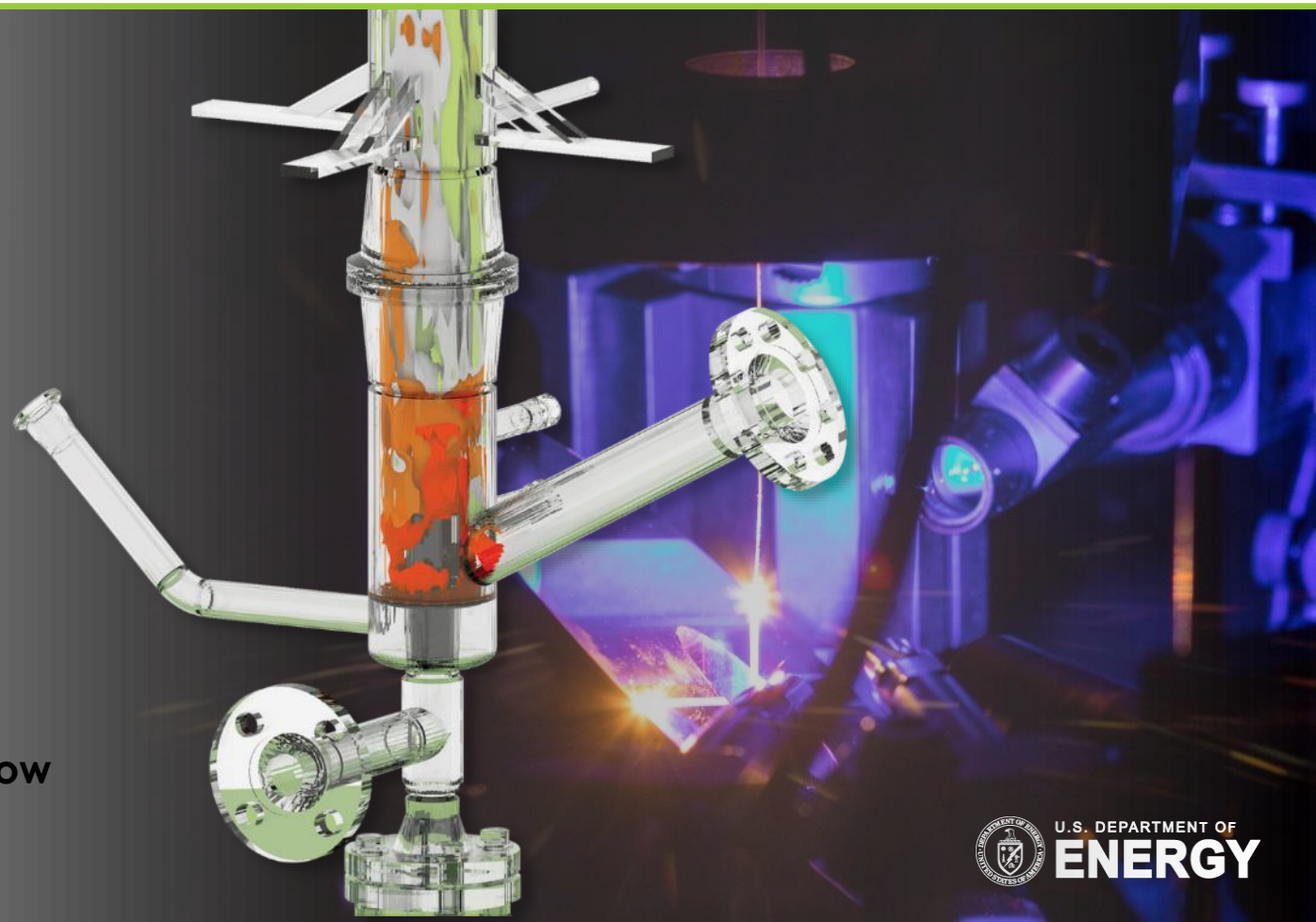
Driving the Technology Innovation Ecosystem through Applied Research and Collaboration

Solutions for Today | Options for Tomorrow

Brian J. Anderson, Ph.D.
Director



Carbon Capture Utilization and Sequestration Roadshow
Washington, D.C. Workshop
January 28, 2020

MISSION

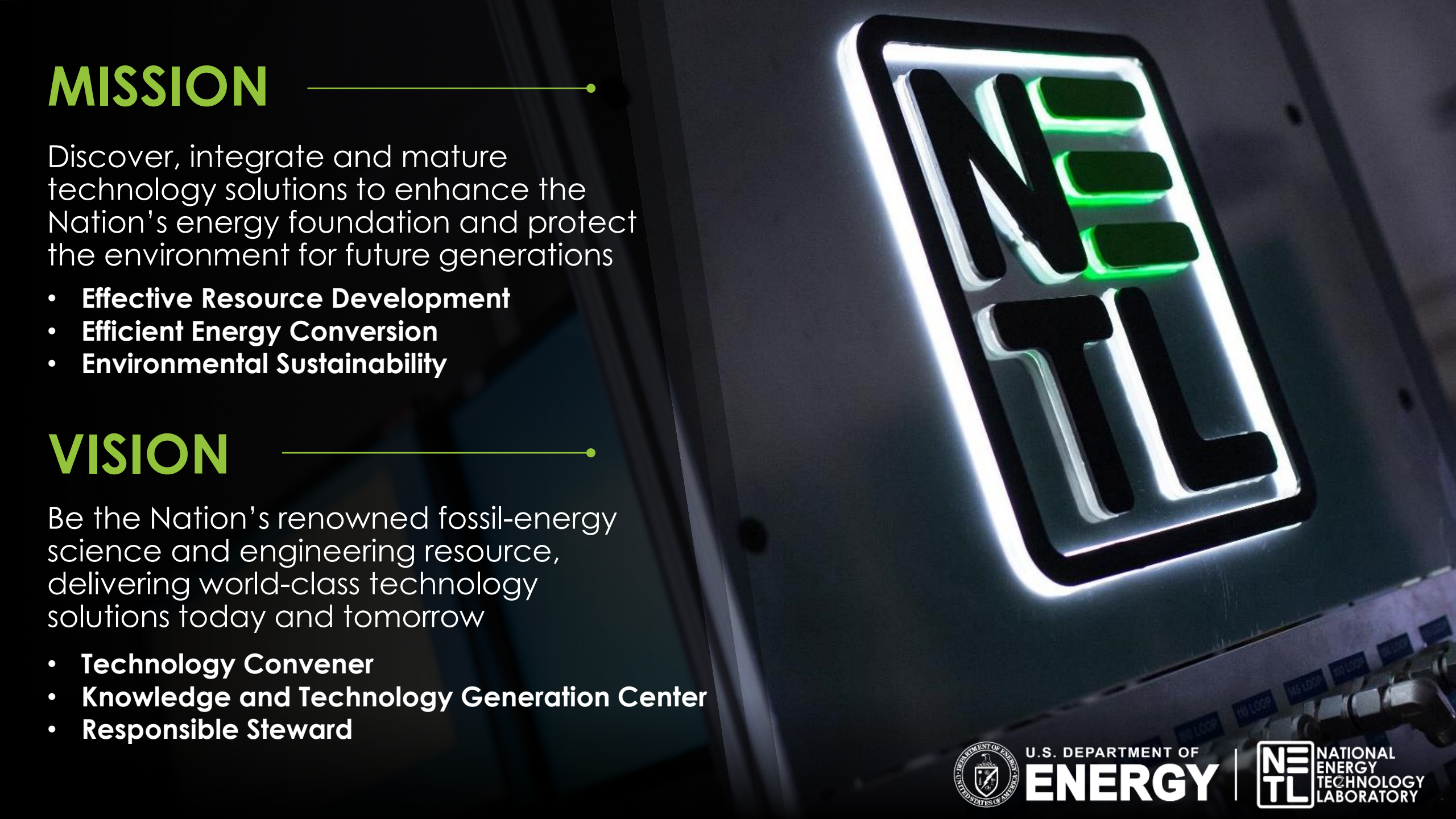
Discover, integrate and mature technology solutions to enhance the Nation's energy foundation and protect the environment for future generations

- **Effective Resource Development**
- **Efficient Energy Conversion**
- **Environmental Sustainability**

VISION

Be the Nation's renowned fossil-energy science and engineering resource, delivering world-class technology solutions today and tomorrow

- **Technology Convener**
- **Knowledge and Technology Generation Center**
- **Responsible Steward**



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

Evolving Topics in Coal

NATIONAL ENERGY TECHNOLOGY LABORATORY

Upgrading the Existing Fleet

Improving the performance, reliability, & efficiency of the existing coal-fired fleet

Advancing Next-Gen Power Plants

Advancing small-scale, modular coal plants that are highly efficient, flexible, & near-zero emissions

Pioneering New Markets for Coal

Enhancing the value of coal as a feedstock & deriving new value-added products from coal

Reducing the Cost of Carbon Capture

Developing advanced computational & simulation tools, & transformational technologies, to reduce the cost of CO_2 capture

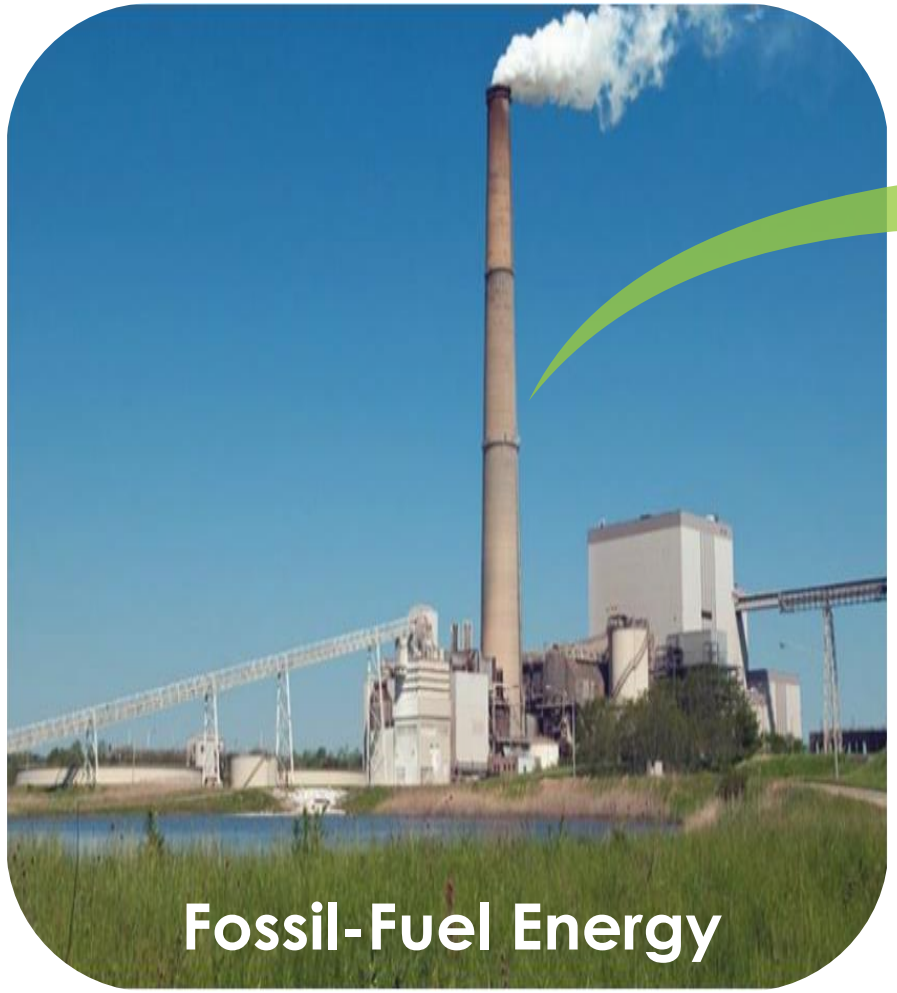
Reducing Water Use in Energy Production

Addressing water quality, sustainability, & availability for power generation

Carbon Capture, Utilization and Storage (CCUS)

NATIONAL ENERGY TECHNOLOGY LABORATORY

Program Areas



Reducing the Cost of Carbon Capture

Integrated R&D Approach

2017
Large Capture Pilots Initiated

2020
R&D Completed for Carbon Capture 2nd Generation Technologies

2025
Integrated CCS Projects Deployed

2035
Transformational Technologies Available for Deployment

Deployments

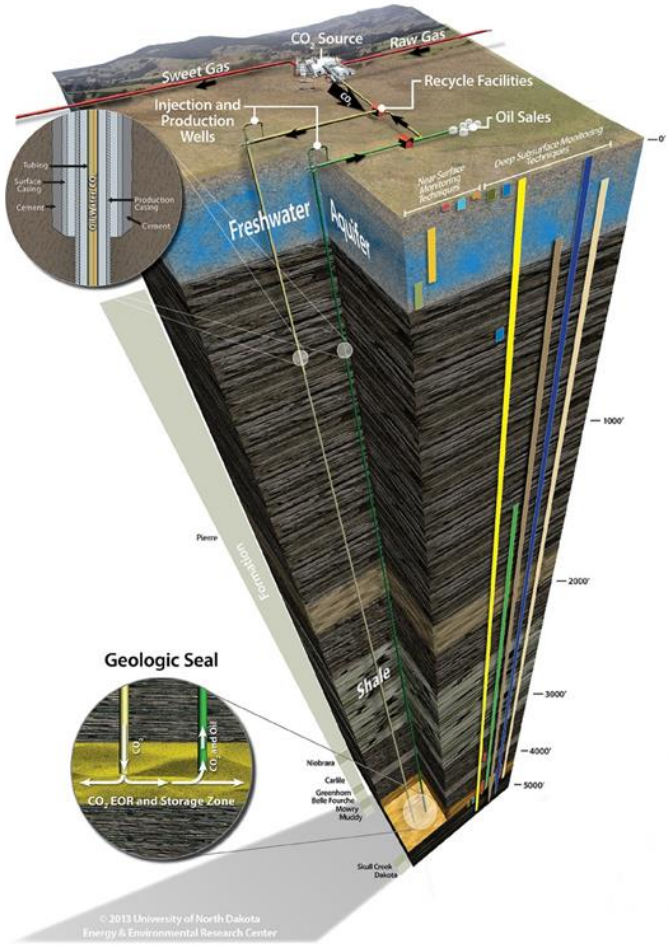
2017
Initiate Storage Feasibility for Integrated CCS

2022
Commercial-scale Storage Complexes Characterized

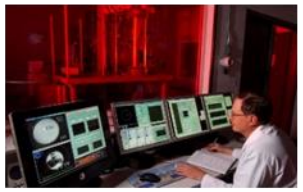
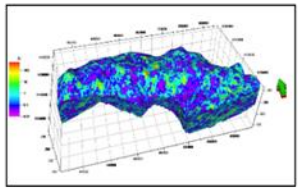
Carbon Storage

Approaches

- Predicting and monitoring CO_2 plume and brine pressure front movement, stabilization, and impacts.
- Optimization of reservoirs for CO_2 storage capacity.
- Developing and validating risk-assessment strategies.
- Mitigating risks, such as leakage from old wells and induced seismicity.
- Carrying out (large-volume and Fit-for-Purpose) field tests for different storage types and depositional environments.






NRAP National Risk Assessment Partnership
Pacific Northwest National Laboratory
BERKELEY LAB
Los Alamos National Laboratory EST.1943
NATIONAL ENERGY TECHNOLOGY LABORATORY

2nd Generation Pilot-scale Technologies

NATIONAL ENERGY TECHNOLOGY LABORATORY

Reduced Cost

$100+/tonne

~50% Reduction

Reduced Energy Penalty

30+% Penalty

~20% Penalty

Program Activity

180+ Projects

15 Technologies Tested at Pilot Scale

Technologies Tested at Pilot Scale

TECHNOLOGY HIGHLIGHTS	Innovation Pathways: Materials	Processes	Equipment	PRINCIPAL DEVELOPER
POST-COMBUSTION				
Imbedded Amine Sorbent*	■	■		ADA-ES
Water-lean Amine Solvent	■	■		Fluor/PNNL
Hybrid Solvent/Membrane	■	■	■	Gas Technology Institute
Amino-silicone Solvent*	■			General Electric Company
Amine/Imidazole Solvent Mixture* *(Large Pilot)*	■			ION Engineering
Advanced Amine Solvent Process*	■	■		Linde/BASF
Advanced Membrane Process*	■	■		MTR
Nozzle-based Solvent Contactor*			■	Neumann Systems Group
Mixed Salt Solvent Process*	■	■		SRI International
Carbon-based Sorbent*	■			SRI International
Alkalized Alumina Sorbent*	■	■		TDA Research
Optimized Amine Solvent Process	■	■	■	University of Kentucky
Piperazine Solvent/Flash Stripper*	■		■	URS/University of Texas
PRE-COMBUSTION				
Ammonium Carbonate/Bicarbonate Solvent*	■			SRI International
Integrated Sorbent Process	■			TDA Research

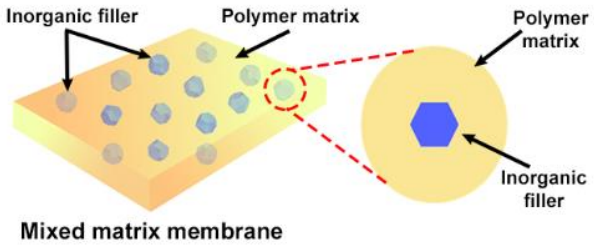
*Project Completed

Accelerating CCUS R&D Using Computational Methods

Data Analytics, Machine Learning and Artificial Intelligence

JOULE
NETL SUPERCOMPUTER

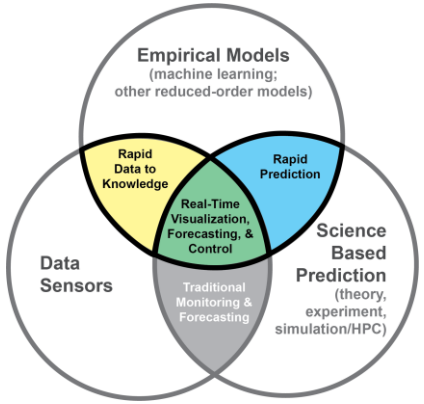
Driving Down the Cost of Carbon Capture



Predicted properties for over a million possible MMMs

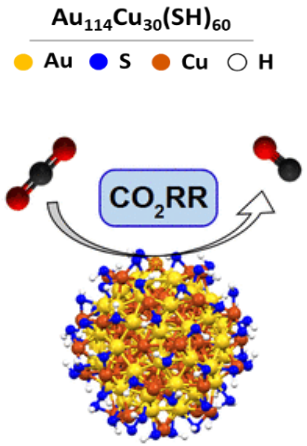
Transform subsurface engineering operations for geologic carbon storage

Science-informed Machine Learning for Accelerating Real Time Decisions in Subsurface Applications (SMART Initiative)



Reduce costs through faster, more efficient, analysis of information, and reduced uncertainty in operations decision-making

Computational/Experimental study of CO_2 to CO Conversion



Predict Catalytic Activity of Yet-To-be-Synthesized Materials

THANK YOU!

VISIT US AT: **www.NETL.DOE.gov**

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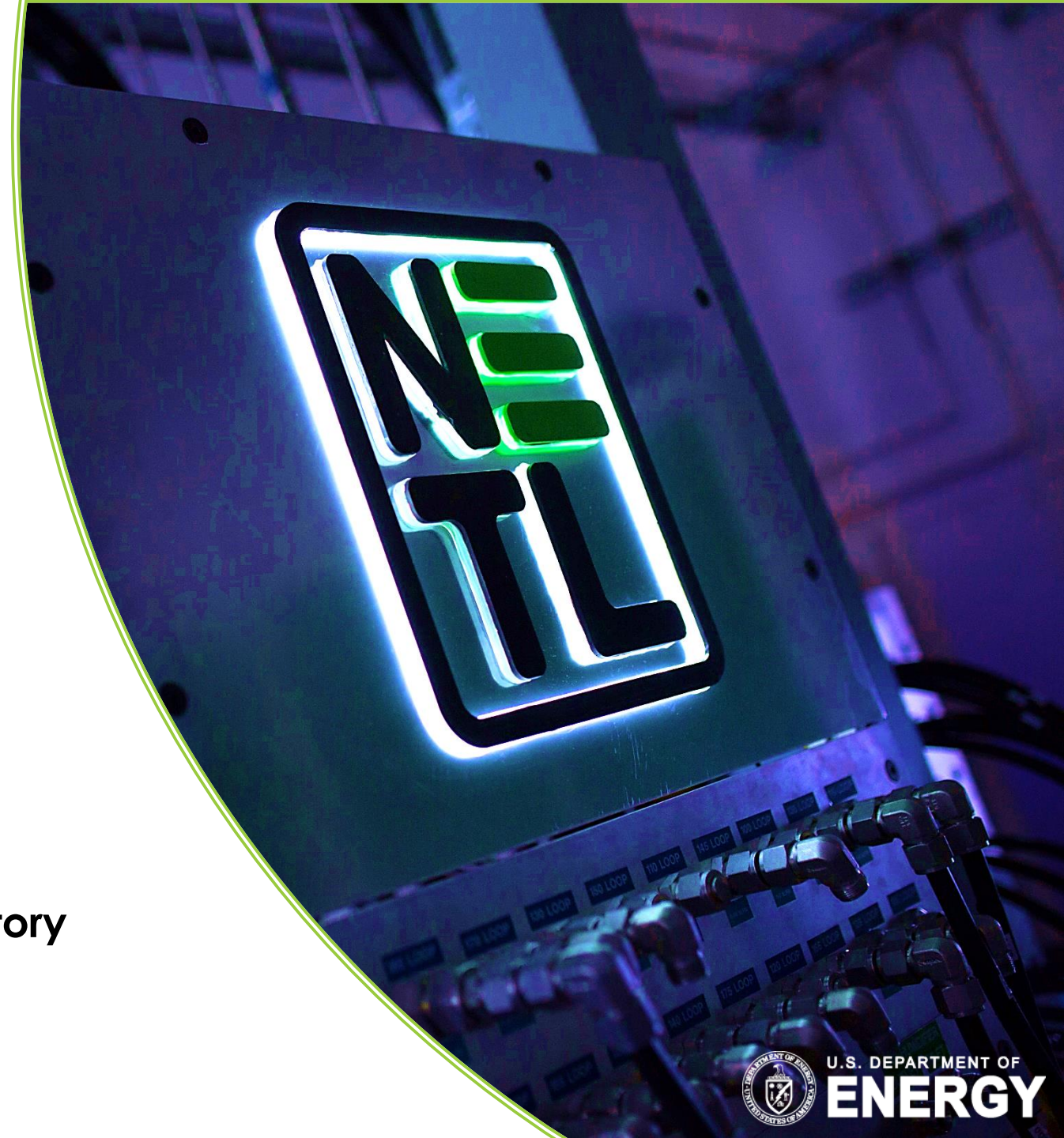
@NETL_DOE

@NationalEnergyTechnologyLaboratory



U.S. DEPARTMENT OF ENERGY

Petra Nova CO2 EOR CCS Plant

From Discovery to Commercialization

NRG W.A. Parish Power Plant – Full Scale Integrated CCS

Government – Industry Partnership to Commercialization

Industry Leading the Effort

TECHNOLOGY MATURATION

Scale
Technology Confidence
Investment

TRL 9

2016
Full Scale Commercialization

TRL 7-8

2011
First-of-a-kind Integrated Coal CCS Small Commercial Scale Plant

First fully Integrated Coal CCS Plant – 500 tons/day Alabama Power

TRL 6-7

2008
Pre-Commercial Prototype Validated in Relevant Environment

First Commercial Plant - w/ Improved KM CDR Process® - 400 tons/day

TRL 4-5

1994 & 1999
Component/Subsystem Validated – KM CDR Process and Improved Process Validated

KM CDR Process® Developed

TRL 2-3

Early 1990s
Proof-of-Concept Developed – Initial Carbon Capture Development

MHI/KEPCO Pilot Plant – 2 tons/day

TRL 9 — COMMERCIALIZATION
Technology available for wide-scale market use

TRL 8 — DEMONSTRATION
System demonstrated in operational environment

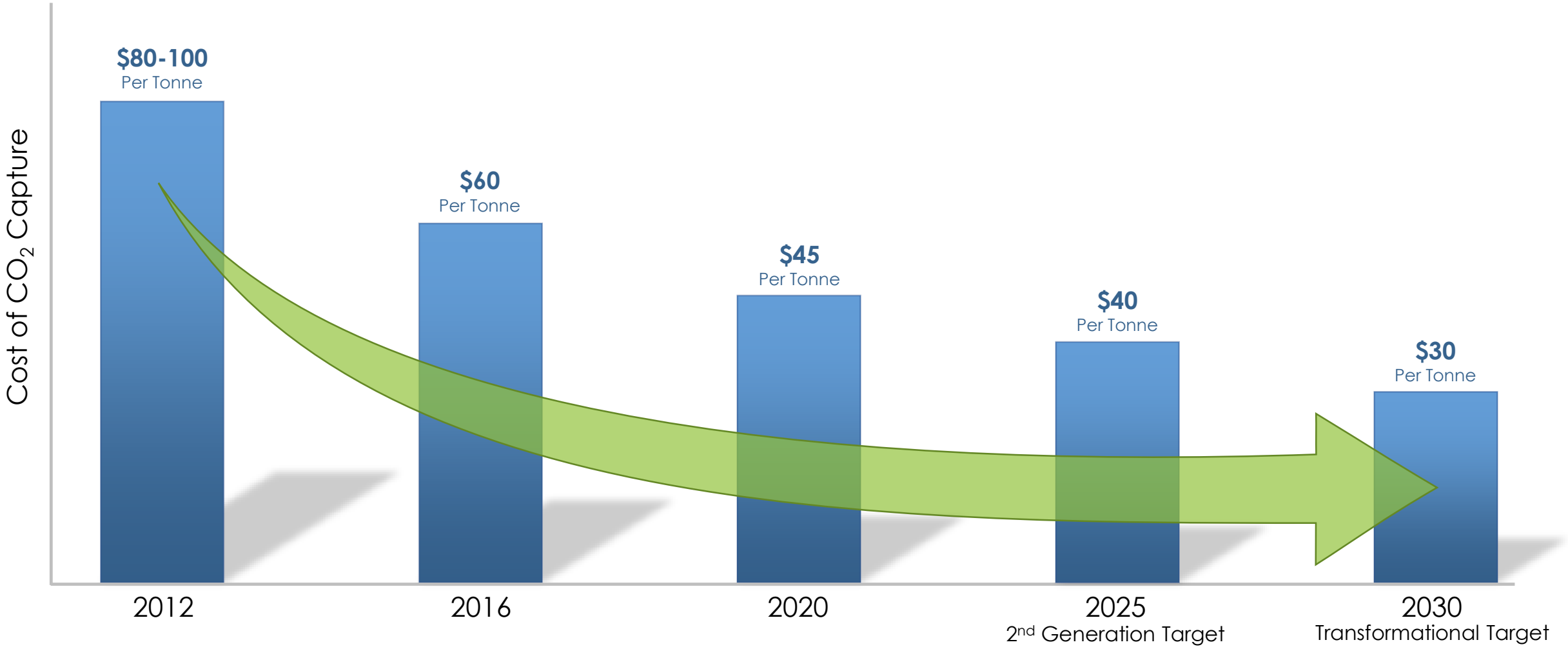
TRL 6-7 — SYSTEM TESTING
System performance confirmed at pilot-scale

TRL 4-5 — DEVELOPMENT
Technology component validated/integrated

TRL 1-3 — DISCOVERY
Concept identified/proven at laboratory-scale

Direction of Fossil Energy Research

Reducing the Cost of Carbon Capture



National Carbon Capture Center

DRAFT – Will update numbers and partners with Andy O'Palko

- **5 year $150 Million of DOE Investment**
- **$100 Million Capture Funding**
- **Independent Test Facility**

Post-combustion Technology Testing

- PC4 Facility – 4.3 MWe
- Actual PC flue gas
- Bench through pilot scale
- > 101,000 hours of testing
- > 30 Technologies tested
- US & 6 other countries

– World Class Carbon Capture Technology Test Facility –

Maturing 2nd Generation Technologies

Research Triangle Institute's Water-Lean Solvent Process

DOE/FE/NETL has sponsored highly successful second-generation technologies that will dramatically reduce CO_2 capture costs. Research Triangle Institute's (RTI's) Water-Lean Solvent Process is one of those technologies.

BACKGROUND

CHALLENGE:

- Current solvent capture technologies use mixtures of ~70% water and 30% amines to absorb CO_2
- The water has negative energy impacts and doesn't capture any of the CO_2 - unlike the amines - but the water controls the corrosivity and viscosity of the amines

RTI'S SOLUTION:

- Replace water with a hydrophobic non-aqueous solvent
- Total water in the mixture goes from ~70% down to ~5-10%

SIGNIFICANT RESULTS

Techno-economic analyses indicate:

Reduced Capital Costs

- Enhanced solvent performance results in smaller columns, heat exchangers, and footprint

Reduced Operating Costs

- Lower energy requirements

Lab/Bench Scale Development

Initiated 2009/2010

- Proof of concept/feasibility in 2009 and lab-scale testing initiated in 2010
- Bench-scale testing initiated 2014
  - Solvent formulation finalized
  - Reboiler heat duty < 2.0 GJ/tonne
  - Preliminary techno-economic analysis shows capture cost ≤ $40/tonne

Scale-Up Testing

Initiated 2016

- Testing at 60-kWe scale conducted using actual flue gas at SINTEF's Tiller Plant pilot-testing facility in Norway
  - 1500+ hours of parametric and long-term testing on coal derived flue gas
- Additional testing at the National Carbon Capture Center
  - 570 hours at 50-kWe scale using coal-derived flue gas to evaluate operational issues

Large Pilot-Scale Testing

Initiated 2018

- ~12 MWe scale testing at Technology Centre Mongstad (TCM) to evaluate the viability of the RTI solvent as a drop-in replacement for conventional capture systems
- Additional testing will modify TCM's existing equipment to evaluate optimized operation with the RTI solvent

Maturing 2nd Generation Technologies

Membrane Technology and Research Advanced Membrane Process

DOE/FE/NETL has sponsored highly successful second-generation technologies that will dramatically reduce CO_2 capture costs. MTR's Advanced Membrane Process is one of those technologies.

BACKGROUND

CHALLENGE:

- CO_2 concentration in post-combustion flue gas was considered too low to provide sufficient driving force for membrane-based separation
- Permeance and selectivity of 1st generation membranes were too low for cost-effective separation of low-CO_2-concentration gases

MTR'S SOLUTION:

- Materials development efforts increased permeance by 3x while maintaining selectivity
- Innovative process design resulted in increased CO_2 concentration in membrane feed gas, enhancing driving force

SIGNIFICANT RESULTS

Establish Viability of Membrane-based Post-Combustion Capture

- Materials and process innovations overcome limitations of low driving force

Nature of Membrane Systems Provides Potential Solutions to Challenging Problems

- Inherently modular, low-cost, high-volume manufacturing; simplifies scale up

Lab/Bench Scale Development

Initiated 2007

- Development of advanced Polaris membrane with increased permeance 10x that of existing membranes and CO_2/N_2 selectivity > 20
- Novel countercurrent sweep CO_2 recycle process design reduced the need for energy intensive compression
- 10,000 hours of stable testing at 1 tonne/day scale on actual flue gas confirmed improved permeance and selectivity

Small Pilot-Scale Testing

Initiated 2011

- Over 1,000 hours of testing at 1 MWe (20 tonnes/day) scale at the National Carbon Capture Center
- Validated countercurrent sweep process and a low pressure-drop sweep module that reduces parasitic energy losses
- Revealed effective boiler operation in the presence of recycled CO_2 to increase flue gas CO_2 concentration, reducing cost

Large Pilot-Scale Testing

Initiated 2018

- Detailed techno-economic analysis and preliminary plant design with engineering/cost estimates for construction of a 10 MWe pilot facility at the Wyoming Integrated Test Center
- Field-scale testing at Technology Centre Mongstad to demonstrate modular membrane concept for use in commercial-scale systems

Driving Computational Science

NATIONAL ENERGY TECHNOLOGY LABORATORY

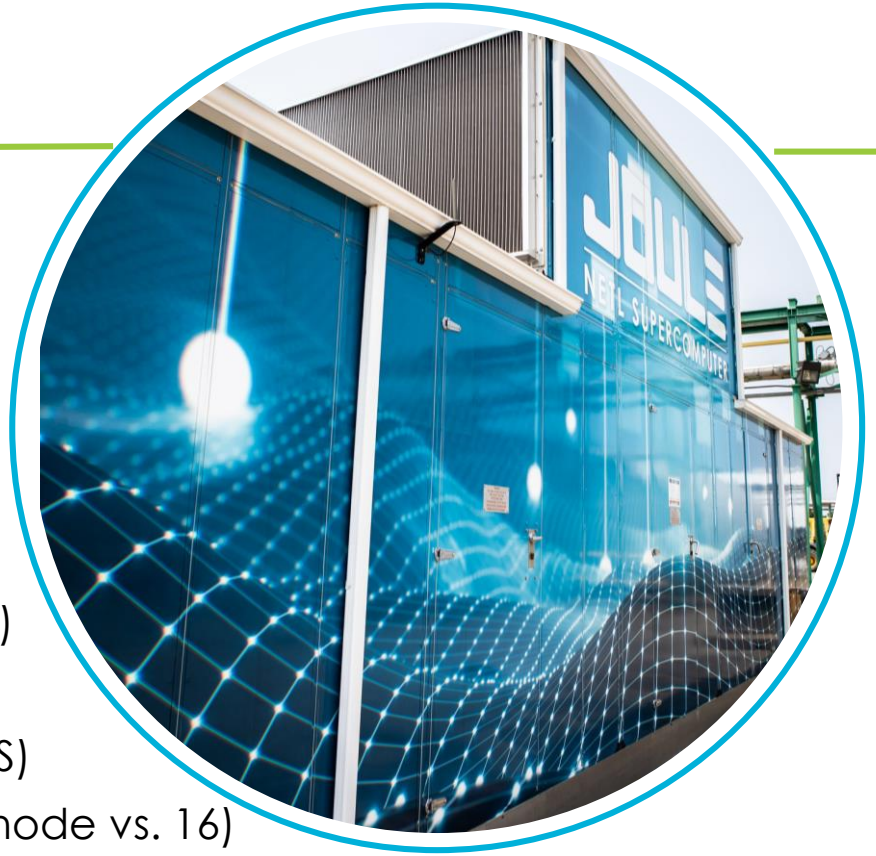
Center for High Performance Computing

JOULE 2.0

With a speed of **3.608 PFLOPS**, Joule 2.0 ranks:

55th in the World

21st in the United States



- **More** CPU cores (73,240 vs. 24,192)
- **More** memory (271 TB vs. 73 TB)
- **Faster** (3.608 PFLOPS vs. 0.5 PFLOPS)
- **Newer Technology** (40 cores per node vs. 16)

Center for Data Analytics and Machine Learning

Phase I – B94:

128 GPU Units

19 Petabytes of Storage

Phase II – B83:

768 GPU Units

60 Petabytes of Storage

66 GB/s write and **122** GB/s read capability

Integrated GPU and CPU will enhance machine learning and data analytic capabilities at all three research locations

Driving Down the Cost of Carbon Capture

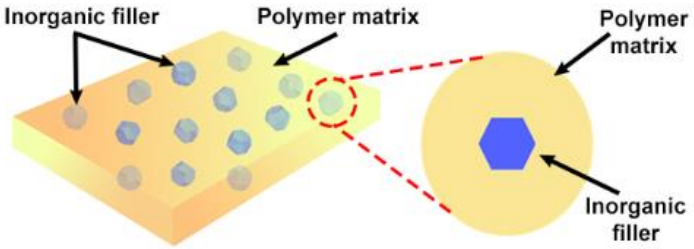
Computational tools to rapidly screening of novel carbon capture materials

- NETL in-house researchers used high-throughput computational methodology to screen over **1 million** possible mixed matrix membranes (MMMs) .
- NETL-developed polymers were found to enhance mechanical stability.
- MMMs, with NETL developed polymer, were estimated to **decrease** the cost of carbon capture from **$63 to $48 per metric ton** of CO_2 removed.

MOF Properties
(Predicted by Calculations)

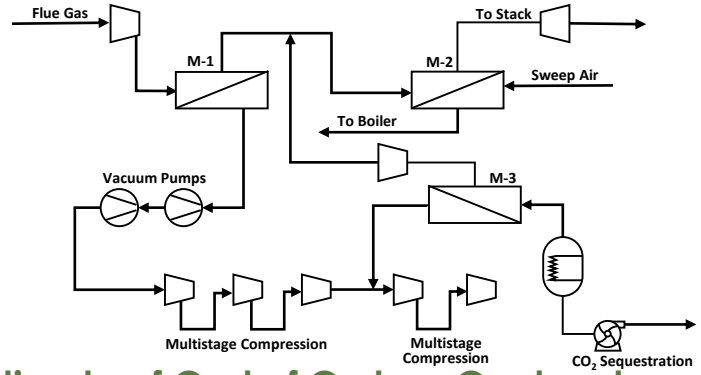
Maxwell Eq.

Pure Membrane Properties for ~10 polymers measured experimentally



Mixed matrix membrane

Predicted Properties for over a million possible MMMs



Estimate of Cost of Carbon Capture based on an assumed configuration

University of Pittsburgh
Department of Chemical & Petroleum Engineering

SMART-CS Initiative

Primary Goals

Real-Time Visualization
"CT" for the Subsurface

Rapid Prediction
Virtual Learning

Real-Time Forecasting
"Advanced Control Room"

Technical Team

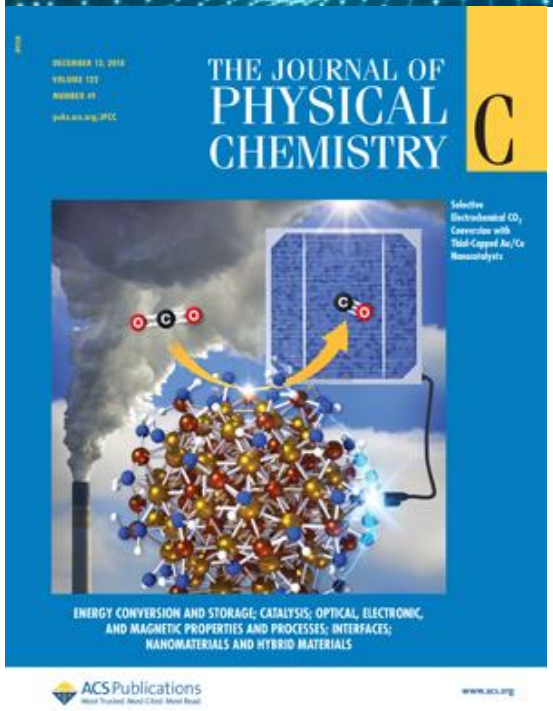
Carnegie Mellon University
Los Alamos National Laboratory
National Energy Technology Laboratory
Battelle
EERC University of North Dakota
Lawrence Livermore National Laboratory
Colorado School of Mines
Oak Ridge National Laboratory
PennState
The University of Utah
Pacific Northwest National Laboratory
Bureau of Economic Geology
Sandia National Laboratories
Illinois University of Illinois at Urbana-Champaign
Berkeley Lab

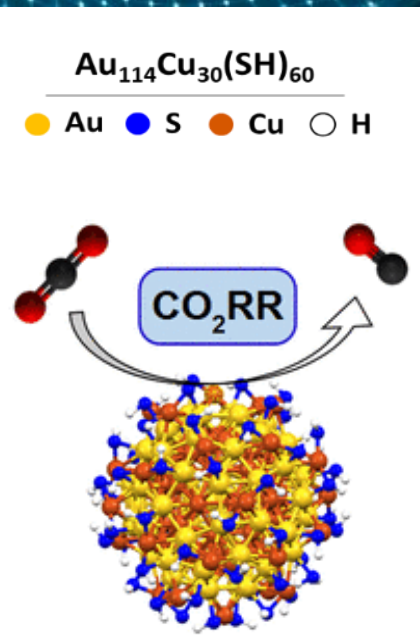
***S**cience-informed **M**achine Learning to **A**ccelerate **R**eal **T**ime (SMART) Decisions in Subsurface Applications*

Computational/Experimental study of CO_2 to CO Conversion

Predict Catalytic Activity of Yet-To-be-Synthesized Materials

- Electrochemical CO_2 reduction reaction (CO_2RR) is a promising approach for converting fossil fuel emissions into environmentally sustainable chemicals and fuels.
- NETL researchers simulated Au-Cu nanoclusters under electrochemistry conditions using an in-house computational electrochemistry code.
  - Experimental studies validated the computational predictions.
- Density functional theory calculations were performed on NETL's Joule supercomputer.
- The alloys retained the activity and selectivity of pure gold with an approximately **50 percent reduction** in precious metal content.





Technology Development Pathway

An Active Portfolio from Concept to Market Readiness

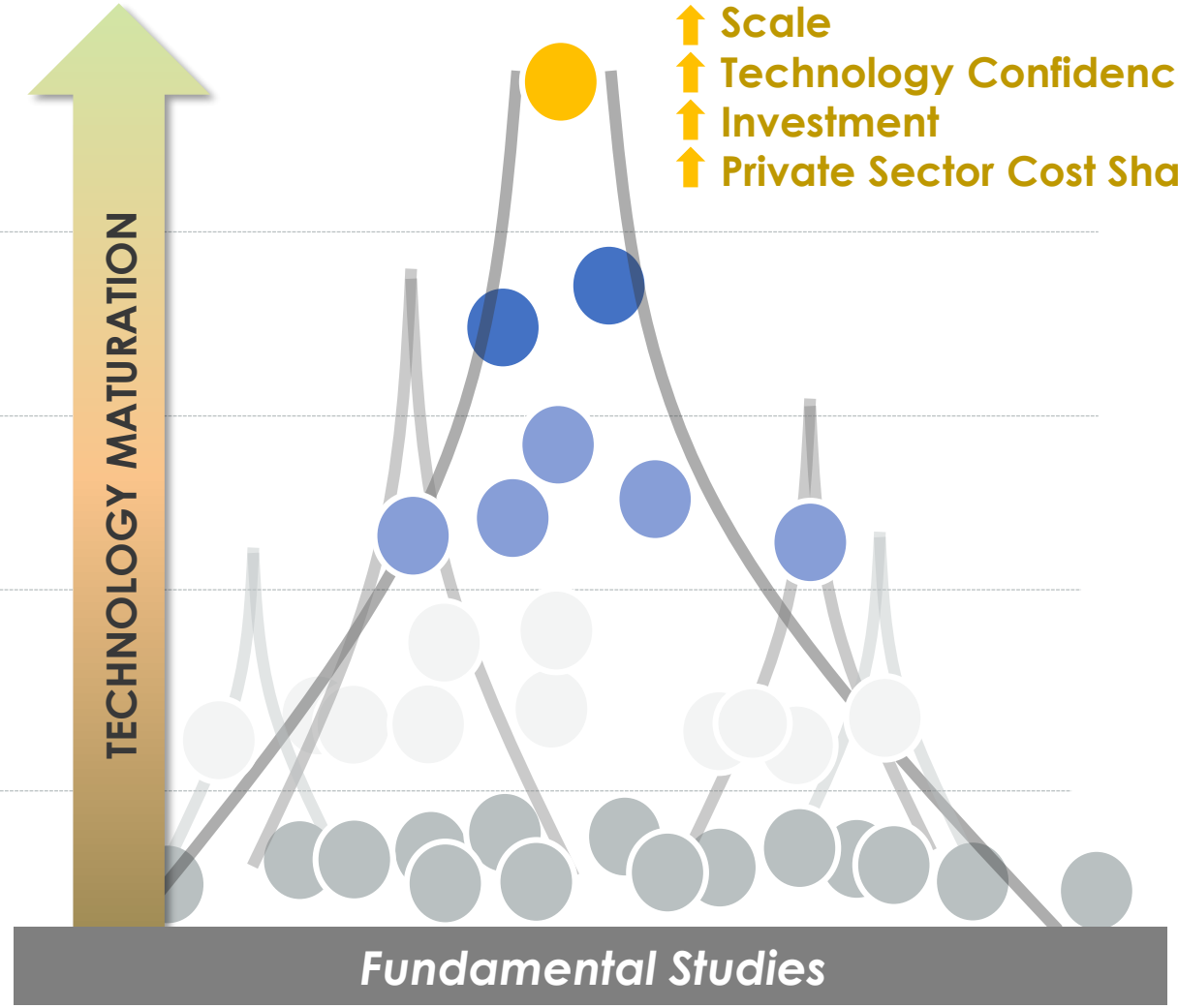
COMMERCIALIZATION
Technology available for wide-scale market use
TRL 9

DEMONSTRATION
System demonstrated in operational environment
TRL 8

SYSTEM TESTING
System performance confirmed at pilot-scale
TRL 6-7

DEVELOPMENT
Technology component validated/integrated
TRL 4-5

DISCOVERY
Concept identified/proven at laboratory-scale
TRL 1-3



KNOWLEDGE-BASED DECISION MAKING

- **Systems Engineering and Integration**
  - Engineering analysis
  - Pre-FEED/FEED studies
  - NEPA
- **Decision Science and Analysis**
  - Screening studies
  - Techno-economic analysis
  - Technology Readiness Assessments