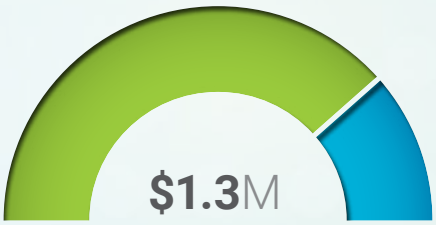
North Dakota Oil and Gas Division

University of North Dakota

AWARD NUMBER

FE0024233-3.2

PROJECT BUDGET



DOE $999,993
PARTNERS $300,000

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FECM RDD&D PRIORITY

CH_4 METHANE MITIGATION

UNDOCUMENTED ORPHANED WELL INITIATIVE PROVIDES ENVIRONMENTAL BENEFITS

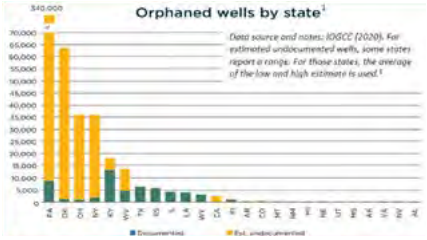
Assisting local and state agencies in identifying and characterizing undocumented orphaned wells to reduce environmental and societal impacts.

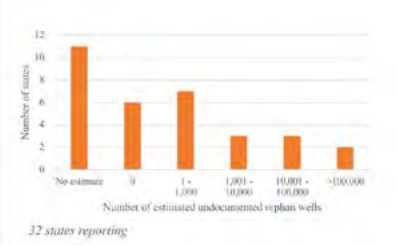
The Bipartisan Infrastructure Law funded Undocumented Orphaned Well (UOW) initiative is a part of NETL's Methane Mitigation Technologies program, focused on eliminating methane emissions throughout the oil and natural gas value chain.

WHAT ARE UNDOCUMENTED ORPHANED WELLS?

Orphaned wells are defined as **idle wells for which the operator is unknown or insolvent**. Undocumented orphaned wells are entirely unknown to a state or local agency or require further research or field investigation for verification. **Unplugged, abandoned wells are a significant source of methane leaks**.

Between 300,000 and 800,000 UOWs are estimated to exist in the United States today. Little is known about these wells, including ownership for establishing custody and completion details for efficient plugging and abandonment. These wells can also present **a significant environmental hazard, with methane and other chemicals of concern leaking into groundwater or the atmosphere**.





BIPARTISAN INFRASTRUCTURE LAW (BIL)

The BIL, signed in 2021, directed the Department of Energy's (DOE) Office of Fossil Energy and Carbon Management to implement a research program focused on identifying and characterizing undocumented orphaned wells.

The BIL provided robust investments to plug these undocumented orphaned wells, helping communities reduce methane emissions and eliminate other environmental impacts.

UNDOCUMENTED ORPHANED WELLS RESEARCH CONSORTIUM

DOE, in collaboration with the Interstate Oil and Gas Compact Commission, created a research consortium that consists of five national laboratories.

The consortium will leverage institutional knowledge, existing processes, and fundamental and applied science expertise to focus on undocumented orphaned oil and gas wells on private and Federal land across the U.S.

COMBINED PROGRAM OVERVIEW

The UOW initiative locates and characterizes UOWs and determines physical locations, methane emissions, wellbore integrity, and other environmental impacts and helps to prioritize remediation by state and Federal agencies.

- Develops modular technologies, materials, and solutions to aid the remediation of orphaned wells.
- Develops advanced sensor technologies to detect and locate emissions from abandoned wells.
- Collaborates with state agencies, industry, national labs, and academia.

NETL – Research and Innovation Center Efforts

Completed and In-progress Study Areas

1. Oil Creek State Park, PA - 138 wells (67 unplugged/56 plugged)
2. Hillman State Park, PA - 31 wells (all unplugged)
3. Oollagah Lake Area, OK - 179 wells (159 unplugged/20 plugged)
4. Private Property near Midland, TX - ~100 to 200 wells (all unplugged)
5. Daniel Boone National Forest, KY - 54 wells (53 unplugged/1 plugged)
6. Private Property near Olean, NY - ~77 wells (21 unplugged/56 plugged)

COMBINED PROGRAM OVERVIEW

The UOW program will develop and test technologies and processes in the field, develop best practices for orphaned well identification and characterization, and ultimately deploy these developed technologies at scale.

NETL's Research and Innovation Center will continue to conduct field exercises to develop advanced sensor technologies to quantify methane emissions related to UOWs.

Technologies developed under the UOW program will help further the Administration's emissions reduction goals to cut methane emissions by 30% compared with 2020 levels by 2030.

PARTNERS

Sandia National Laboratories

U.S. Department of the Interior – March 3, 1849

BERKELEY LAB
Bringing Science Solutions to the World

Los Alamos National Laboratory

Lawrence Livermore National Laboratory

Interstate Oil & Gas Compact Commission

AWARD NUMBERS

FWP-LANL-AE-963-1161, FWP-FP00015308, FWP-FEW0285, FWP-22-025107, FWP-1025006

PROJECT BUDGET

FY22 FUNDING

$6.8M

DOE $6,848,367

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FECM RDD&D PRIORITY

CH_4 METHANE MITIGATION

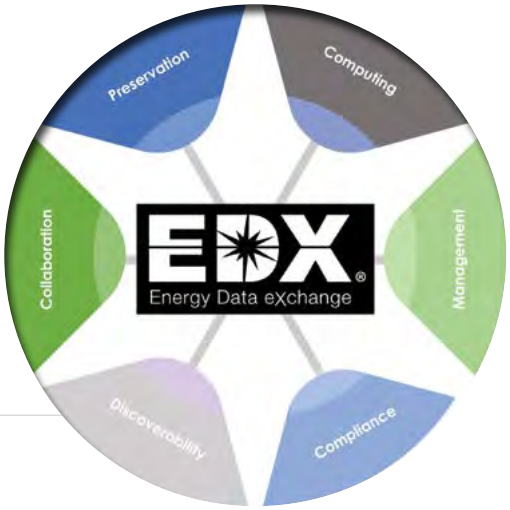
CLICK HERE FOR MORE INFORMATION

EDX® TEAM RECEIVES DOE SECRETARY OF ENERGY'S ACHIEVEMENT AWARD

The Energy Data eXchange (EDX) is NETL's flagship R&D data curation and collaboration platform.

BIG DATA CAPABILITIES SUPPORTING MODERN RESEARCH

- In FY22, NETL's EDX received the highly coveted **Secretary of Energy's Achievement Award**.
- The award recognizes a decade of sustained effort that has led EDX to its current powerful form, **incorporating big data capabilities to meet the Department of Energy's Office of Fossil Energy and Carbon Management (FECM) and NETL's data-driven future**.



EDX: a virtual data laboratory built to find, connect, curate, and re-use data to advance energy and environmental R&D.

EDX PLATFORM STREAMLINES R&D

Supports Solutions to Energy and Environmental Problems

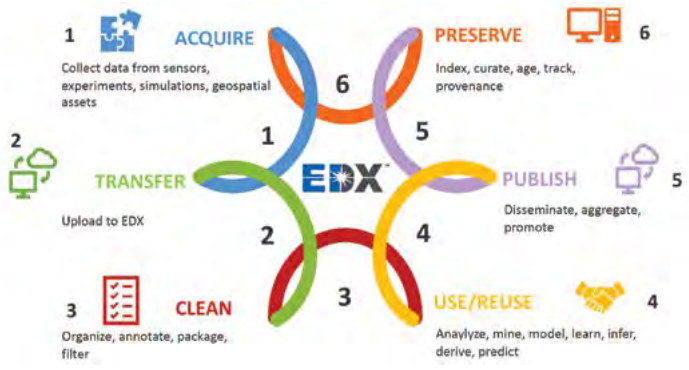
- **Provides access to data from more than 17,000 data submissions.**
- **Hosts >1.2 million resources** on the primary platform and provides access to more than 25 million files hosted on NETL's Watt cluster.
- **Connecting researchers, program management, industry, and the public** with data, analytical tools, and advanced computing resources (cloud and on-premise) via a single web interface.

>2.2 million downloads (>14.6 petabytes of data resources) and growing!

EDX USAGE MEETS A WIDE RANGE OF END-USER NEEDS

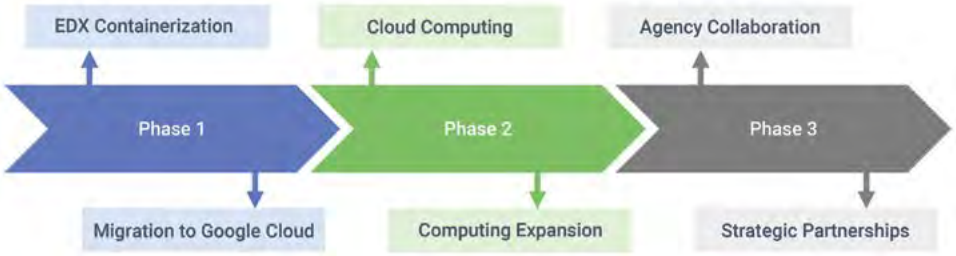
Users include NETL and other national laboratories, government agencies, universities, non-profits, and industry engaged in NETL/FECM-funded research.

Published data products and information are accessible to the general public.



EDX SUPPORTS THE FUTURE OF FECM DATA PRODUCTS AND PROGRAMS

Strong Growth and Operational Enhancements



A multi-cloud hosted solution to connect NETL's EDX with advanced computing resources will be developed over the next three years.

- Connecting FECM data curation and publishing with **artificial intelligence, machine learning, cloud, and data analytics capabilities**.
- Enables **high availability of big data, reduces long-term costs, and minimizes duplication** in IT investments.
- Directly **supports Bipartisan Infrastructure Law** objectives and FECM strategic priorities.
- Forward emphasis on **data-driven solutions** for the FECM community.

PROVIDES INNOVATIVE SOLUTIONS FOR DATA LIFECYCLE MANAGEMENT

- **Improves preservation** of our NETL R&D products for future access.
- **Provides efficient and easily discoverable access** to authoritative, relevant, external data resources.
- **Nurtures energy research products** with capabilities such as secure and private collaboration environments for R&D teams.

PARTNERS

SAMI SCIENCE-BASED AI/ML INSTITUTE

U.S. DEPARTMENT OF ENERGY | Fossil Energy and Carbon Management

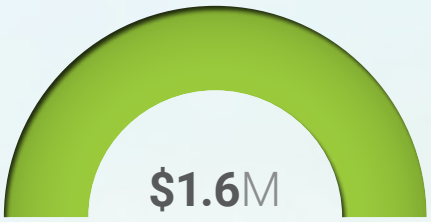
KEY RESOURCES

EDX® Energy Data eXchange

https://edx.netl.doe.gov/reference-shelf/
https://edx.netl.doe.gov/user/register

PROJECT BUDGET

EY22 FUNDING



DOE $1,561,348

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Chad Rowan

FECM RDD&D PRIORITIES

- HYDROGEN WITH CARBON MANAGEMENT
- POINT-SOURCE CARBON CAPTURE
- CARBON DIOXIDE CONVERSION
- CARBON DIOXIDE REMOVAL
- RELIABLE CARBON STORAGE AND TRANSPORT
- DOMESTIC CRITICAL MINERALS PRODUCTION
- METHANE MITIGATION

CLICK HERE FOR MORE INFORMATION

NETL'S AWARD-WINNING CLIMATE AND RISK FORECASTING MODEL MOVES BEYOND ENERGY-RELATED USES

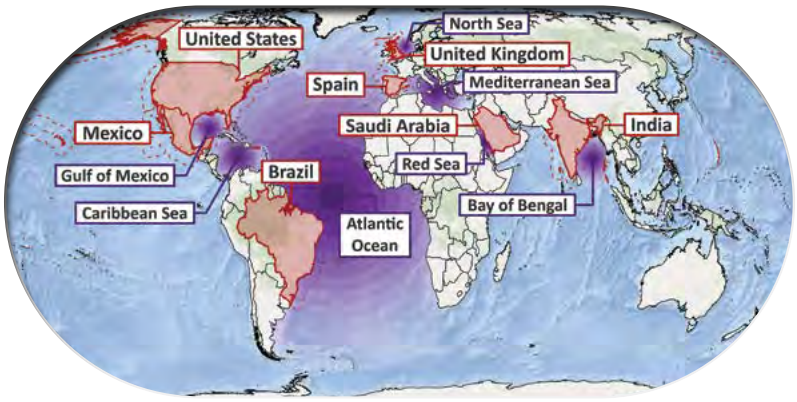
Offshore R&D

CLIMATOLOGICAL AND INSTANTANEOUS ISOLATION AND ATTRACTION MODEL (CIIAM) APPLIED TO INTERNATIONAL WATERS FOR TRANSPORT MODELING

Researchers worldwide are using NETL's CIIAM — a metocean model — to extract climatological ocean-current pathways, and to aid in forecasting by identifying instantaneous dominant trajectory patterns.

These forecasts are beneficial and innovative for a variety of applications beyond their energy-environment origins within **NETL's Offshore Spill Prevention Research Portfolio**.

Ten external research groups have **applied CIIAM to international offshore regions** to address the topics highlighted in the infographic below.

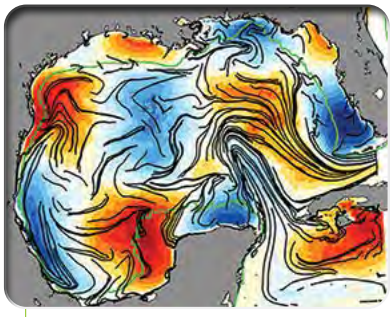


CIIAM is being applied globally, including in the areas and countries highlighted above.

CIIAM IS USED TO UNDERSTAND AND ANTICIPATE TRANSPORTATION OF:

- Oil Spills
- Derelict Vessels
- Fisheries
- Marine Larvae Transport
- Search and Rescue Ops
- Red Tides
- Sargassum Pathways and Arrival Forecasts
- Flotsam
- Global Climate-Change Induced Pathway Shifts
- Current-Induced Stress Regions

IDENTIFYING PREDOMINANT METOCEAN TRANSPORT FOR RISK ASSESSMENT



CIIAM outputs for ocean current trajectory showing how tracers representing hazmat material would deform under the influence of ocean currents in the Gulf of Mexico.

CIIAM **efficiently extracts ocean current and wind pathways as well as transport behavior from large datasets** using advanced mathematical and oceanographic theoretical developments. This information:

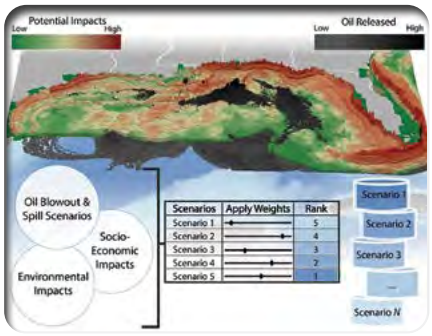
- Improves the understanding of transport within areas under review.
- Extracts the main patterns from large data sets.
- Provides scientists and policymakers with general and accurate guidelines for understanding complex systems.

As an ongoing effort, CIIAM is being used to monitor the Great Pacific Garbage Patch for cleanup activities. The Ocean Cleanup, a Rotterdam-based non-profit organization developing technologies to rid the world's oceans of plastic, is collaborating with the University of Hamburg to adapt CIIAM for use as a valuable tool in forecasting debris movement so collection vessels can more effectively conduct operations.

CLIMATE MODELING FOR IMPROVED OFFSHORE SPILL PREVENTION

Comprehensive Environmental Hazard Assessment

CIIAM, a component of NETL's award-winning **Offshore Risk Modeling Suite (ORM)**, is being **integrated into multiple software and online tools**, including NETL's Common Operating Platform, making it accessible for integrated analyses. As a component of the ORM, CIIAM can:



- Improve planning and prevention activities for oil spills.
- Inform socially and environmentally prudent development.
- Forecast pathway variations related to climate variations.

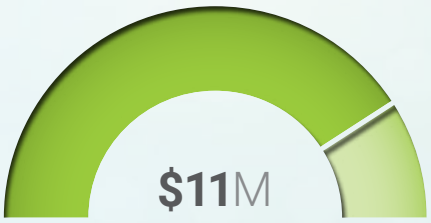
The ORM suite, a group of tools developed under NETL's **Offshore Spill Prevention Research Portfolio**, focuses on innovative solutions to solve challenges associated with:

- Oil spill prevention.
- Hazard prediction.
- Geohazard and subsurface uncertainty reduction.
- Infrastructure integrity and optimization for new and existing infrastructure systems.

AWARD NUMBER

FWP-1022409

PROJECT BUDGET



DOE - *TOTAL BUDGET* ... $10,998,777
DOE - *EY22 FUNDING*..... $2,425,000

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Lloyd's Register
NIO
UH
Institut de Ciències del Mar
The Ocean Cleanup
National Oceanography Centre
CICESE
INPE Unidade de Pesquisa do MCTI
United States Coast Guard 1790
Universidad Nacional Autónoma de México
King Abdullah University of Science and Technology

CLICK HERE FOR MORE INFORMATION

MACHINE LEARNING METHODOLOGY FOR WASTEWATER SORBENT DESIGN INVENTED BY NETL RESEARCHERS

Sorbents made from fly ash can treat leachate from coal ash impoundments.

PROTOTYPE MACHINE LEARNING-BASED METHODOLOGY COMPLETED

Provides Efficient and Rapid Sorbent Design Application

While investigating the problem of wastewater leaching from coal ash impoundments, NETL researchers realized that an artificial intelligence/machine learning (AI/ML) methodology could be used to design sorbents to treat leachates. **The researchers have successfully fitted an ML model to predict boric acid sorption and used the model with a genetic algorithm to design the optimal zeolite sorbent for various boric acid concentrations in aqueous solution.**

This methodology will be invaluable in the rapid computational design of sorbents that can be tuned to specific ash impoundment wastewater contaminants, minimizing the need for laboratory screening and enabling custom sorbent performance potential.

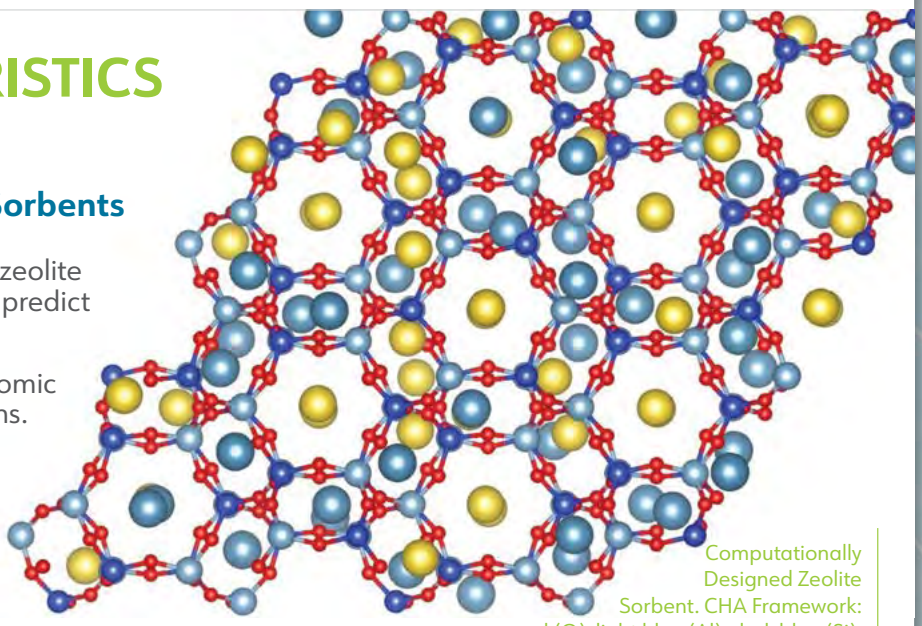
SORBENT CHARACTERISTICS IDENTIFIED

Model Facilitates Design of Zeolite Sorbents

The team generated a structure database of zeolite structures and used physics-based models to predict boric acid sorption for each structure.

The structural models were encoded using atomic property weighted radial distribution functions. The database was then used to train an ML model to predict boron sorption for any zeolite structure.

Combining a genetic algorithm with the ML model resulted in a sorbent that would take up ~2.7 mol boron/kg sorbent.



Computationally Designed Zeolite Sorbent. CHA Framework: red (O), light blue (Al), dark blue (Si). Cations: yellow (Na), gray-blue (Ca)

MODEL RAISES POSSIBILITY OF SORBENTS FROM COAL ASH

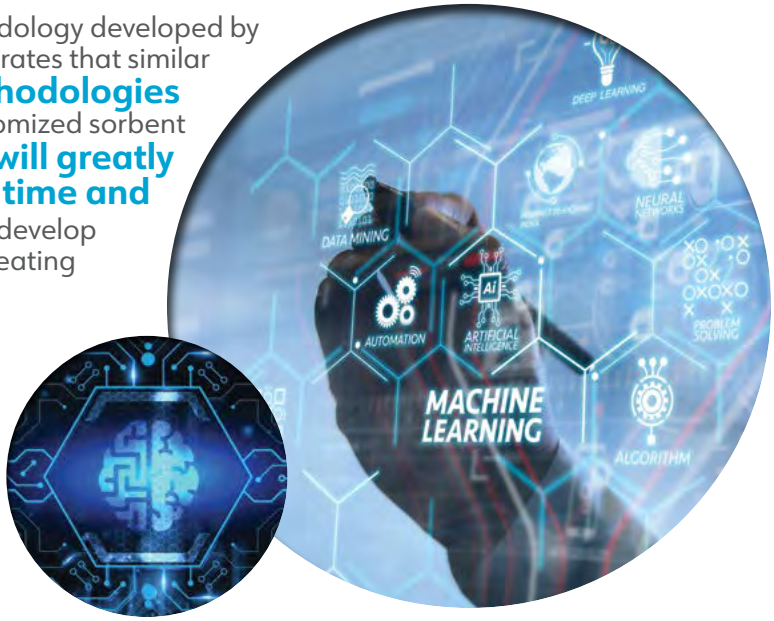
Identifies a Possible Use of Coal Ash to Address Leaching From Coal Ash Impoundments

Interestingly, **the zeolite sorbents identified by the NETL model could be synthesized from fly ash**. These synthesized sorbents could then be deployed to treat leachate from legacy coal ash impoundments, **thereby using coal combustion residuals to treat environmental liabilities from coal combustion residuals**.

AI/ML TECHNIQUES REDUCE SORBENT DEVELOPMENT TIME AND EXPENSE

Leverages NETL's Areas of Expertise

The ML methodology developed by NETL demonstrates that similar **AI/ML methodologies** for rapid, customized sorbent development **will greatly reduce the time and expense** to develop sorbents for treating impoundment leachates.



METHODOLOGY CAN BE GENERALIZED

Similar methods can be used to design sorbents for other pollutants and valuable elements.

Currently, the NETL team is generalizing this method to design zeolites for the adsorption of other pollutants such as strontium, chromium, cobalt, lead, and mercury.

REDUCES FUTURE IMPOUNDMENT MANAGEMENT COSTS

Provides Environmental Justice and Economic Benefits

Innovative concepts to treat leachates and related discharges from both active and inactive (legacy) unlined or inadequately lined coal combustion residual impoundments and ponds will have significant value as efforts to close and control these sites begin.

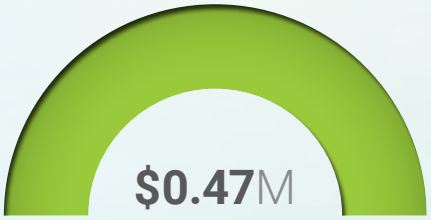
Additional benefits include the potential for recovery/creation of valuable combustion byproducts for U.S. **economic benefit in overburdened and underserved communities**.

AWARD NUMBER

FWP-1022479

PROJECT BUDGET

EY22 FUNDING



DOE $464,989

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CLICK HERE FOR MORE INFORMATION

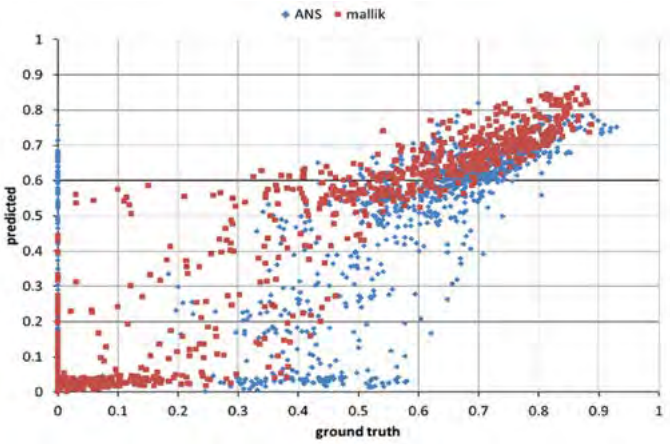
MACHINE LEARNING TOOL PREDICTS HYDRATE SATURATION AND MORPHOLOGY IN ONSHORE AND OFFSHORE BASINS

For the first time, Machine Learning with an Artificial Neural Network (ANN) has been used by NETL researchers to predict gas hydrate saturation and morphology in subsurface reservoirs.

WHAT'S NEW?

MACHINE LEARNING TOOL TO PREDICT GAS HYDRATE SATURATIONS

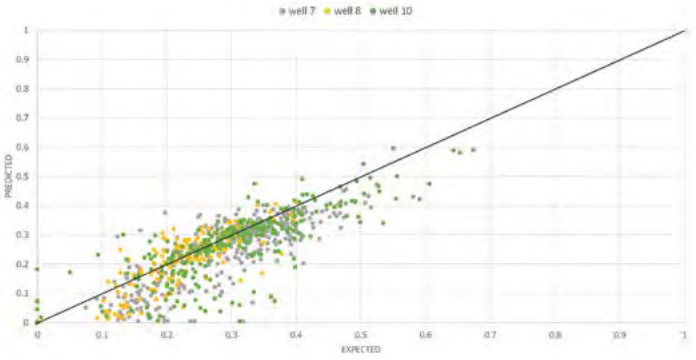
- Machine learning (ML) tool indicates subsurface hydrate saturation.
- ML models based on Artificial Neural Network (ANN) trained with conventional well log data.
- Resulting predictions **provide up to 90% accuracy** compared to physics-driven methods that rely on nuclear magnetic resonance (NMR) logs.



Graph showing NMR-derived (horizontal axis) vs. ML-predicted (vertical axis) hydrate saturation values at the Mallik (red squares) and Alaska North Slope wells (blue diamonds).

PROBLEM: PREDICTING HYDRATE SATURATION WITH LIMITED LOG DATA

Physics-based models rely on NMR logs, which are expensive to acquire and uncommon in the industry.



Graph showing NMR-derived (horizontal axis) vs. ML-predicted (vertical axis) hydrate saturation for fracture-filling hydrate, offshore India.

SOLUTION:

An ML tool trained with a robust ANN can provide reliable hydrate saturation predictions without NMR logs.

HOW IT WORKS

The ML tool is trained with conventional logs, including:

- Density
- Porosity
- Electrical resistivity
- Gamma radiation
- Acoustic wave velocity

Hydrate saturation and morphology predictions can be made with three to five conventional logs.

BEAUFORT-MACKENZIE BASIN

Onshore Basin

- ANN trained on log data from permafrost-associated deposits in the Eileen Gas Hydrate Trend on the Alaska North Slope.
- ML models predicted gas hydrate saturations with **80 to 90% accuracy** compared with physics-driven models.

Chong, L., Singh, H., Creason, C.G. et al. Application of machine learning to characterize gas hydrate reservoirs in Mackenzie Delta (Canada) and on the Alaska north slope (USA). Comput Geosci 26, 1151–1165 (2022). https://doi.org/10.1007/s10596-022-10151-9

INDIAN OCEAN

Offshore Basin

- ML was used to predict key reservoir properties in the Krishna-Godavari Basin, offshore India.
- ANN was trained using log data from six wells drilled in 2015 as part of India's NGHP-02 expedition.
- ML models **predicted gas hydrate morphology with accuracies of 79 to 86%** and **gas hydrate saturation with accuracies ranging from 68 to 92%**.
- The morphology is the type of hydrate deposit in the reservoir. The ML models can distinguish between pore-filling hydrate (potentially economically attractive), fracture-filling hydrate (not attractive as a resource), or no hydrate present.

ML Models Make Reliable Predictions of Hydrate Saturation in Both Onshore and Offshore Basins

IMPACT

- ML tool can **serve as an alternative to physics-driven methods**.
- ML tool can **be applied to both onshore and offshore basins**.

Enables Accurate Predictions of Hydrate Saturation and Morphology

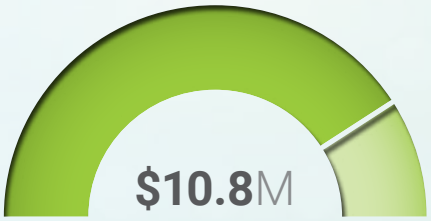
PARTNER

U.S. DEPARTMENT OF ENERGY | Fossil Energy and Carbon Management

AWARD NUMBER

FWP-1022410

PROJECT BUDGET



DOE - *TOTAL BUDGET*.... $10,836,215
DOE - *EY22 FUNDING*..... $2,023,000

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CLICK HERE FOR MORE INFORMATION

COAL COMBUSTION RESIDUAL-BASED SUPPORT COLUMNS FABRICATED

Low-value coal ash can be encapsulated and used to form strong structural materials.

MOVING COAL COMBUSTION RESIDUALS UP THE VALUE CHAIN

Providing Strong Building Materials

Semplastics EHC LLC is developing high-strength, encapsulated, commercially useful composite support columns from coal combustion residuals (CCRs)—mainly coal combustion fly ash.

Hollow columns (approximately 9 inches in diameter by 18 inches in length) have been successfully fabricated and exhibit excellent compressive and flexural strength.

Hollow Support Columns

ENCAPSULATING CCRS PROVIDES MULTIPLE BENEFITS

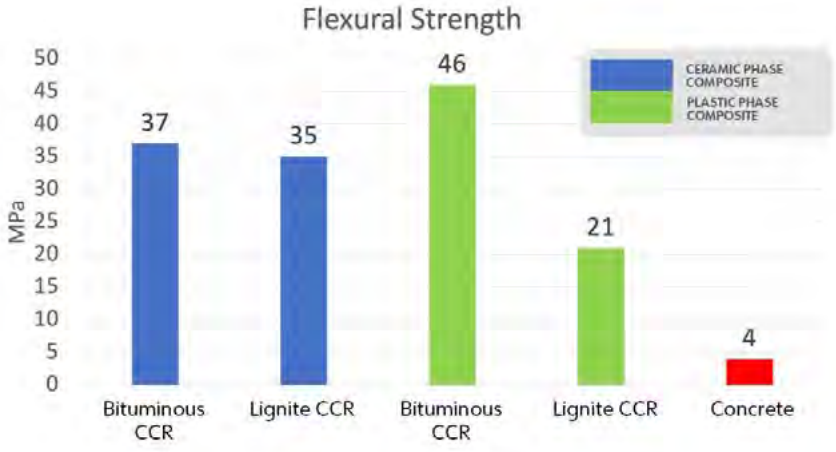
Prevents Leaching of Toxic Elements

Semplastics encapsulates CCR particles with plastic or polymer-derived ceramic composite coatings. The coatings serve as both a particle binder and means of effectively encapsulating particles to prevent leaching of toxic elements (e.g., heavy metals such as arsenic, chromium, and selenium) from the CCRs.

IMPROVED PERFORMANCE WITH CCRS

Boosting Structural Strength

Fabricated materials show excellent compressive strength, flexural strength, and relatively light bulk density compared to conventional concrete. These properties provide substantial benefits over the status quo in heavy building materials.



CCR-based materials have up to 10x higher flexural strength than concrete.

PROVIDING A PATH TO PRODUCTION OF LARGE-SCALE CONSTRUCTION COLUMNS

Scale-up, Design, and Modeling

Success in small column fabrication is enabling larger prototypes and eventual commercial offerings.

Moving from casting techniques to compression molding, predictive modeling, and interlocking column design will advance technology maturation toward commercialization.

Solid Ceramic Aggregate Column

REMEDIATES LEGACY WASTES AND SUPPORTS ECONOMIC DEVELOPMENT

Enhances Environmental Sustainability

Successful development and market penetration of the composite CCR-containing columns remediates legacy wastes and supports economic development in coal/power generation communities.

Using waste materials in the production process also reduces the environmental burden associated with the use of virgin raw materials.

PARTNERS

UND UNIVERSITY OF NORTH DAKOTA

EERC

CART Center for Applied Research and Technology, Inc.

Semplastics

CLEMSON UNIVERSITY

AWARD NUMBER
FE0031932

PROJECT BUDGET

DOE $998,585
PARTNERS $409,000

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