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

OVERVIEW OF FECM HYDROGEN PROGRAM R&D

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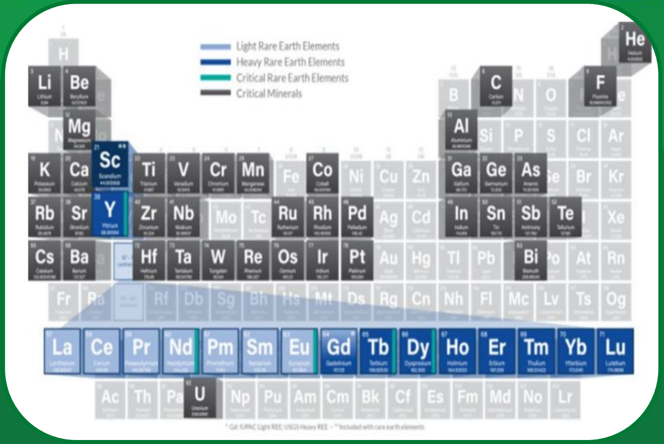
Fossil Energy and Carbon Management Office at US DOE

June 22-23, 2023



Fossil Energy and Carbon Management (FECM)

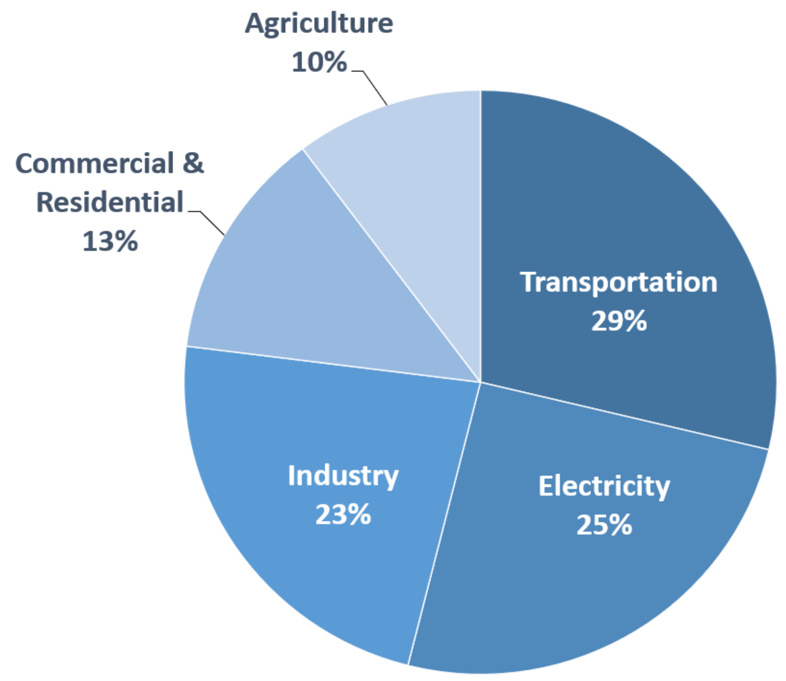
Office of Fossil Energy and Carbon Management

DOE-FE is now DOE-FECM

New name for our office reflects our **new vision**

- President Biden's goals:
  - 50% emissions reduction by 2030
  - CO_2 emissions-free power sector by 2035
  - Net zero emissions economy by no later than 2050

Total U.S. Greenhouse Gas Emissions by Economic Sector in 2019



U.S. Environmental Protection Agency (2021). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019

FECM Priorities with New Strategic Vision

FECM Strategic Vision

Point-Source Carbon Capture (PSC)

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 dedicated and reliable storage.

Carbon Dioxide Removal (CDR)

Invest in a diverse set of 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.

Reliable Carbon Storage and Transport

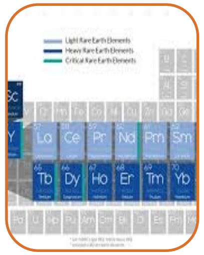
Make advancements in storage technologies and transport mechanisms, provide technical assistance in Class VI well permitting and support large-scale transport and storage facilities and regional hubs.

Carbon Dioxide Conversion

Accelerate capabilities for large-scale conversion of CO_2 into products that advance net-zero goals, facilitated by markets that use CO_2 as a feedstock.

Methane Mitigation

Develop technologies and deploy regional initiatives to quantify and reduce methane emissions from fossil fuel infrastructure including coal, oil, and gas.



Domestic Critical Minerals (CM) Production

Support demonstrations for extraction and remediation to processing and refining for building a strong CM supply chain while creating jobs.

Hydrogen with Carbon Management

Hydrogen production coupled with CCUS using sustainably sourced carbon-based feedstocks. Invest in the advancement of hydrogen storage, fuel cells, and 100 percent hydrogen-fired turbines, supporting DOE's Hydrogen Shot target.

Justice, Labor, and Domestic and International Collaboration

Collaborate with domestic and international partners to create a sustainable energy infrastructure with equity and justice at the core of FECM's work.

FECM Hydrogen Program R&D

- Clean hydrogen production using gasification, natural gas reforming, methane pyrolysis and solid oxide electrolysis cell technologies (SOEC/RSOFC)
- Hydrogen end use in electricity and other energy sectors
  - Solid Oxide Fuel Cells
  - Hydrogen Turbines
- Safe and reliable hydrogen production, transport, storage and utilization
- FECM also collaborates with EERE's Hydrogen and Fuel Cell Technologies Office and Bioenergy Technology Office.

Hydrogen with Carbon Management

- Program elements include Advanced Gasification, Advanced Turbines, and Reversible Solid Oxide Fuel Cells, Sensors and Controls, Computational Science

Methane Mitigation Technologies

- Focus areas for the program include advancing technologies for the carbon-neutral production, transport, and storage of hydrogen sourced from natural gas

DOE Efforts on Hydrogen Programs

EERE HYDROGEN

Feedstocks:
- Renewables and Water

Technologies:
- Electrolysis – Low- and High-Temperature
- Advanced Water Splitting – Solar/High-Temp Thermochemical, Photoelectrochemical
- Biological Approaches

FECM HYDROGEN

Feedstocks:
- Fossil Fuels, Solid Wastes and Water

Technologies:
- Gasification, Reforming, Methane Pyrolysis
- Electrolysis – High temperatures (RSOFC)
- Natural Gas to Solid Carbon plus Hydrogen

NE HYDROGEN

Feedstocks:
- Nuclear Fuels and Water

Technologies:
- Electrolysis Systems for Nuclear
- Advanced Nuclear Reactors
- Systems Integration and Controls – LWRs and Advanced Reactors

Areas of Collaboration

Reversible Fuel Cells, Biomass, Municipal Solid Waste, Plastics, Polygeneration including Co-Gasification with Biomass, High-Temperature Electrolysis, Systems Integration

Cross-Cutting R&D Offices: Office of Science (SC) and ARPA-E

Foundational research and innovation; user facilities and tools, materials and chemical processes (e.g., catalysis, separations), artificial intelligence/machine learning, databases and validation, high risk-high impact R&D, and other crosscutting activities

Hydrogen Provisions in Recent Legislation

Bipartisan Infrastructure Law

- **Covers $9.5B** for clean hydrogen:
  - $8B for at least four regional clean hydrogen hubs
  - $1B for electrolysis research, development and demonstration
  - $500M for clean hydrogen technology manufacturing and recycling R&D
- **Aligns with Hydrogen Shot priorities by directing work to reduce the cost of clean hydrogen to $2 per kilogram by 2026**
- **Requires developing a National Hydrogen Strategy and Roadmap**

President Biden Signs the **Bipartisan Infrastructure Bill** on November 15, 2021.
Photo Credit: Kenny Holston/Getty Images

Inflation Reduction Act → **Includes production tax credit for clean Hydrogen**

Inflation Reduction Act – 45Q Modifications

	Old	New
Commence Construction	January 1, 2026	January 1, 2033
DAC Facility	100,000 metric tons/year*	1,000 metric tons/year
Electric Generator	500,000 metric tons/year*	18,750 metric tons/year
All other facilities	100/000 metric tons/year*	12,500 metric tons/year
Saline Storage Credit	$50/metric ton	$85/metric ton (industry and power); $180/metric ton (DAC)
EOR and Conversion Credit	$35/metric ton	$60/metric ton (industry and power); $130/metric ton (DAC)

** Non-EOR Conversion facilities were previously 25,000 metric tons/year regardless of facility/source.*

Notes: New Modifications allows up to 5 years for direct pay (up to 12 years certain entities)

Inflation Reduction Act – Clean H2 Production Tax Credit

Commence Construction	January 1, 2033
kg of CO2 per kg of H2	Credit Value ($/kg)
4 to 2.5	*0.60*
2.5 to 1.5	*0.75*
1.5 to 0.45	*1.00*
0.45 to 0	*3.00*

Clean hydrogen: lifecycle greenhouse gas emissions rate of no greater than 4 kilograms of CO2 equivalent ("**CO2e**") gas per kilogram of hydrogen. Section 45V of the Act creates a new tax credit for the production of qualified clean hydrogen (the "**Clean Hydrogen Production Credit**").

As an alternative to the Clean Hydrogen Production Credit, taxpayers may elect the Section 48 Investment Tax Credit (the "**ITC**") with respect to clean hydrogen production facilities, receiving an ITC of up to 30% depending on the carbon intensity of the production process.

The Clean Hydrogen Production Credit is not available, however, for clean hydrogen produced at a facility that also includes carbon capture equipment for which the Section 45Q carbon capture tax credit is allowed to any taxpayer.

Hydrogen Energy Earthshot Initiative (HEEI)

Cost of Clean Hydrogen to $1 per 1 kg in 1 Decade (1-1-1)

- Goal to accelerate innovations and spur demand of clean hydrogen
- Enable decarbonization of high-polluting heavy-duty transportation and industrial sectors, while delivering good-paying clean energy jobs and realizing a net-zero economy by 2050.

Goals for Clean Hydrogen Production Systems of FECM

- Gasification of biomass, waste streams, and recovered coal waste with CCS for net-zero carbon
- Reforming with CCS for near net-zero carbon
- Methane emissions reduction in the upstream natural gas supply chain
- Renewable natural gas sources
- Solid Oxide Electrolysis Cell (SOEC) or Reversible Solid oxide fuel cell (R-SOFC)

HEEI Goals:

- \$1/kg H_2
- One decade (i.e., 2030)
- "1, 1, 1"

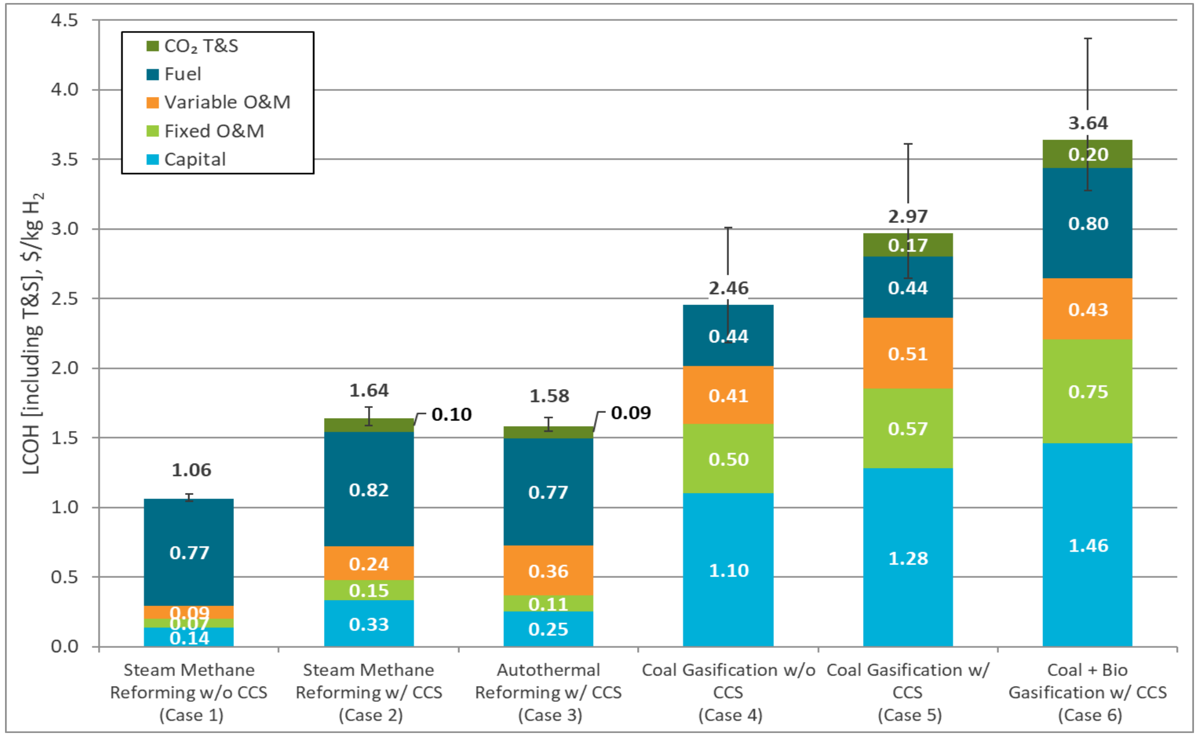
Comparison of Commercial, SOTA, Fossil-Based Hydrogen Production

Objectives

- Study of fossil-to-H_2 production methods using current, commercial technologies[1]
- Estimated levelized cost of hydrogen (LCOH) production
- Estimated lifecycle (LCA) greenhouse gas (GHG) footprint
- Identified R&D areas to improve performance, cost, and LCA GHG profiles

Justification

- Establish technology references for DOE FECM R&D program planning to reduce LCOH and GHG footprint of future fossil-to-H_2 plants



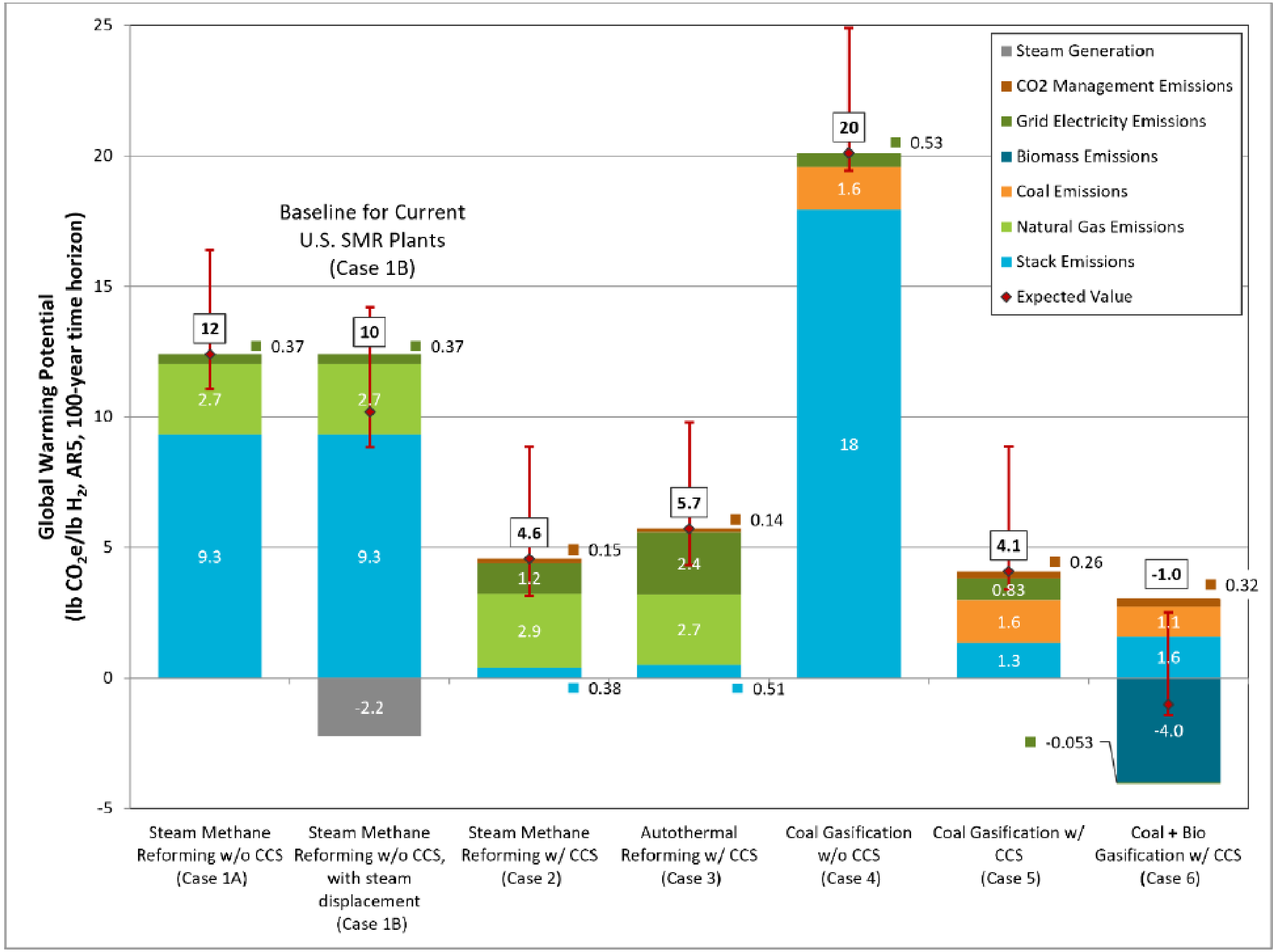
Highlights

- \$1.58/kg H_2 - lowest LCOH of cases examined w/ CCS – Auto-Thermal Reforming (ATR)
- 3.9 kg CO_2e/kg H_2 - lowest LCA GHG profile of fossil-only cases examined w/ CCS - coal gasification
- Co-gasifying 43.5 wt.% biomass with coal enables net-zero GHG H_2 production
- NG infrastructure and grid electricity are significant contributors to LCA GHG emissions of NG plants

Source: NETL
https://netl.doe.gov/projects/files/ComparisonofCommercialStateofArtFossilBasedHydrogenProductionTechnologies_041222.pdf

CO_2e Life Cycle Emissions for All Commercial H_2 Production Methods

- Natural gas emissions represent a major portion of total process emissions of all reforming cases with CCS.
- Coal gasification has 2x the emission profile of SMR (both without CCS).
- It is possible to reach negative emissions when co-gasifying with biomass and pairing it with CCS.



Source: NETL

https://netl.doe.gov/projects/files/ComparisonofCommercialStateofArtFossilBasedHydrogenProductionTechnologies_041222.pdf

Gasification Systems Program Goals

FECM Gasification Systems Goals

- Cost-effective clean hydrogen production for fuels synthesis and decarbonization (especially industry)
- Remediate/utilize wastes (unrecyclable plastics, MSW, coal waste)
- Blend carbon-neutral biomass: reduce GHG emissions
- Modular gasification in disadvantaged areas: provide jobs, remediate legacy sites
- Reduces disposal burden of wastes in landfills
- Gasification with capture: carbon neutrality/negative carbon potential

Gasification Systems Approach

Modular Technology: Helping Gasification Access New Markets

Smaller, modular gasifier

- Faster development
- Lower capital investment
- Lower financial risk

New Markets

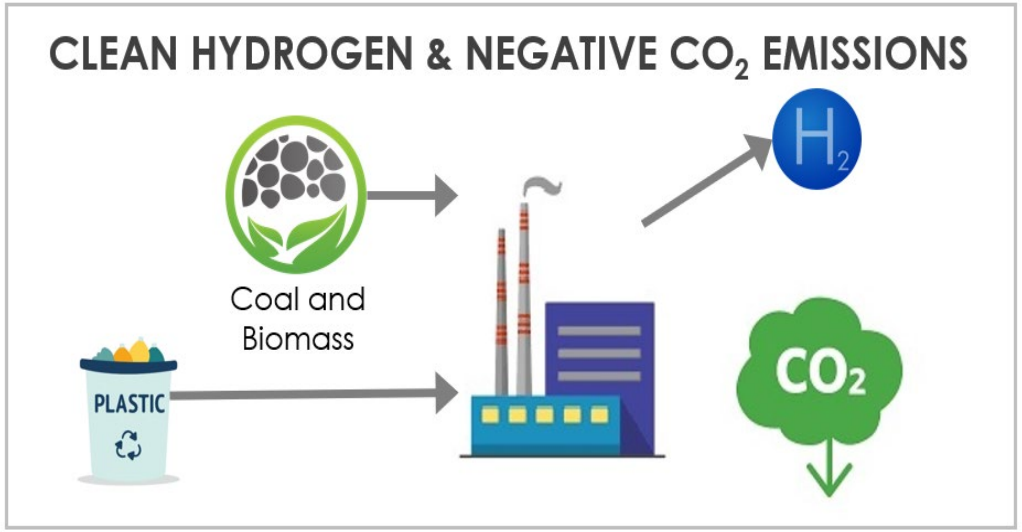
Business Impacts:

- **CapEx/OpEx reduction:** through process intensification, plant-wide cost reduction opportunities
- **Reduce investment risk:** reduce the cost of functional prototypes
- **Regional opportunities:** enable local markets to quickly and cost-effectively utilize local feedstocks (including biomass and wastes)

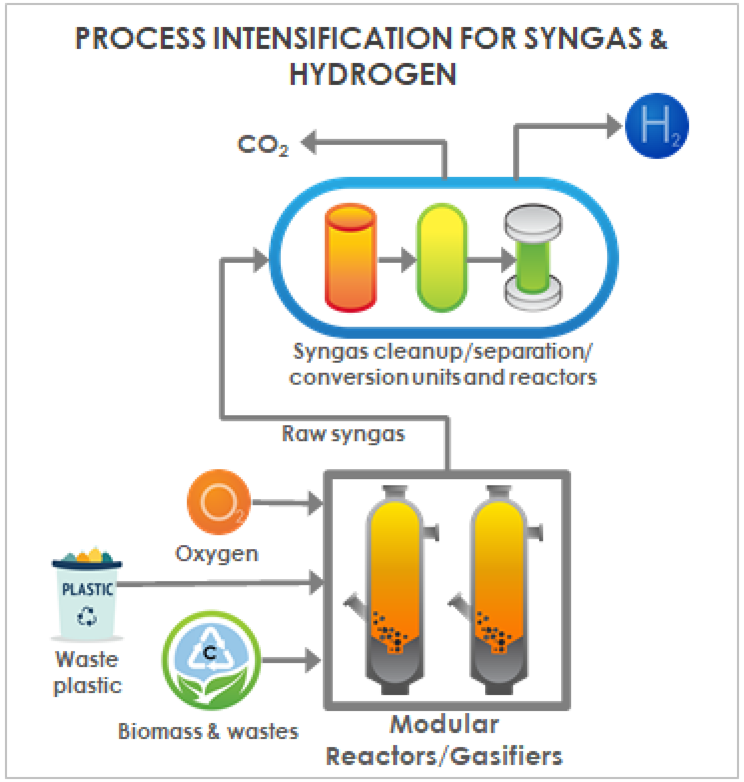
Addressing Technology Challenges

Today's Approach

- Multiple Unit Ops/Separate Reactors & Process Steps
  - Gasifier with feedstock preparation
  - Syngas cleanup
  - Multiple-stage Water Gas Shift
  - CO_2 separation
- Air Separation
  - Cryogenic (big investment, scale limitation)
  - SOTA membranes (costly, purity limitations)
- Hydrogen Separations/Carbon Capture
  - Energy intensive (PSA, solvent approaches)

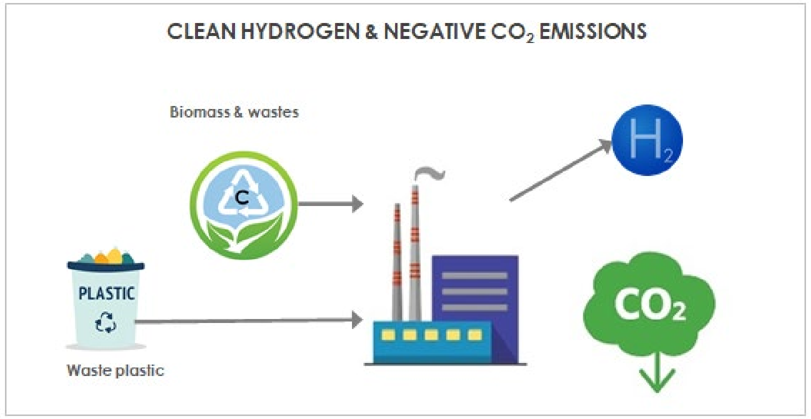


Gasification Systems Program Areas



Innovative gasifiers and zero emissions systems

Efficient ASUs for any net-zero system scale



Biomass blending enables Bioenergy with Carbon Capture & Storage (BECCS)

Feedstock-flexible systems accommodate seasonal/limited supply of biomass and MSW/plastics

Gasification Technology Development Timeline

2015 | 2020 | 2025 | 2030

- Location-based Study
- TEA Modular Systems

Completed

Modular Gasifier Design
- 25-50 lb/hr coal

Modular Test
- Syngas Cleanup
- Fluid bed desulfurization

Syngas Cleaning Process Intensification
- COE reduction

Gasification Component Integration
- IGFC
- IGCC w/ precombustion capture

Designs of Modular Units
- CHP
- 42 percent HHV
- TEA support

Pilot Gasification System Test
- 10–50 MWe utility-scale

CHP Gasification Technology
- Enable modular energy systems

Commercial Demon Systems
- Co-gasification
- Privately funded

MODULAR TECHNOLOGY DEVELOPMENT
- Process and Reaction Intensification (NETL-RIC)
- Modeling & Simulation (NETL-RIC)
- Systems Integration
- Advanced Manufacturing

Gasification Pathways to Clean Hydrogen Production

Current R&D Focus

- Biomass feed implements BECCS for net zero or negative GHG emissions
- Gasification allows use of wastes (MSW, plastic, biomass, etc.) as feedstock
- Modular gasification at waste impoundments promotes environmental justice
    - Distributed deployment near feedstock
- Cost reduction via modularity and process intensification

Current Projects & FOAs

FY21 FOA 2376 Gasification selected four projects for enabling co-gasification of blended coal, biomass and plastic wastes to produce clean hydrogen

FY 22 FOA 2400 Gasification 13 projects funded in Gasification AOIs

- AOI 1—Clean Hydrogen Cost Reductions via Process Intensification & Modularization for Hydrogen Shot
- AOI 2A—Clean Hydrogen from High-Volume Waste Materials and Biomass
- AOI 2B—Sensors & Controls for Co-gasification of Waste Plastics in Production of Hydrogen with Carbon Capture

FOA 2400 Awards - Gasification

AOI 4- Advanced Air Separation for Low-Cost H2 Production via Modular Gasification

FOA Issue Date	08/26/2022
Submission Deadline for Full Applications	10/25/2022
Sr. Technical Briefing	3/9/2023
Date for Selection Notifications	3/24/2023
Date for Award	**June 2023**

FECM Funding Opportunities – FY23

FOA 2400 New AOI

Clean Hydrogen Production, Storage, Transport, and Utilization to Enable A Net Zero Carbon Economy

- **Issue Date: FY23**
- **Application Submittal Deadline:** TBD
  Selection Notifications: TBD
- **Awards:** TBD

Objective

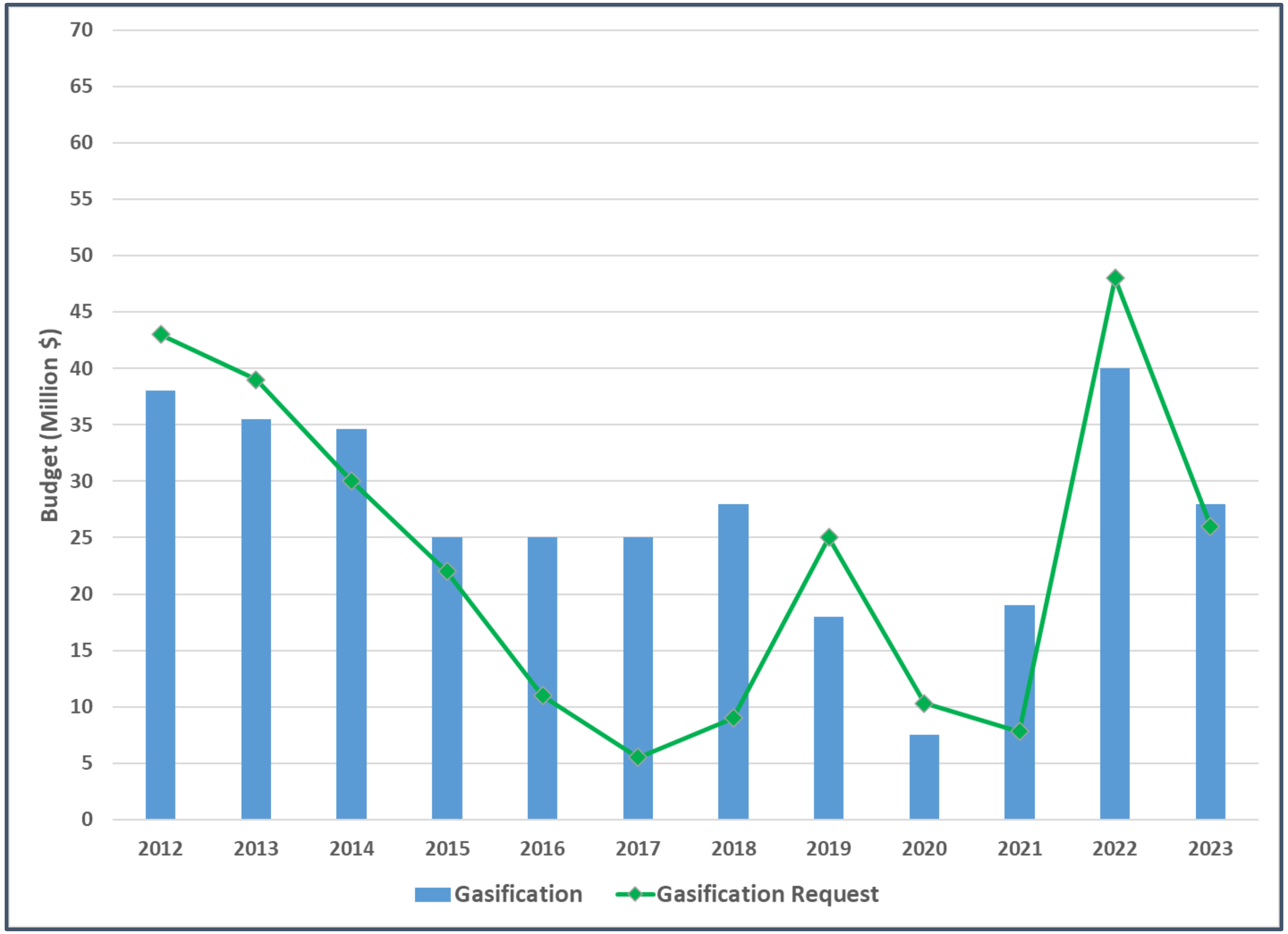
Develop technologies enabling clean hydrogen production, transport, storage, and use in the energy sector, including electricity, heat, transportation, and industrial use.

FOA Areas of Interest

Significant advances in co-gasification technology and economics are needed in areas of interest

- Life-Cycle Net Zero-Carbon and Negative-Carbon Emitting Technologies for Clean Hydrogen Production from Modular Gasification
- Sensors & Controls for Co-gasification of Waste Feedstocks in Production of Hydrogen with Carbon Capture

Advanced Gasification Program Budget History



Gasification Program Funding ($M)		
FY 23 Requested	FY 23 Enacted	FY 24 Requested
26	28	30

SOFC/RSOFC R&D Goals

- Highest efficiency and lowest cost electricity generation from hydrogen/natural gas/syngas
- Efficient and cost-effective distributed/utility scale hydrogen production (RSOFC)
- Flexible modular hybrid SOFC/SOEC system design depending on grid
- Hydrogen production as an energy storage or power production from hybrid RSOFC systems
- Data center backup power systems & distributed H2 production for short term (kW - MW scale)
- Utility scale hybrid RSOFC system for long term (10 MW - 50 MW)

KEY TECHNOLOGIES

Cell Development

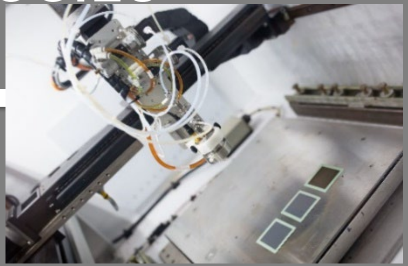


Figure courtesy NETL

Core Technology

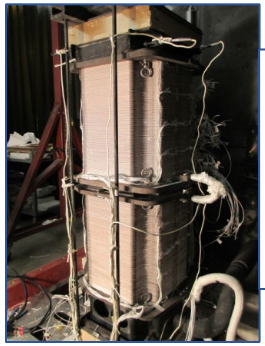
Figure courtesy LG Fuel Cell Systems

Systems Development for SOFC and Reversible Systems

Figure courtesy FuelCell Energy

SOFC/RSOFC Program – Technology Evolution

SYSTEMS
MODULES
STACKS
CELLS



10 kWe-Class Stack Tests
- Improved efficiency, 35 – 41%
- Reduced degradation, <2%/1000 hr
- Cost target at high volume achieved (extrapolated)

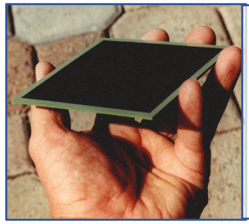

200 kWe Prototype Field Tests

~5 KW Electrolyzer Systems
(in Progress)

Utility-Scale Demo
(Envisioned)

Cell and Stack Performance Improvements
- Increased cell area by 5x
- Increased cell power by 10x
- Degradation reduced to 0.2 - 0.5%/1,000 hrs

MWe-Class SOFC Pilot
(planned)



Cell Development
- increased power
- Established material set
- Improved reliability
- Reduced cost

~10 KW SOFC Systems
(in Progress)

Proof-of-Concept Systems
- Two POC systems, 50kW & 200 kW
- Efficiency improvements to >55%

Technology Validation

200 kWe POC
(courtesy LG Fuel Cell Systems)

50 kWe POC
(courtesy FuelCell Energy)

2000 2010 2020 2030

RSOFC Pathways to Clean Hydrogen Production

Current R&D Focus

- Conduct R&D to address critical needs   and mature technology for reversible solid oxide fuel cell technology for hydrogen production
  - Cell materials and fabrication to improve performance and lower cost
  - Understanding cell and stack degradation mechanisms
  - Balance-of-plant components – cost reduction and reliability improvement
- Acquired fabricating and operational experience on integrated, prototype field tests – SOFCs and RSOFCs

Current Projects

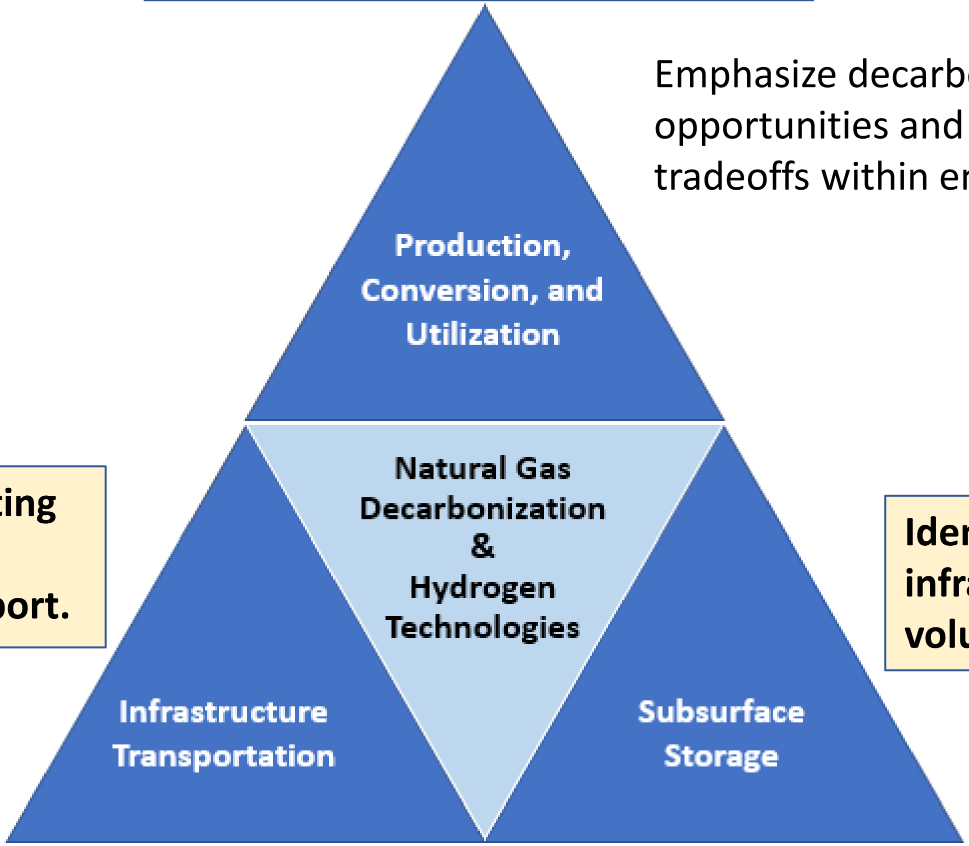
- **FY20 FOA 2300** selected 12 projects and among them, 8 projects are RSOFC systems development for hydrogen and electricity production including the validation and development of materials and systems required for improving the cost, performance and reliability.
- **FY 21 FOA 2400** selected 8 projects focusing on solid oxide electrolysis cell (SOEC) technology development for clean hydrogen production.

200 kWe integrated SOFC Power System: ~2,000 full-scale cells (Photo courtesy FuelCell Energy

Natural Gas Decarbonization & Hydrogen Technologies

Transformational concepts for clean H_2 production from domestic natural gas resources.

Emphasize decarbonization opportunities and value tradeoffs within energy markets.



Ensuring suitability of existing natural gas pipelines and infrastructure for H_2 transport.

Emphasize technology opportunities to detect and mitigate emissions.

Identify underground storage infrastructure to handle high volume fractions of H_2.

Emphasize demonstration opportunities for novel bulk storage mechanisms.

FOA2400 Awards – Natural Gas Decarbonization & Hydrogen Technologies

Date for Award: June 2023

- **AOI 14 – Clean Hydrogen Production and Infrastructure for Natural Gas Decarbonization**
  - **AOI 14a – Methane pyrolysis/decomposition, in situ conversion, or cyclical chemical looping reforming**
  - **AOI 14b – Hydrogen Production from Produced Water**
- **AOI 15 – Technologies for Enabling the Safe and Efficient Transportation of Hydrogen Within the U.S. Natural Gas Pipeline System**
- **AOI 16 – Fundamental Research to Enable High Volume, Long-term Subsurface Hydrogen Storage**

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Questions?

Thank You!

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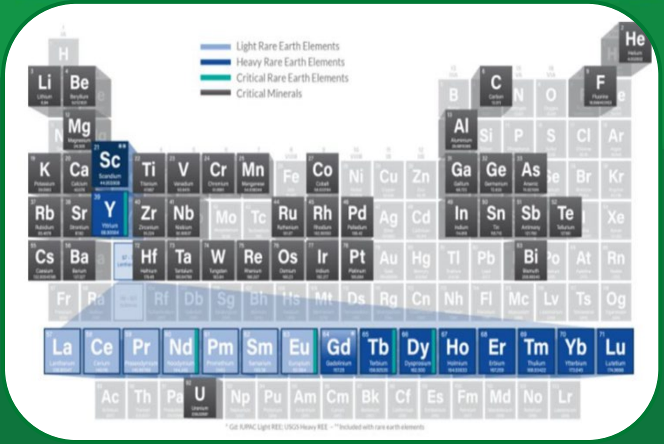
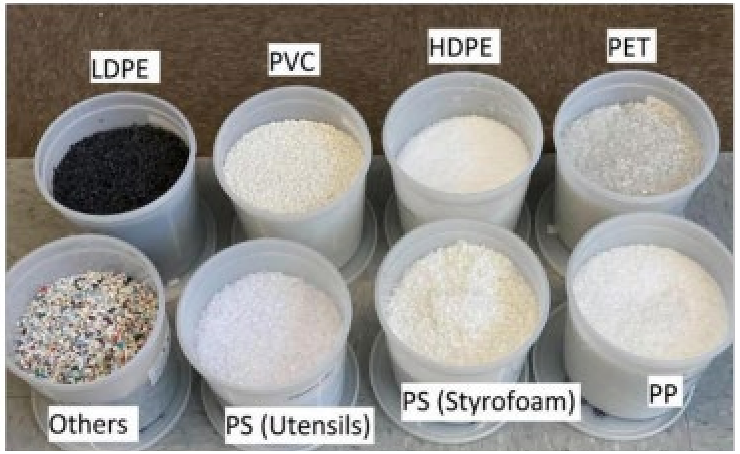
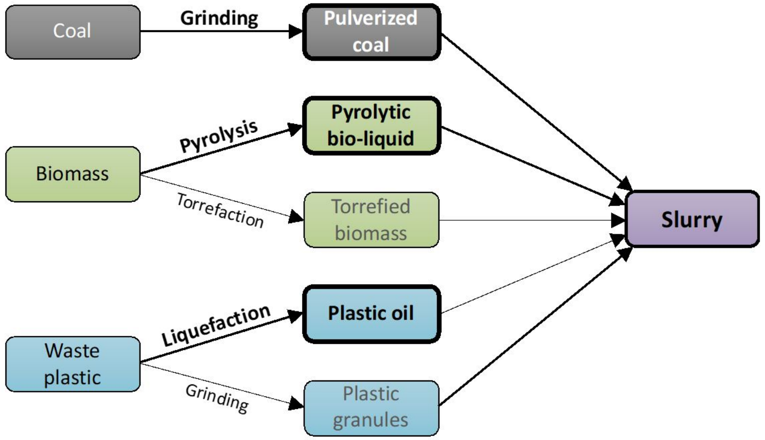


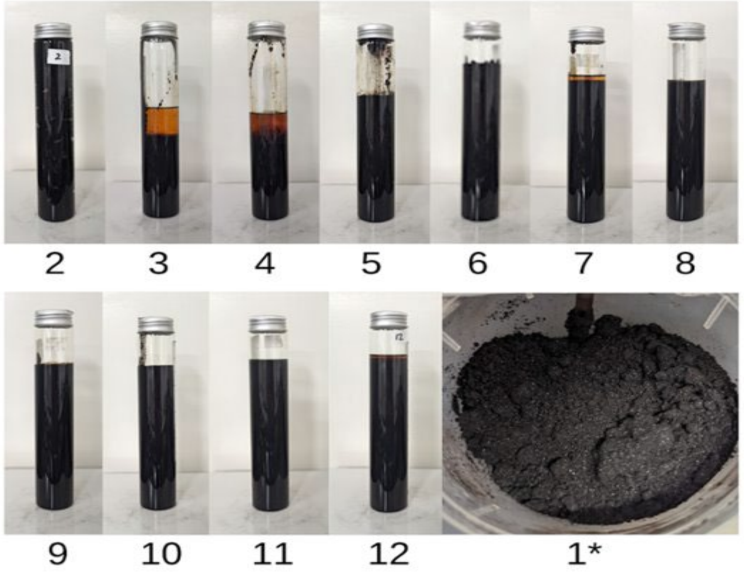
Biomass/Wastes Co-Gasification

- Fluidized-Bed Gasification of Coal-Biomass (Southern Pine)-Waste Plastic Blends -Auburn University
- Development and Characterization of Densified Biomass-Plastic-Coal Blends for Entrained Flow Gasification-UKy
- Testing of a Moving-Bed Gasifier using Coal, Biomass (Corn Stover), and Waste Plastic (Car Fluff) Blends -EPRI



- Entrained-Flow Gasification of Blends of Coal, Biomass and Plastic by Creating Slurries of Plastic Oil, Pyrolysis Oil & Coal- University of Utah



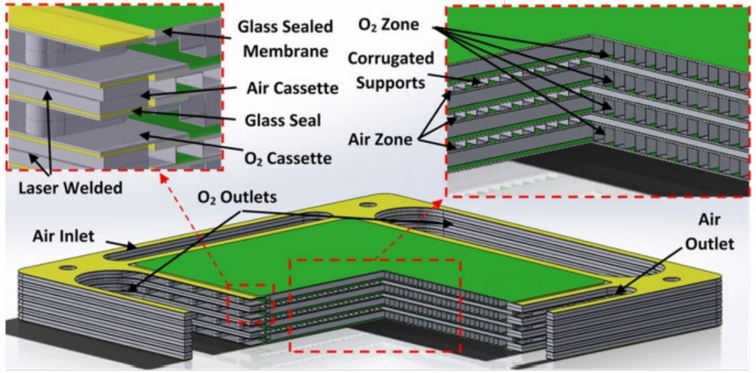


Air Separation/Oxygen Production R&D

Innovative air separation/oxygen production technologies for zero emissions gasification systems-National Laboratories

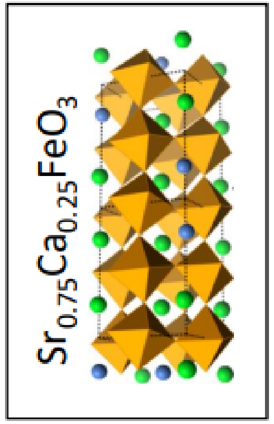
Pressure Driven Oxygen Separation

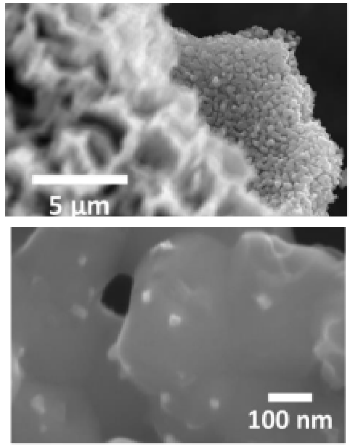
Pacific Northwest NATIONAL LABORATORY



Metal Oxide Oxygen Carrier Materials

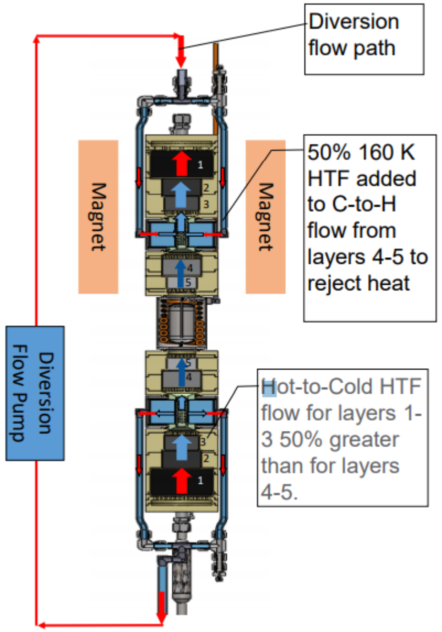
NATIONAL ENERGY TECHNOLOGY LABORATORY





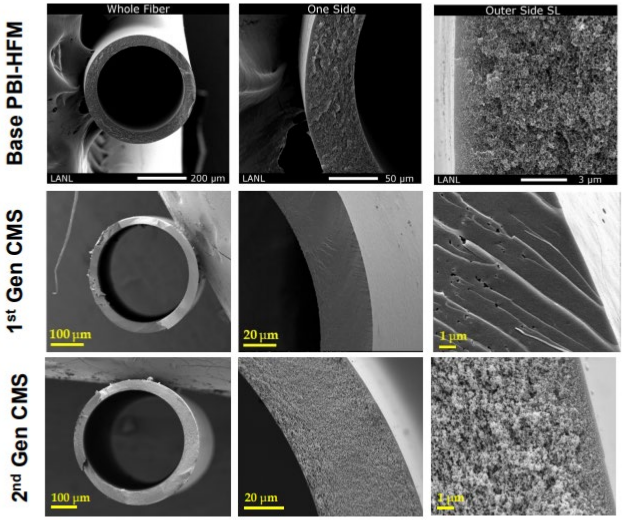
Magnetocaloric Cryogenic System

Pacific Northwest NATIONAL LABORATORY



Carbon Molecular Sieve Hollow Fiber Membranes

Los Alamos NATIONAL LABORATORY EST. 1943



RSOFC in Progress

FuelCell Energy

Stack size for system demonstration

0.87 KW SOFC
1.6 KW SOEC

2.8 KW SOFC
5.4 KW SOEC

6.7 KW SOFC
12.7 KW SOEC

PNNL

Design, build and validate operation of a 5-kW co-electrolysis stack with an active cell area of 300 cm^2 for H2 and CO/H2 production

INL

- 30-kW electrolysis mode/10-kW fuel cell mode testing at INL Site
- INL is testing RSOFC systems manufactured by OxEon
- Improve catalyst in the fuel electrode - MIT