2025 Compendium of GASIFICATION SYSTEMS TECHNOLOGY

APRIL 2025

U.S. DEPARTMENT of ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

DISCLAIMER

TABLE OF CONTENTS

OVERVIEW

The U.S. Department of Energy's (DOE) Office of Fossil Energy and Carbon Management (FECM) pursues development of multiple technology areas supporting increased efficiency and cost effectiveness of fossil fuel energy systems. Within this context, the DOE Gasification Systems Program is developing innovative designs and technologies for converting diverse types of solid feedstocks into clean synthesis gas to enable the low-cost production of hydrogen, transportation fuels, chemicals, electricity, and other useful products to suit market needs. Advancements in this area will help enable syngas-based technologies and energy systems to be competitive in both domestic and international markets, and spur on the use of domestic resources towards increased energy security and emissions reduction goals of the United States.

The Gasification Systems Compendium is compiled periodically to provide a technical summary of R&D sponsored by DOE/NETL's Gasification Systems Program. The current Compendium presents 30 projects active at the end of calendar year 2024. The Compendium is organized into three main sections. The first section includes extramural projects managed under the Gasification Systems Program, organized in subsections based on the application of the technologies (i.e., Process Intensification, Air Separation, and Novel Technologies for Chemicals & Fuels). The second section covers projects managed through NETL's federal work plan grants to other National Laboratories. The third section covers research performed by NETL's Research and Innovation Center (RIC).

Projects/tasks covered include nearly completed projects, while others are in earlier stages. Accordingly, some of the summaries are limited in coverage, with the expectation that future revisions of the Compendium will provides updates with final results and a more complete picture of the accomplishments in gasification technology development that the NETL Gasification Systems Program facilitates.

GASIFICATION SYSTEMS
TECHNOLOGY SHEETS

Extramural Projects

Process Intensification of Hydrogen Production Through Sorption-Enhanced Gasification of Biomass

primary project goal

The University of Utah is partnering with Idaho National Laboratory (INL) to demonstrate the feasibility of sorption-enhanced biomass gasification (SEG) for production of hydrogen (H_2)-rich syngas in a dual fluidized bed reactor. By preprocessing the biomass feedstock to ensure consistent composition and trouble-free feeding and leveraging an existing dual fluidized bed process development unit with addition of limestone to achieve in situ removal of carbon dioxide (CO_2) from the gasifier, a clean, high-hydrogen syngas can be produced.

technical goals

- Demonstrate that waste biomass can be preprocessed to promote SEG.
- Understand and model fundamental processes of SEG.
- Evaluate SEG performance and syngas quality over a range of industrially relevant conditions.
- Demonstrate oxy-SEG to produce separate H_2- and CO_2-rich streams.

technical content

The technical basis of the process under development consists of fluidized bed gasification to convert biomass into syngas from which hydrogen can be obtained. Instead of a conventional single-vessel fluidized bed gasifier with multiple downstream steps to clean syngas and separate H_2, in this case a dual fluidized bed gasification process is utilized, with the basic configuration as illustrated in Figure 1. The first of the dual beds is an initial gasifier vessel in which bed material consisting of sand (e.g., olivine) is fluidized by steam injection. Biomass introduced into the gasifier vessel undergoes gasification steps consisting of devolatilization and steam reforming at moderate temperatures, consuming about 80% to 85% of the biomass, and forming syngas containing carbon monoxide (CO) and H_2. Unconverted biomass in the form of char is withdrawn from the gasifier vessel along with the sand and circulated to a second fluidized bed combustor vessel. Here, the char is combusted at high temperature in air, consuming the char, heating the sand, and exhausting flue gas. The heated sand is circulated back to the initial gasifier vessel as a heat carrier to provide both energy input for the syngas forming reactions there and to maintain bed inventory. The dual fluidized bed arrangement has the effect of limiting CO_2 content in the syngas relative to a single bed, improving syngas quality.

program area:
Gasification Systems

ending scale:
Small Pilot (150-250 kW_{th})

application:
Hydrogen Production

key technology:
Process Intensification for Syngas and Hydrogen

project focus:
Sorption-Enhanced Gasification of Biomass

participant:
University of Utah

project number:
FE0032174

predecessor projects:
N/A

NETL project manager:
Sarah Pfeiffer
sarah.pfeiffer@netl.doe.gov

principal investigator:
Kevin J. Whitty
University of Utah
kevin.whitty@utah.edu

partners:
Idaho National Laboratory

start date:
10.01.2022

percent complete:
67%

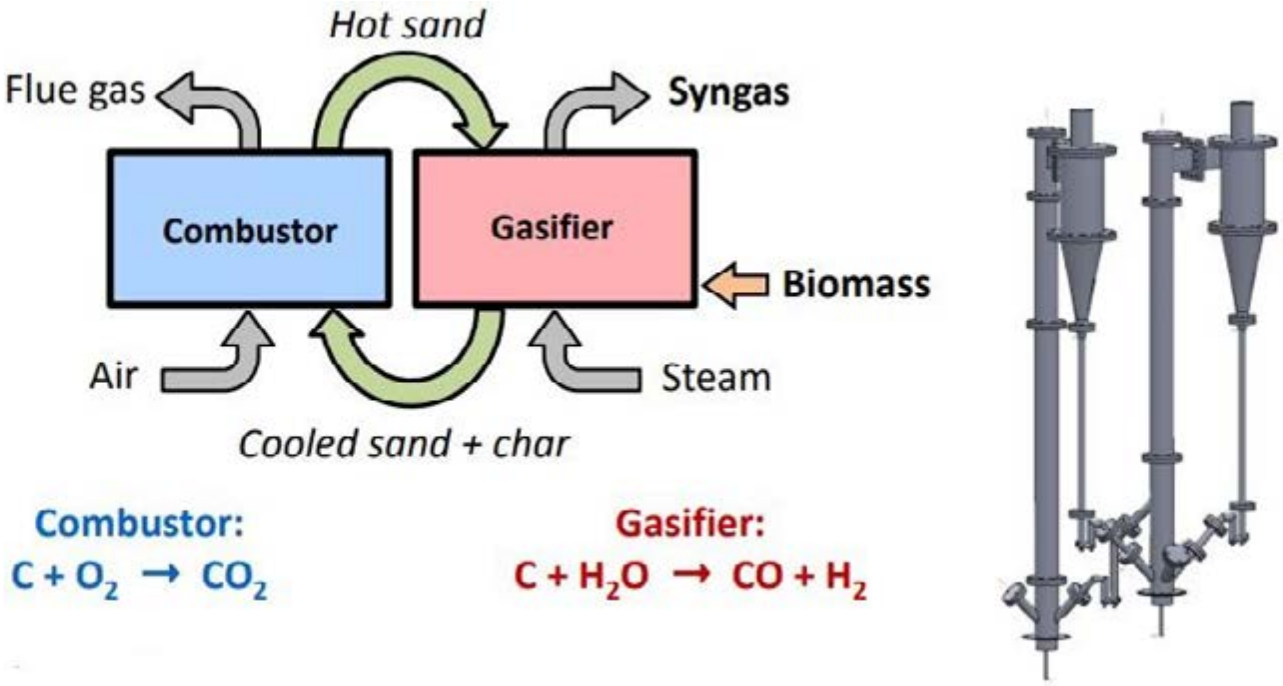


Figure 1: University of Utah dual fluidized bed gasification process schematic.

The syngas resulting from the baseline configuration results not in the desired product of clean hydrogen, but syngas of moderate quality. A process variation is possible yielding a gasifier product stream of mostly hydrogen. This involves addition of limestone ($CaCO_3$) to the bed material (sand), which is still circulated as heat carrier, but the limestone is reduced in the high-temperature combustor to lime (CaO), which carries over into the gasifier. The CaO reacts with and scavenges out CO_2, which not only enriches the gas in hydrogen but also promotes reaction of remaining CO with steam to produce more CO_2 and H_2 by the water-gas shift reaction, so that the gas stream exiting the gasifier is mostly hydrogen. This is illustrated in Figure 2, along with the chemical reactions taking place.

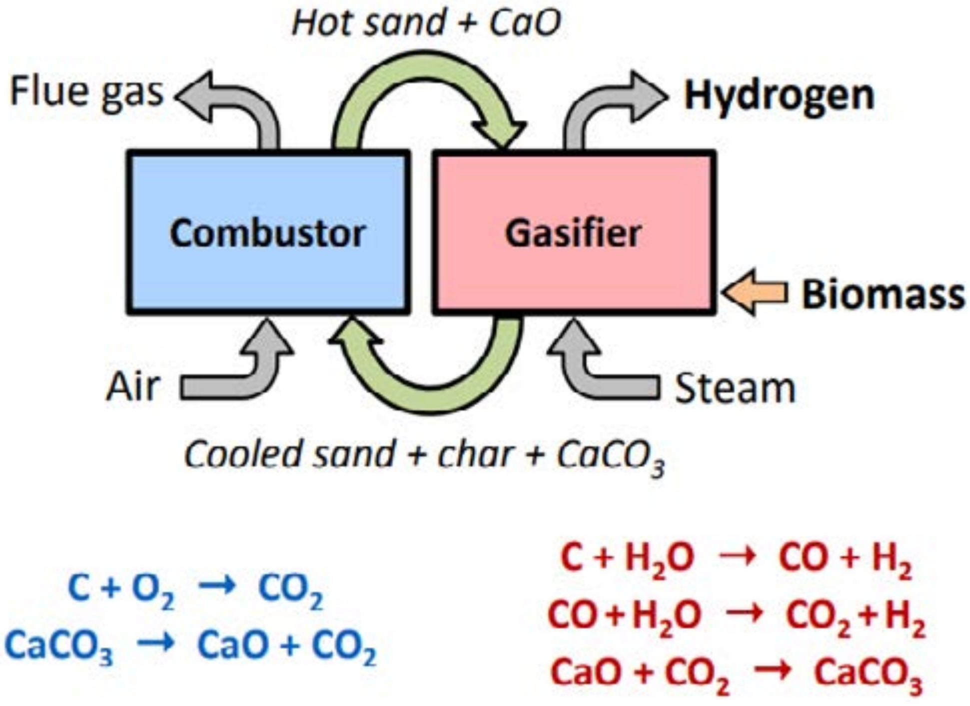


Figure 2: Sorption-enhanced dual fluidized bed gasification.

Another variation is the same as the SEG, but instead of air as oxidant for the combustor, oxygen is supplied mixed with recycled CO_2 (to moderate combustor operating temperature). Because no nitrogen is introduced into the system, this results in relatively pure CO_2 as the combustor flue gas, with this approach preferred over the relatively inefficient post-combustion capture of CO_2 from flue gas that would otherwise be required to realize a net-zero carbon emissions process system.

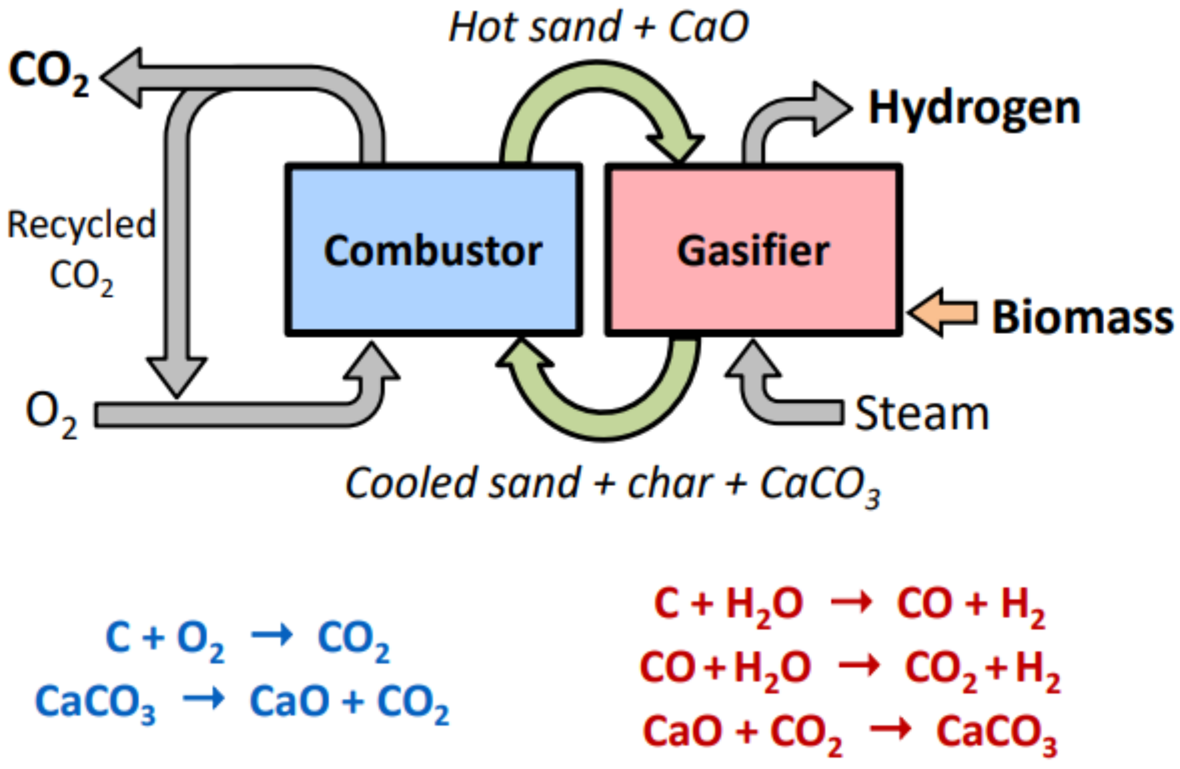


Figure 3: Oxy-sorption-enhanced dual fluidized bed gasification.

Biomass Feedstock Preparation

INL is focusing on feedstock preparation, specifically for the SEG process system. Biomass choices of clean Loblolly pine, Loblolly pine residues, red oak, corn stover and wheat straw were considered, but for anticipated pilot-scale work, Loblolly pine has been chosen.

Although the initial charge of the fluidized bed with sand will include a large fraction of limestone, attrition of the limestone over time is a concern. Reliable makeup of limestone can be made by combining fractional amounts of limestone with the biomass in the feedstock pellets, and such pellets have been produced by INL for evaluation.

Biomass Conversion

Understanding the conversion behavior of biomass in the SEG process in terms of chemical, physical and gasification rate/kinetics respects is essential to modeling and optimizing a large-scale gasification process. Specifically, Utah is studying distribution into volatiles and char, volatiles composition, and ash chemistry as the most important chemical transformations to understand. Impacts of feedstock preparation, char properties and fluidizing characteristics are also of concern. In terms of gasification rates, the influences of temperature, pressure and concentrations of syngas species are being evaluated to support kinetic modeling development.

Tar Cracking

Condensable hydrocarbon "tars" will be formed as a result of biomass gasification at characteristic fluidized bed gasifier conditions. Management of tar is essential to a workable process, both to avoid operational problems and to maximize conversion to syngas. Utah is studying ways to crack tars in situ to form smaller molecules, specifically through addition of catalytic components to the bed material to accelerate breakdown of aromatic hydrocarbons.

CO_2 Sorbents Evaluation

The University of Utah has studied effects of varying gasification conditions on sorbents in terms of sorption capacity, rates of reaction, suitable temperature regime, Influence of steam/CO/H_2, use of different types of limestone and dolomite materials, and Influence of particle size. Ultimately, the aim is to understand how best to maintain sorbent activity/effectiveness for sorption of CO_2 in the gasifier reactor. It has been discovered that more open microstructures and increased pore volume of CaO persist with steam treatment, which affords less resistance to CO_2 diffusion to the core of the CaO particles. Sorbent grain sizes are noticeably larger in the case of steam carbonation due to sintering enhanced with steam. Also, it was found that particles formed aggregates with CO/H_2 additions during gasification reactions, resulting in a loss of surface area and pore volume for CO_2 sorption. Visible changes in CaO sorbent structure reflect these findings, as illustrated in Figure 4. Essentially, steam enhances and syngas species inhibit sorption performance.

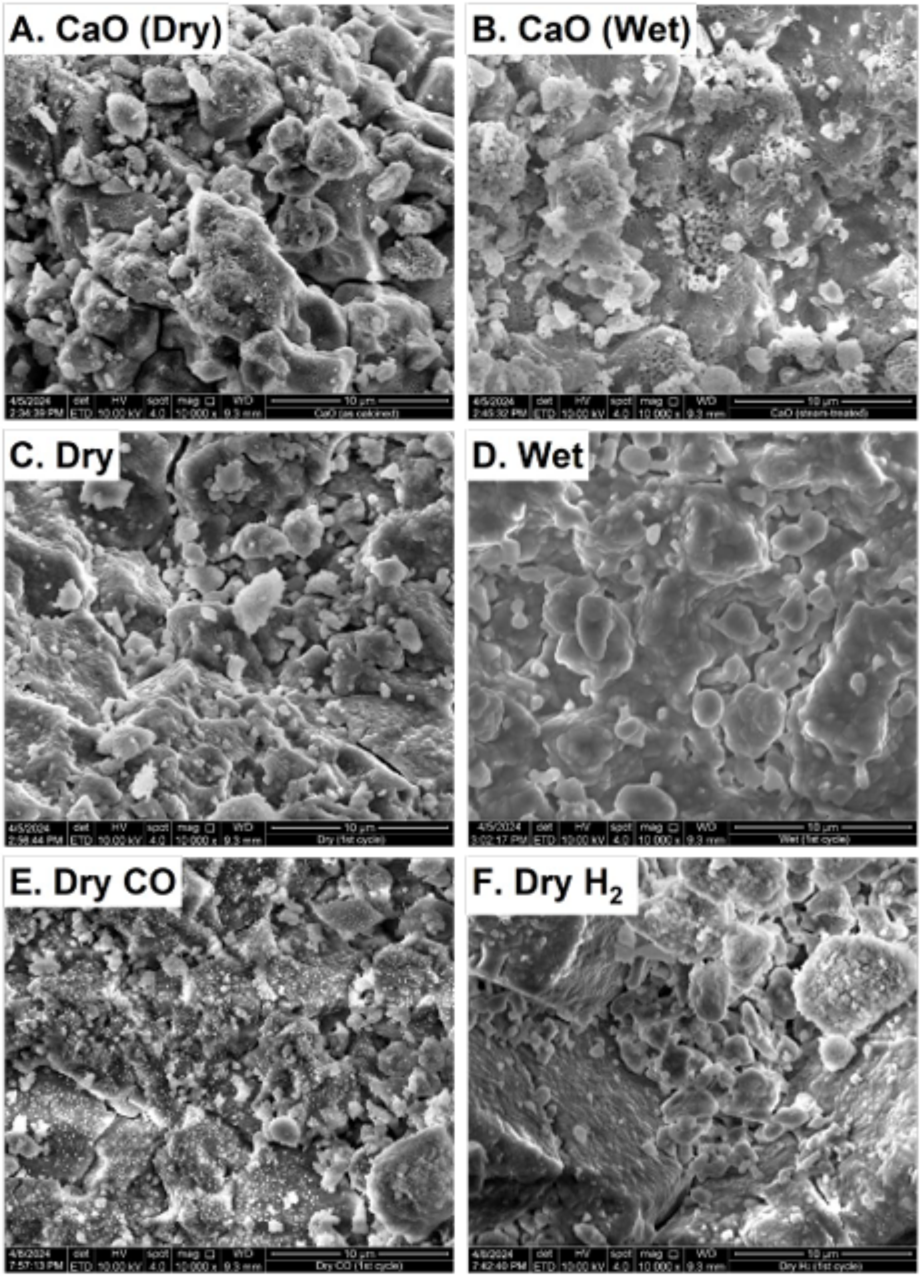


Figure 4: Sorbent structure visualization.

Process Development Unit (PDU)

The University of Utah is leveraging and modifying an existing apparatus to realize a small pilot-scale gasification unit for testing and evaluation of the SEG process. The process development unit (PDU) has a nominal feed rate of 60-100 lb/hr of biomass, depending on the form (chips, pellets, etc.). This corresponds to roughly 150-250 kW thermal input. The schematic of the PDU is given in Figure 5, while the actual unit hardware at the University of Utah Advanced Energy Systems Research Facility is illustrated in Figure 6.

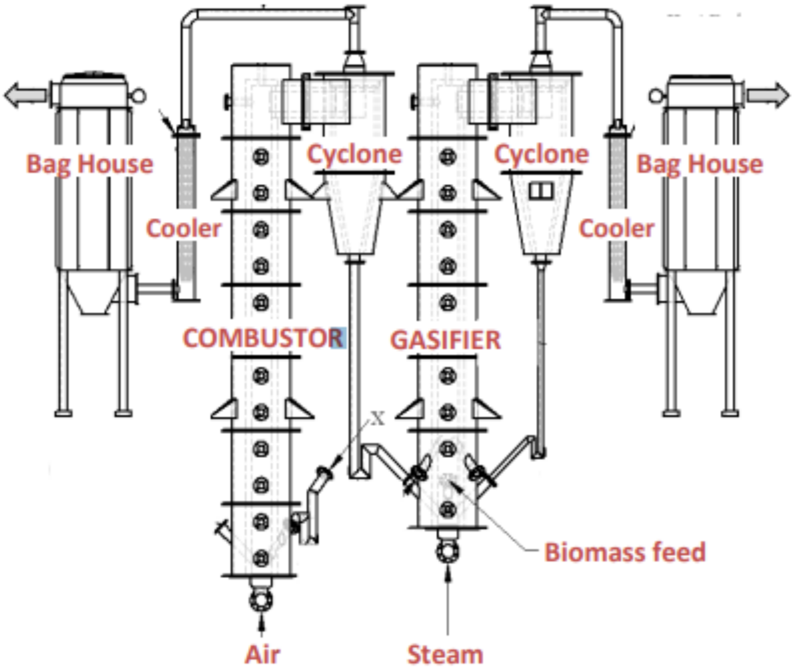


Figure 5: University of Utah dual fluidized bed process development unit schematic.

Figure 6: University of Utah dual fluidized bed process development unit.

The current estimated results and target research and development (R&D) values for hydrogen production economics are shown in Table 1. For target capital expenditures, a roughly approximate basis assumed a $150 million plant amortized at 7% over 25 years.

TABLE 1: HYDROGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Hydrogen	$/kg H_2	5.00	2.30
Capital Expenditures	$/kg H_2	2.50	0.85
Operating Expenditures	$/kg H_2	2.50	1.45

Definitions:

Cost of Hydrogen – Projected cost of capture per mass of H_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of H_2 produced over the life of the plant.

Operating Expenditures – Projected operating expenditures in dollars per kg of H_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M, feedstock cost.

Other Parameter Descriptions:

Waste Streams Generated – Spent bed material, spent sorbent, ash, biomass preprocessing waste. No other waste streams are expected.

Process Design Concept –See Figure 5.

technology advantages

- Reduction of the complexity and number of unit operations compared to the conventional multistep process for conversion of biomass to hydrogen.
- Increased efficiency and reduced costs.
- Advances clean hydrogen production technology toward the goal of achieving $1/kg of H_2 per Hydrogen Shot goals.

R&D challenges

- Ensuring consistent composition and trouble-free feeding of biomass feedstocks.
- Biomass gasification tar management: effective cracking to form smaller molecules.
- Limestone/CaO sorbent effectiveness and durability over multiple sorption-enhanced gasification cycles.

status

Loblolly pine chosen for trials and pelletized feedstock prepared and shipped to Utah; CO_2 sorption studies with effects of multiple parameters studied; preliminary testing of the PDU has occurred.

available reports/technical papers/presentations

"Process Intensification of Hydrogen Production through Sorption-Enhanced Gasification of Biomass," Michael Nigra, University of Utah, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Nigra.pdf*.

"Process Intensification of Hydrogen Production through Sorption-Enhanced Gasification of Biomass," Kevin Whitty and Michael Nigra, University of Utah, Project Update Presentation for DOE/NETL, August 26, 2024.

Sufyan, S.A., Whitty, K.J., Nigra, M.M., "CO_2 Sorption Capacity and Cyclic Performance of Quicklime (CaO) Under Gasification Conditions," *Chem Eng J* 507:160534 (2025).

Intensification of Hydrogen Production Enabled by Electrochemical Pumping Module for Purification and Compression

primary project goal

Washington University is developing and demonstrating an innovative electrochemical hydrogen pump (EHP) technology. It combines two energy-intensive process steps of hydrogen purification and compression into a single step, utilizing a small amount of electricity to treat product gas from a standard water-gas shift reactor in an electrochemical cell, simultaneously extracting and pressurizing high-purity hydrogen (H_2) for subsequent storage/utilization or pipeline injection.

technical goals

- Demonstration of a custom anode catalyst that is tolerant to carbon monoxide (CO).
- Demonstration of hydrogen pressurization in a 10 x 82 cm^2 cell stack up to at least 70 bar, enabled by membrane advancements to reduce contaminant crossover and maintain high purity.
- Advance EHP Technology Readiness Level (TRL) from TRL 3 to TRL 4.
- Generate and disseminate a comprehensive operating dataset and cost analysis for techno-economic analysis (TEA).

technical content

The concept of the EHP technology aims to enhance the efficiency and cost-effectiveness of hydrogen production from small-scale gasification units. Traditional hydrogen production methods involve multiple steps of gas separation (typically by pressure swing adsorption [PSA]) and mechanical compression, which are energy-intensive and costly. The EHP technology seeks to integrate H_2 separation/purification and compression into a single, modular unit with no moving parts, thereby reducing energy consumption and operational complexity.

The EHP (see Figure 1) operates by passing syngas into an electrochemical cell, where the syngas contacts the anode. At the anode, hydrogen in the syngas is oxidized to produce protons, which migrate through a proton exchange membrane (PEM) and recombine at the cathode to form pure hydrogen at a higher pressure. This process allows for simultaneous purification and compression of hydrogen. However, challenges such as catalyst poisoning by syngas species/contaminants like CO and hydrogen sulfide (H_2S), as well as membrane degradation, need to be addressed.

program area:
Gasification Systems

ending scale:
Bench scale prototype (82 cm^2 active cell area)

application:
Hydrogen Production

key technology:
Process Intensification for Syngas and Hydrogen

project focus:
Combine H_2 purification and compression into a single step with EHP

participant:
Washington University

project number:
FE0032178

predecessor projects:
N/A

NETL project manager:
Diane Revay Madden
diane.madden@netl.doe.gov

principal investigator:
Vijay Ramani
ramani@wustl.edu

partners:
Skyre Inc.

start date:
10.01.2022

percent complete:
70%

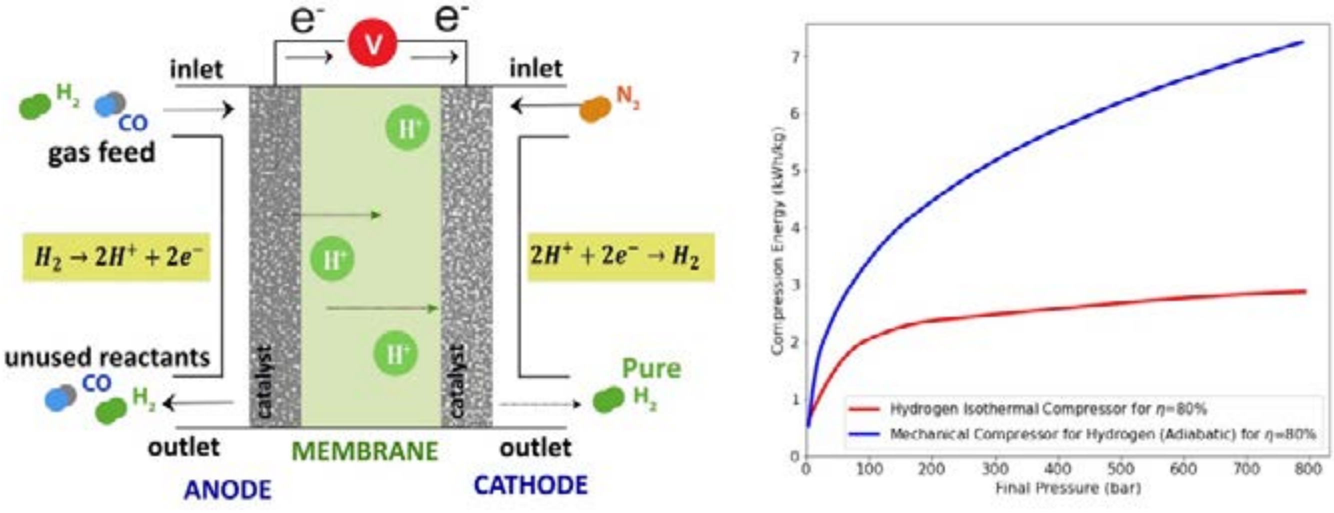


Figure 1: Concept for electrochemical hydrogen pump (left); hydrogen compression energy consumption (right).

To mitigate catalyst poisoning, CO-tolerant electrocatalysts such as platinum-ruthenium on carbon support (PtRu/C) are utilized, which have shown improved performance in the presence of CO. Additionally, strategies like pulsed oxidation are employed to oxidize adsorbed CO to carbon monoxide (CO_2), thereby regenerating the catalyst's active sites. The development of thermally stable membranes, such as polybenzimidazole (PBI)-based membranes doped with phosphoric acid, is also pursued to enable high-temperature operation without the need for humidification, further enhancing the system's robustness.

Initial tests on PtRu/C electrocatalysts with simulated gasifier syngas containing 2% CO showed that PtRu/C retains more than 85% of its performance after 24 hours of operation, compared to significant performance degradation suffered by standard platinum catalysts. Pulsed oxidation regeneration strategies have successfully mitigated CO poisoning by oxidizing CO to CO_2, maintaining catalyst activity; results for those strategies are illustrated in Figure 2.

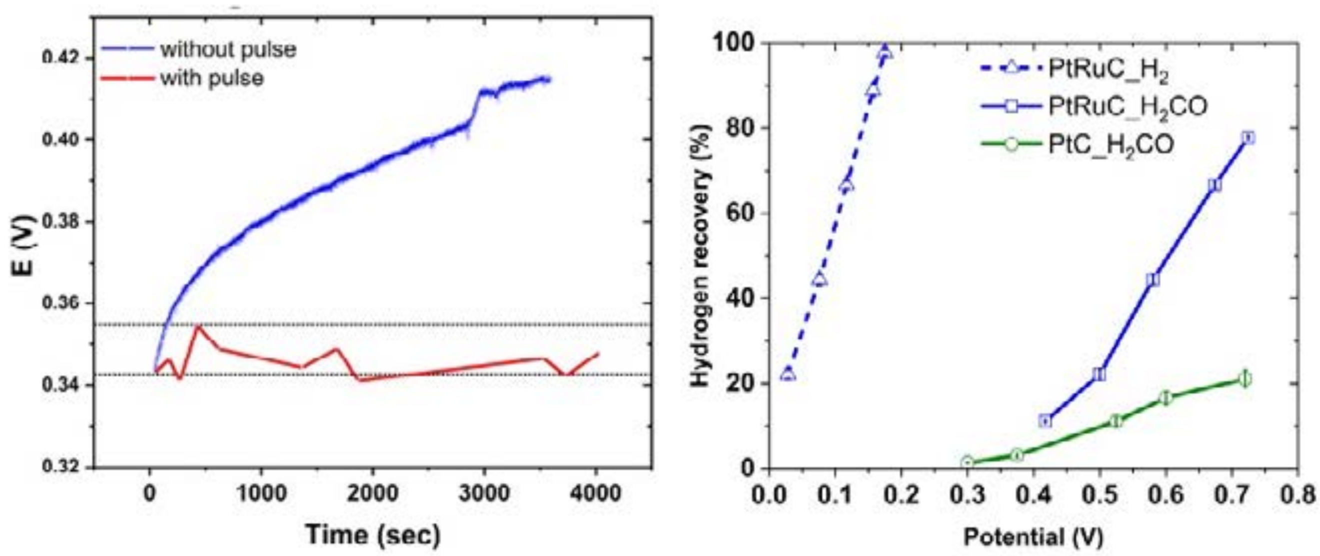


Figure 2: Strategies for CO poisoning: pulsed oxidation regeneration (left) and platinum-ruthenium catalyst (right). H_2CO in legend refers to H_2+ 1%CO

High-temperature, CO_2-resistant membranes have been fabricated using phosphoric acid-doped PBI polymers. These membranes enable stable operation at temperatures up to 180°C, which reduces the need for external humidification and enhances contaminant resistance. Membrane stability tests show less than a 5% loss in proton conductivity after 500 hours of operation in simulated syngas environments.

The current 10 x 82 cm^2 cell stack prototype has demonstrated hydrogen pressurization up to 50 bar in laboratory tests, with ongoing optimization targeting 70 bar by the end of the project. Purity measurements confirm that hydrogen produced by the EHP exceeds 99.99% purity, meeting industry standards for fuel cell applications.

Bench-scale tests to evaluate the EHP's performance when integrated with a simulated biomass gasifier syngas stream have indicated successful hydrogen recovery and compression with negligible crossover of contaminants such as nitrogen, sulfur or CO_2.

Preliminary TEA results comparing a baseline reference case (with conventional PSA and hydrogen compression) with a case with EHP replacing conventional hydrogen separation and compression (see Figure 3) suggest that EHP technology can reduce the energy cost of hydrogen compression by up to \$0.47/kg H_2 compared to mechanical compressors. The modular nature of the EHP system makes it economically viable for small-scale gasification systems (5-50 megawatts [MW]), where traditional mechanical systems are less efficient.

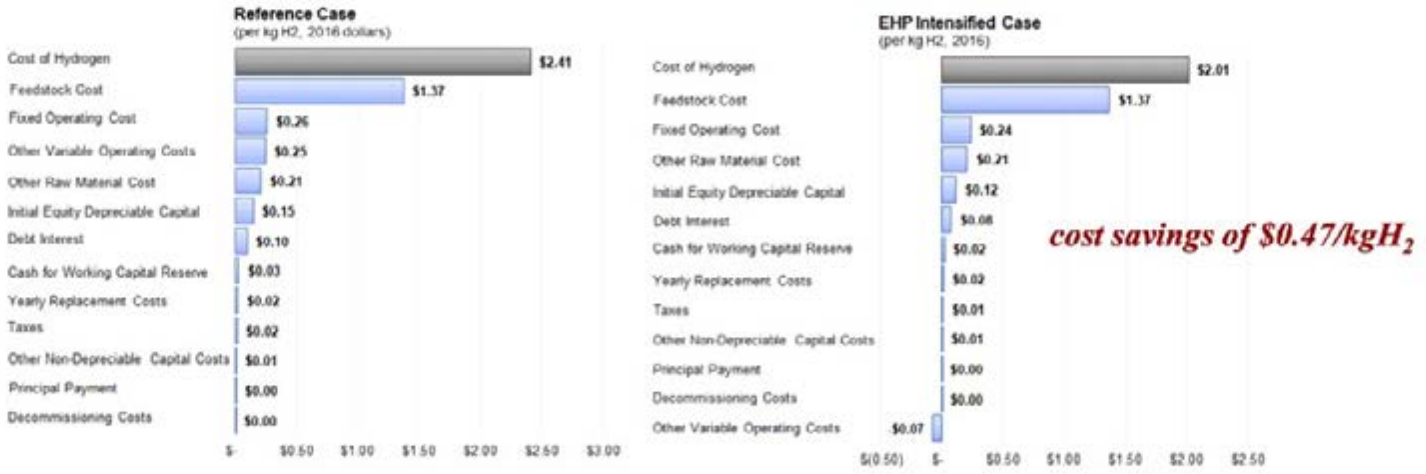


Figure 3: Comparison of costs of an EHP-intensified process case versus reference case

Techno-Economic Analysis

The current estimated results and target research and development (R&D) values for hydrogen production economics are shown in Table 1.

TABLE 1: HYDROGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Hydrogen	\$/kg H_2	TBD	TBD
Capital Expenditures	\$/kg H_2	TBD	TBD
Operating Expenditures	\$/kg H_2	TBD	TBD

Definitions:

Cost of Hydrogen – Projected cost of capture per mass of H_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of H_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of H_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M, feedstock cost.

Other Parameter Descriptions:

Waste Streams Generated – Not specified

Process Design Concept –

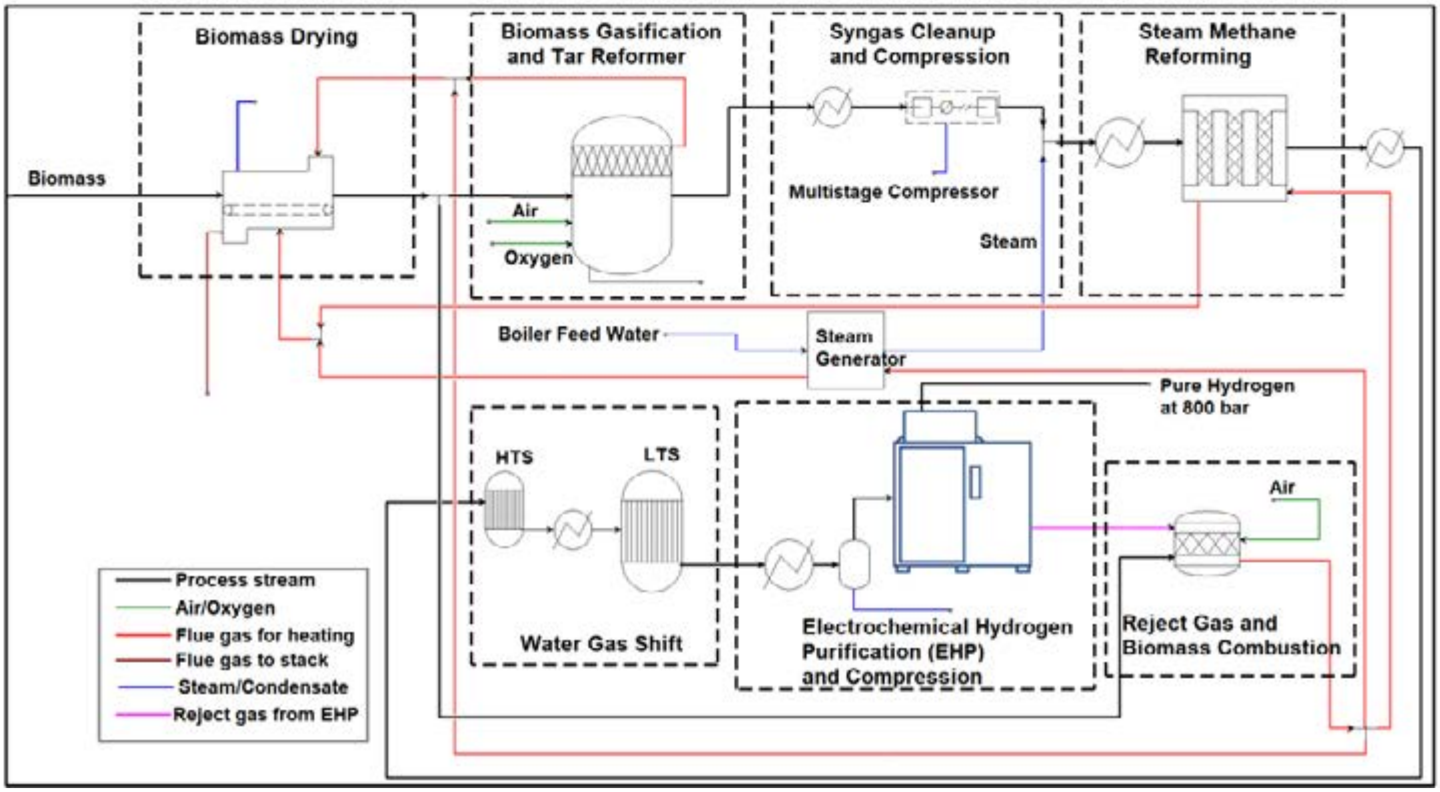


Figure 4: Biomass-to-hydrogen process concept incorporating EHP

technology advantages

- **Integrated Purification and Compression**: The EHP combines purification and compression into a single unit, reducing the number of components and simplifying the hydrogen production process.
- **Energy Efficiency**: By eliminating mechanical compressors and utilizing electrochemical methods, the EHP significantly reduces energy consumption associated with hydrogen compression.
- **Modular Design**: The EHP's modularity allows for scalability and adaptability to various hydrogen production scales, particularly beneficial for small-scale biomass gasification units.
- **Reduced Maintenance**: With no moving parts, the EHP is expected to have lower maintenance requirements and increased operational reliability compared to traditional mechanical systems.

R&D challenges

- **Catalyst Poisoning**: Developing catalysts that are resistant to contaminants such as CO and H_2S to maintain high performance over time.
- **Membrane Durability**: Ensuring the longevity and stability of PEMs under operating conditions, especially at elevated temperatures.
- **Contaminant Management**: Addressing the effects of complex gas mixtures and potential contaminant crossover that could impact hydrogen purity and system performance.

- **System Integration**: Effectively integrating the EHP with existing biomass gasification processes to optimize overall system efficiency and cost-effectiveness.

status

A CO-tolerant electrocatalyst has been identified (PtRu/C) that shows improved hydrogen recovery, and a thermally stable PBI membrane (doped with phosphoric acid) has been fabricated and tested.

available reports/technical papers/presentations

"Intensification of Hydrogen Production Enabled by Electrochemical Pumping Module for Purification and Compression," Ben Kumfer, Washington University in St. Louis, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS. *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Kumfer.pdf*.

Skyre Hydrogen Recovery, *https://www.skyre-inc.com/h2solutions*.

Modular Biomass Gasification for Co-Production of Hydrogen and Power

primary project goal

The University of North Dakota is developing a novel process-intensified and modular combined hydrogen, heat and power (CH^2P) production technology, integrating a novel adaptation of the steam-iron process to produce high-purity hydrogen and a compression-ready carbon dioxide (CO_2) stream from the gasification of biomass and biomass blends. Key features include use of a low-cost, modular fixed bed gasifier, and a novel, iron-based oxygen carrier material for syngas conversion to hydrogen (H_2) and CO_2 separation.

technical goals

- Demonstrate the technical and economic feasibility of CH^2P technology for small-scale applications (5–50 megawatt-electrical [MWe]), targeting hydrogen production rates of approximately 60 metric tons per day.
- Utilize biomass residues, such as sunflower hulls, beet pulp and refuse-derived fuel (RDF), as feedstocks for hydrogen production.
- Develop and evaluate novel oxygen carrier materials (OCMs) to enhance the efficiency and stability of the CH^2P process.
- Advance the Technology Readiness Level (TRL) of the CH^2P technology from TRL 3 to TRL 4, preparing for subsequent pilot-scale demonstrations.

technical content

Technical focus is on integration of oxy-gasification and chemical looping technologies for efficient hydrogen production. The core innovation is the use of engineered OCMs to enable simultaneous syngas conversion, clean H_2 generation and compression-ready CO_2. A modular approach allows for small-scale applications (5–50 MWe) using diverse feedstocks, including biomass, legacy coal waste and RDF.

The gasification portion of the overall system utilizes Singularity Energy Technologies' "Smart Gasifier" (see Figure 1). A key feature of the Smart Gasifier is its "sandwich" structure, where one or multiple reduction zones are placed between two or more high-temperature oxidation zones. This design allows precise temperature control, better fuel conversion and lower tar formation compared to conventional fixed bed, fluidized bed and entrained bed gasifiers. Even feedstocks with high moisture or volatile content can be processed efficiently while maintaining high-quality syngas rich in carbon monoxide (CO) and H_2. The reduction zone, maintained above 700°C (see Figure 1), produces energy-rich CO and H_2. The lower oxidation zone ensures nearly complete carbon conversion, even for challenging feedstocks.

program area:
Gasification Systems

ending scale:
Bench scale prototype
CH^2P Unit: 1 – 2 kW_{th}
Gasifier: 2 & 10 kW_{th}

application:
Hydrogen Production

key technology:
Process Intensification for Syngas and Hydrogen

project focus:
Development of CH^2P Process and integration with SET's Smart Gasifier Technology

participant:
University of North Dakota

project number:
FE0032182

predecessor projects:
FE0031534

NETL project manager:
John Homer
john.homer@netl.doe.gov

principal investigator:
Junior Nasah
nasah.domkam@und.edu

partners:
Envergex, LLC.
Singularity Energy Technologies (SET) LLC

start date:
10.01.2022

percent complete:
70%

SET’s Smart Gasifier is scalable and can be deployed in different sizes based on demand. It can be located near feedstock sources to reduce transportation costs and can use feedstocks without requiring energy-intensive preprocessing. The system efficiently handles high-moisture content feedstocks, with a cyclone to remove particulates, and a built-in wet scrubber to remove contaminant gases for cold syngas applications.

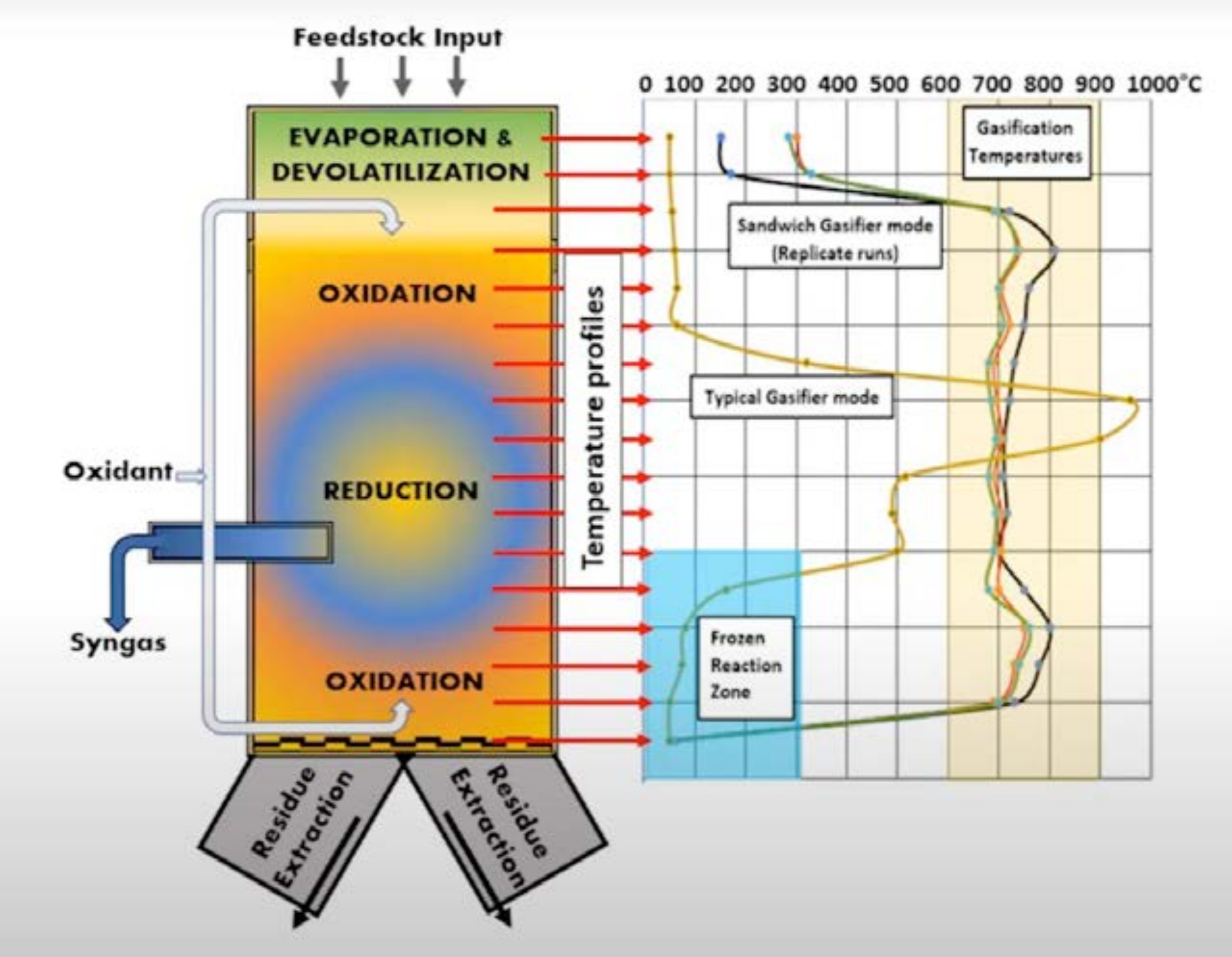


Figure 1: SET’s Smart Gasifier operating approach.

Feedstock Characterization

The technology developers seek to leverage the abundant, geographically distributed and limited (tonnes per year) availability of biomass residues in North Dakota and Minnesota, which includes sunflower hulls and beet pulp shreds. Another opportunity feedstock includes RDF from municipal solid waste, which is abundant and allows communities to convert wastes into valuable chemicals while reducing landfill use. Characterization of these feedstocks revealed variability in composition and physical properties (See Table 1 and Figure 2), highlighting that SET’s Smart Gasifier is well suited for treating such wastes and enabling the assessment of OCM stability through its feed-flexible capabilities.

TABLE 1: CHARACTERIZATION OF BIOMASS RESIDUES

Parameter	Units	Sunflower Hulls	Beet pulp shreds (air dried)	RDF
Higher Heating Value (HHV)	MJ/kg	19.7	14.9	20.7
Sulfur Content	Wt.%	0.15	0.38	0.10
Chlorine content	µg/g	650	200	1000

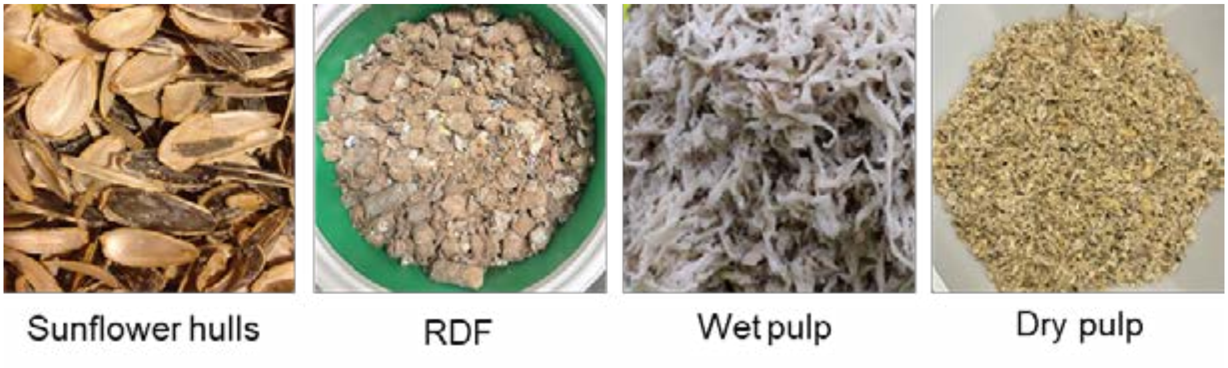

Sunflower hulls RDF Wet pulp Dry pulp

Figure 2: Biomass feedstocks.

Combined Hydrogen, Heat and Power (CH^2P) Process

The CH^2P process is designed for utilization of high-temperature syngas; therefore, syngas leaving the gasifier island undergoes minimal processing to remove entrained ash prior to entering the CH^2P process cycle. The CH^2P process adopts a chemical looping scheme using cycled fixed beds of OCM to convert the syngas to separate H_2 and CO_2 streams (see Figure 3). The heat from the hot streams leaving the process is recovered to generate power or heat. OCM cost, stability and performance are key to the techno-economic performance of the CH^2P process and the primary focus of the University of North Dakota's development efforts.

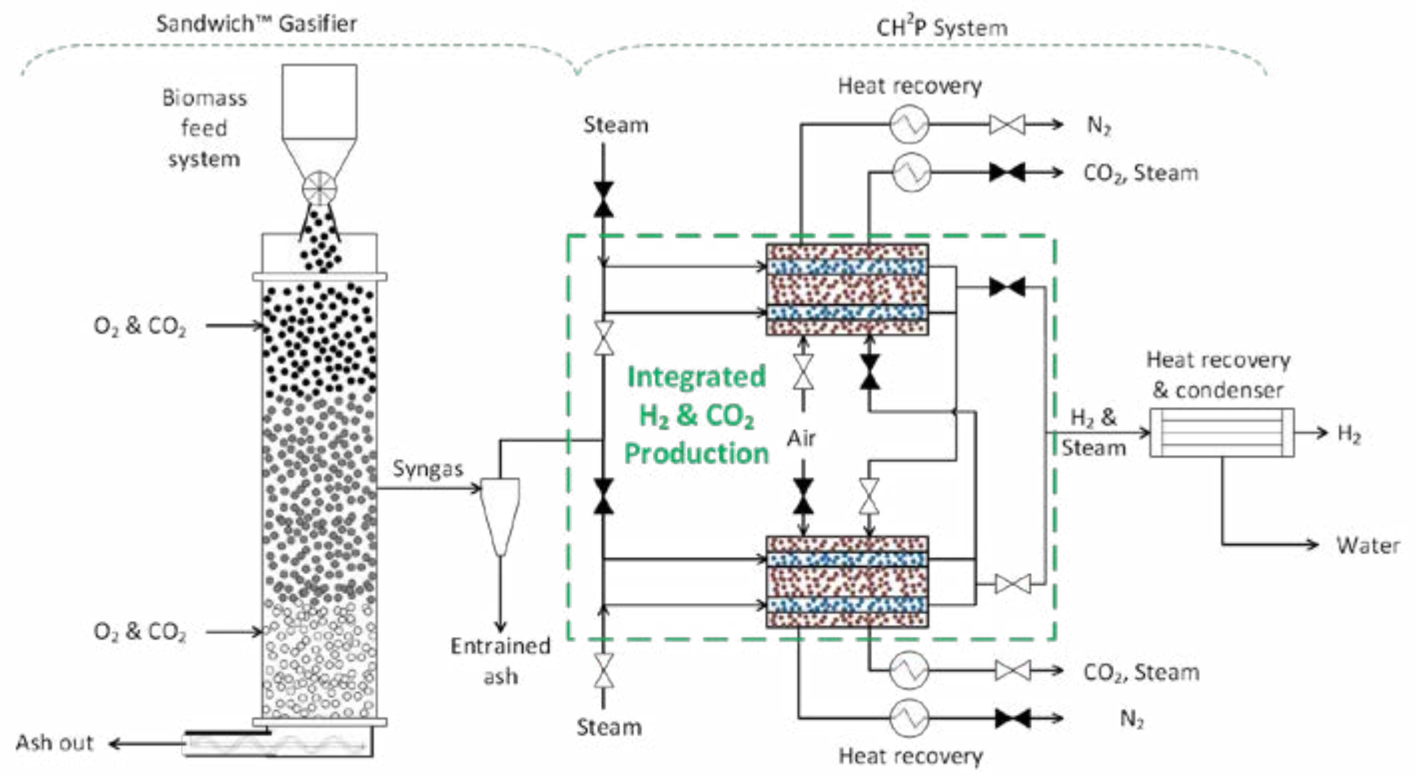
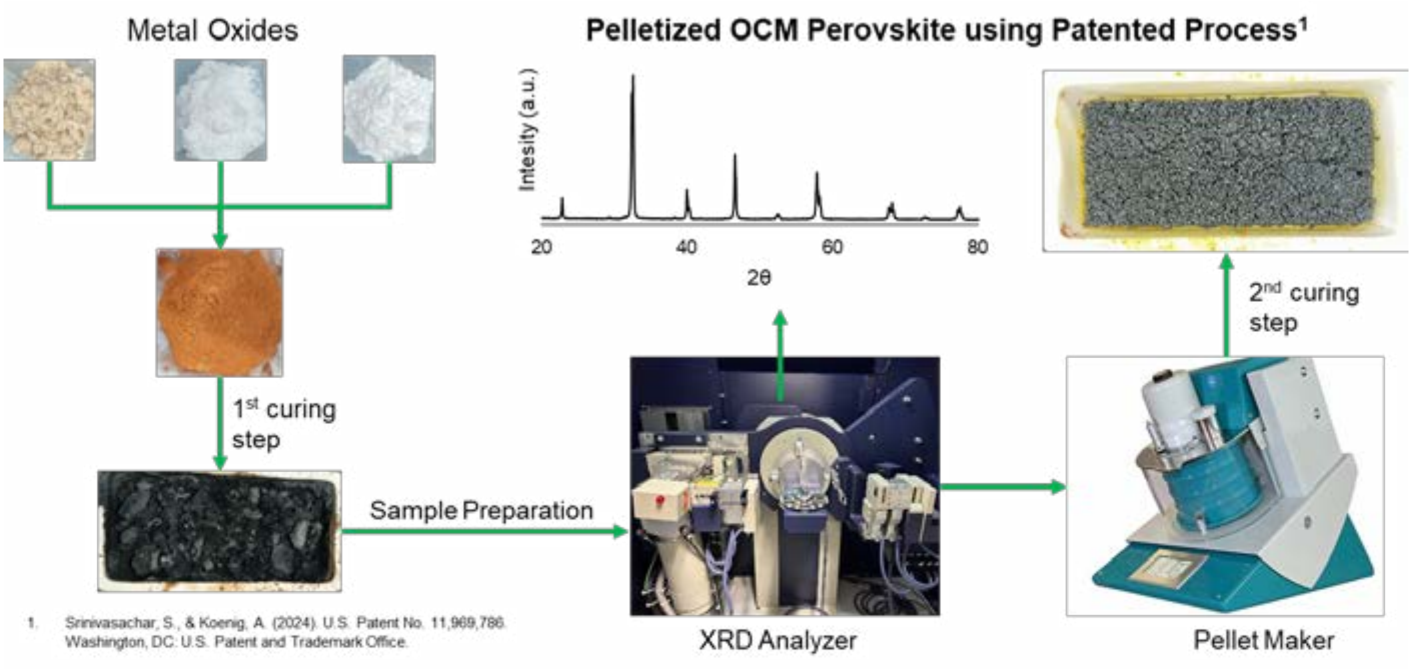


Figure 3: Process flow of gasifier and CH^2P process.

Oxygen Carrier Material (OCM) Development

OCM development is focused on two main types — an iron-based material FEH31, developed in a previous NETL project (FE0031534) using Envergex' s patented low-cost, mechanically mixed manufacturing method, and a pelleted perovskite material. Envergex's low-cost manufacturing method has been successfully adapted to manufacture the perovskite material, traditionally prepared using expensive wet chemistry methods such as the Pechini method (See Figure 4).



1. Srinivasachar, S., & Koenig, A. (2024). U.S. Patent No. 11,969,786. Washington, DC: U.S. Patent and Trademark Office.

Figure 4: Diagram showing perovskite manufacturing for OCM development.

Integrated Gasification and Syngas Conversion Evaluation

An integrated bench-scale CH2P system (1–2 kilowatt-thermal [kW_{th}]) and Sandwich™ gasification unit (0.2–1 lb/hr biomass) is planned to evaluate the system's performance under actual syngas composition and determine fate of syngas impurities on OCM lifetime and product gas purity. Ongoing cyclic performance testing of the pelleted OCM materials using the university's high-temperature bench-testing system and simulated syngas is determining performance and operating and maintenance (O&M) costs. The results will be used to inform the TEA, providing data and insights that will guide the optimization of the system and allow the team to refine the design and operation of a commercial system.

Techno-Economic Analysis

The current estimated results and target research and development (R&D) values for hydrogen production economics are shown in Table 2.

TABLE 2: HYDROGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Hydrogen	\$/kg H_2	TBD	< 2.50
Capital Expenditures	\$/kg H_2	TBD	< 15
Operating Expenditures	\$/kg H_2	TBD	< 1.00

Definitions:

Cost of Hydrogen – Projected levelized cost of capture per mass of H_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of H_2 produced annually.

Operating Expenditures – Projected operating expenditures in dollars per kg of H_2 produced.

Other Parameter Descriptions:

Waste Streams Generated – Not specified.

Process Design Concept – See Figure 3.

technology advantages

- The CH^2P system is designed for modular or small-scale applications, making it suitable for distributed hydrogen production in various locations.
- Utilizing diverse biomass residues and RDF as feedstocks promotes waste valorization and reduces reliance on fossil fuels.
- Integrating the gasification with chemical looping enhances efficiency and allows for the co-production of hydrogen, heat and power.
- The process aims to produce versatile hydrogen (useful in high-value chemicals synthesis) with reduced emissions from varied feedstock materials of low value.

R&D challenges

- Creating oxygen carrier materials with high reactivity, stability and longevity over multiple cycles is critical for process efficiency.
- Seamlessly integrating the gasifier with the CH^2P reactor poses engineering challenges, particularly in maintaining optimal operating conditions.
- Achieving a hydrogen production cost of $1 per kilogram necessitates overcoming technical hurdles and adopting low-to-negative-cost waste streams to boost revenues.

status

An integrated CH_2P system unit able to process all syngas from the test gasifier is being assembled for testing. A conceptual design for a commercial facility capable of processing 25–100 tons per day of biomass feedstock will inform the TEA.

available reports/technical papers/presentations

"Low-Cost Recyclable Oxygen Carrier and Novel Process for Chemical Looping Combustion," February 2022. Nasah, Junior, et al.
https://doi.org/10.2172/1846668.

“Modular Biomass Gasification for Co-Production of Hydrogen and Power,” Junior Nasah, University of North Dakota, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems - PROCEEDINGS
https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Nasah.pdf.

“Modular biomass Gasification for Co-Production of Hydrogen and Power,” Junior Nasah (PI), U.S. Department of Energy, National Energy Technology Laboratory, Fossil Energy and Carbon Management, October 24, 2024 Annual Meeting.

"Sandwich gasification process for high-efficiency conversion of carbonaceous fuels to clean syngas with zero residual carbon discharge." US 11220641, United States Patent and Trademark Office, January 2022. N.M. Patel, 2022
https://image-ppubs.uspto.gov/dirsearch-public/print/downloadPdf/11220641.

"Techno-economic Analysis for a Low Cost and Recyclable Oxygen Carrier," August 2022. Nasah, Junior, et al.
https://www.osti.gov/biblio/2204052.

Producing Clean Hydrogen Using a Modular Two-Stage Intensified Membrane-Enhanced Catalytic Gasifier

primary project goal

West Virginia University Research Corporation (WVURC) is developing a process-intensified two-stage bubbling fluidized bed (BFB) gasifier for hydrogen production from biomass. The BFB gasifier system would be integrated with a membrane separator and precombustion carbon dioxide (CO_2) capture system with syngas recycle. The overall goal of the project is to reduce the costs of hydrogen production by developing a modular and highly efficient and intensified gasification system with significantly less equipment items than traditional systems.

technical goals

- Develop a modular, two-stage intensified membrane-enhanced catalytic gasifier for clean hydrogen production.
- Integrate biomass gasification with high-temperature, hydrogen-selective membranes to achieve ultrapure hydrogen output.
- Enhance process intensification and modularization to reduce costs and improve efficiency in hydrogen production, making progress toward a target cost of $1 per kilogram.
- Conduct comprehensive process modeling, optimization and techno-economic analysis (TEA) to assess the feasibility and scalability of the technology.

technical content

West Virginia University's gasification technology development integrates catalytic gasification with advanced membrane separation to enable efficient hydrogen production while capturing CO_2. The system employs a BFB reactor for gasification. High-temperature hydrogen separation membranes are embedded in the system to selectively extract hydrogen, streamlining the process and reducing the need for complex downstream separation steps. Carbon dioxide can be efficiently captured for storage or other treatments, supporting reduced greenhouse gas (GHG) emissions performance. WVURC's process concept is illustrated in Figure 1.

program area:
Gasification Systems

ending scale:
Laboratory (<1 kg/hr biomass)

application:
Hydrogen Production

key technology:
Process Intensification for Syngas and Hydrogen

project focus:
H_2 from biomass using bubbling fluidized bed (BFB) catalytic gasifier

participant:
West Virginia University

project number:
FE0032191

predecessor projects:
N/A

NETL project manager:
Sarah Pfeiffer
sarah.pfeiffer@netl.doe.gov

principal investigator:
Debangsu Bhattacharyya
West Virginia University
debangsu.bhattacharyya@mail.wvu.edu

partners:
N/A

start date:
10.01.2022

percent complete:
65%

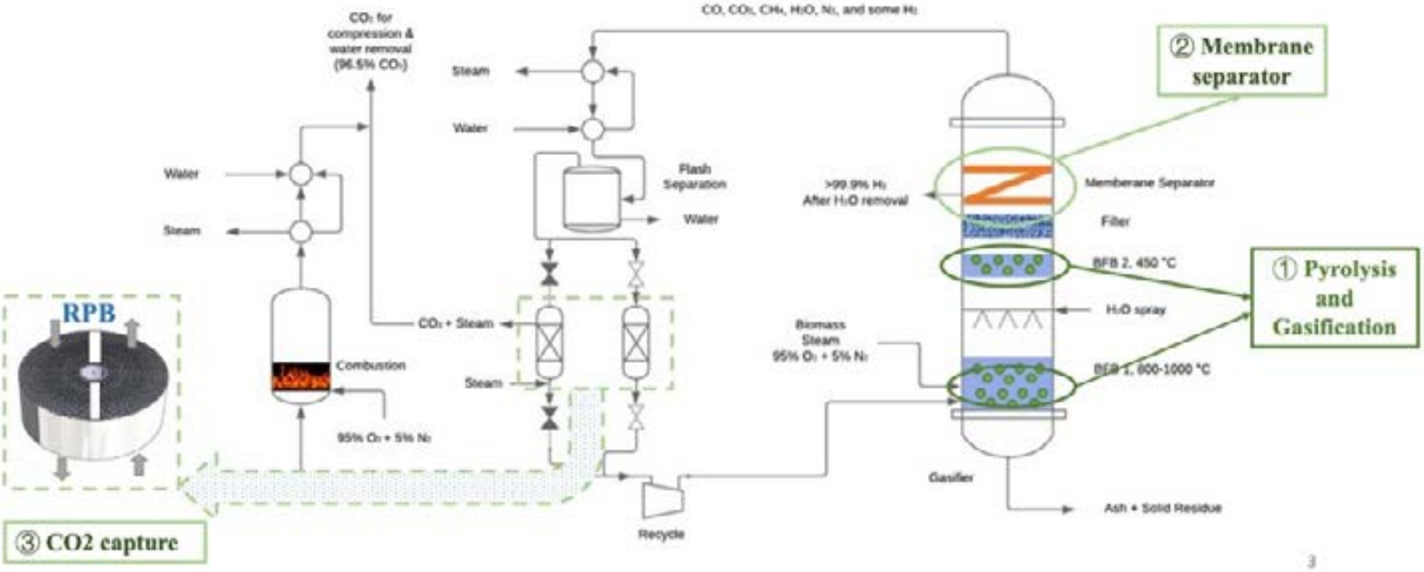


Figure 1: Process concept for modular, two-stage intensified membrane-enhanced catalytic gasifier.

Experimental testing, system optimization and modeling are helping to advance this technology. The team is developing and testing a pilot-scale system that integrates catalytic gasification with hydrogen-permeable membranes, focusing on validating system performance under real-world conditions. Advanced modeling tools are used to optimize the reactor design, gasification parameters and membrane integration, ensuring efficient operation and scalability.

Initial gasification tests were performed using a BFB reactor to assess its ability to convert biomass feedstock into syngas under various conditions. Key operating parameters such as temperature and pressure were varied to optimize the production of hydrogen-rich syngas. High-pressure reactions produced syngas with a high amount of methane (i.e., through a high pressure-driven methanation reaction). Low-pressure conditions produced syngas with a low amount of methane and CO_2. In pressurized noncatalytic gasification, 99.24% carbon conversion was attained, while catalytic gasification at high pressure gives nearly 100% carbon conversion. In low-pressure, noncatalytic gasification, 86.54% carbon conversion was attained, while catalytic gasification gives nearly 100% carbon conversion. These results are illustrated in Figure 2. The experiments confirmed BFB gasification ability to generate a syngas composition with significant hydrogen content suitable for downstream gas separations. Challenges related to feedstock variability were noted, emphasizing the need for consistent feedstock preparation and handling strategies.

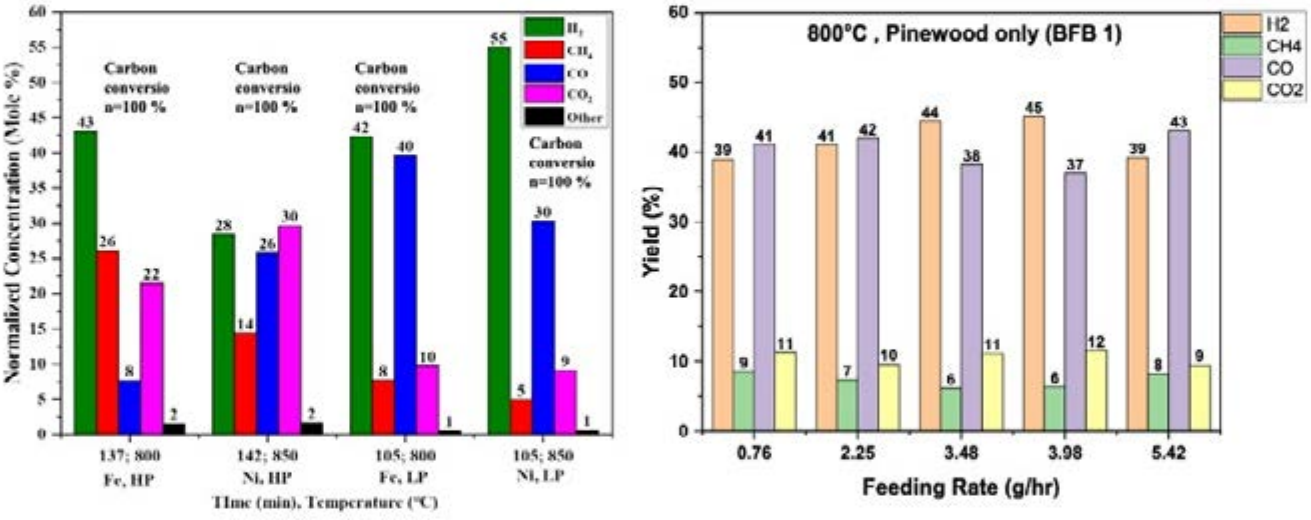
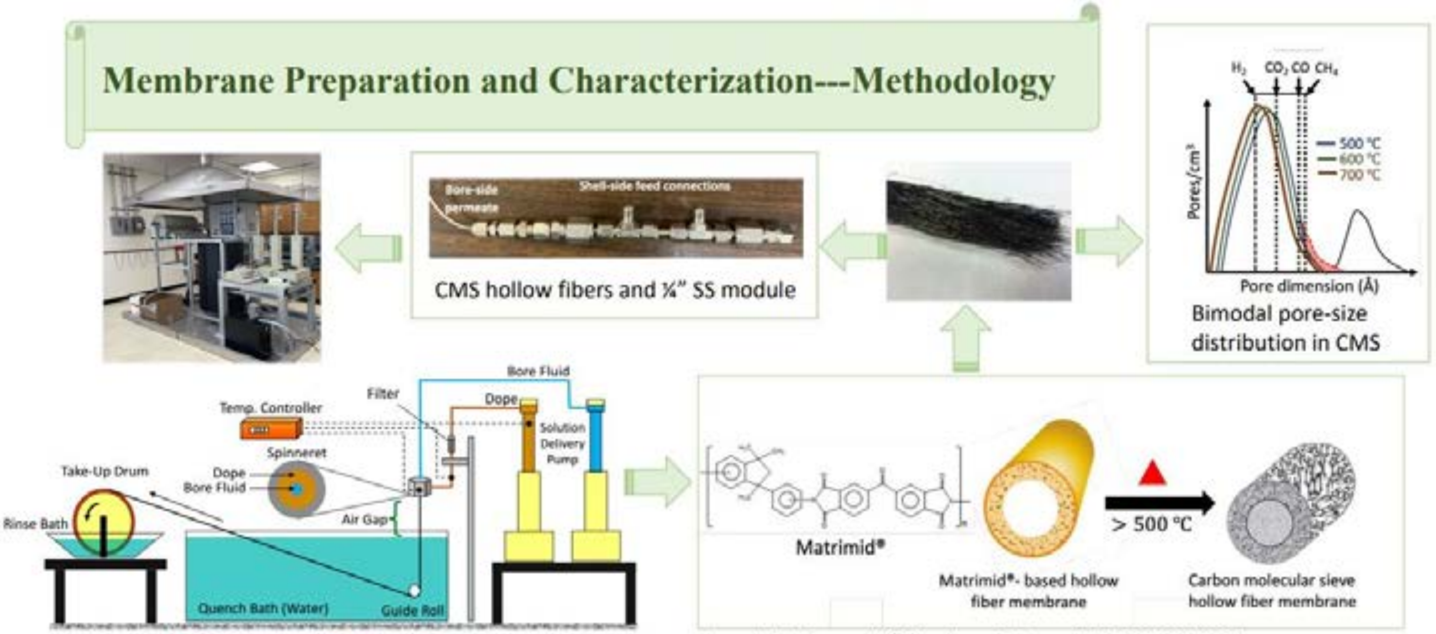


Figure 2: Syngas compositions in catalytic gasification of pinewood in a fixed bed gasifier.

Thermogravimetric analysis (TGA) of biomass materials showed that thermal decomposition mainly occurs at 250-400°C. After 400°C, biomass undergoes 17% to 26% weight loss. After testing various gasifying agents added at different concentrations, the team found that when using air as a gasifying agent, no char residue is found at higher flow rates. Additionally, using CO_2 as a gasifying agent brought about low char residue at higher temperatures, with the reversible Boudouard reaction likely playing an important role. In conclusion, low flowrates of gasifying agents (air/CO_2) are effective.

High-temperature hydrogen-separation membranes were evaluated for their ability to selectively extract hydrogen from the syngas. Matrimid®-derived hollow-fiber membranes are spun using a conventional (dry-jet/wet-quench) method of fiber spinning. The polymer hollow fibers are pyrolyzed in an inert environment in a three-zone furnace to form carbon molecular sieve (CMS) hollow-fiber membranes. In the molecular level, the CMS microstructure has microporous Langmuir voids, which allow for high sorption of gases as well as ultramicroporous sites, which provide selectivity between similar-sized (e.g., H_2: 0.289 nm; carbon monoxide [CO]: 0.376 nm, and CO_2: 0.38 nm) penetrants.



Sanyal *et al.* Journal of Membrane Science, 551, 113-122, 2018

Figure 3: Schematic and images detailing membrane development.

Finally, the team is using advanced computational modeling to simulate and optimize the integrated gasification system. This includes modeling the BFB gasifier to evaluate syngas composition, thermal efficiency and contaminant behavior, while integrating these models with hydrogen-separation membranes to assess overall system performance. Sensitivity analyses aim to identify key parameters, such as operating temperature and feedstock composition, that influence hydrogen yield and contaminant management. Also, system performance is to be simulated at different scales, from small modular systems (5-50 megawatt-electric [MWe]) to larger configurations, to understand the impacts of scale on efficiency and economic feasibility. These models found that optimal results strongly depend on the design of each specific stage of the intensified BFB reactor, as well as its hydrodynamics, operating temperature and pressure, number of membrane stages and their specific design and operating conditions, etc.

Techno-Economic Analysis

A TEA will evaluate the system's economic viability and identify pathways for commercialization.

The current estimated results and target research and development (R&D) values for hydrogen production economics are shown in Table 1.

TABLE 1: HYDROGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Hydrogen	$/kg H_2	TBD	TBD
Capital Expenditures	$/kg H_2	TBD	TBD
Operating Expenditures	$/kg H_2	TBD	TBD

Definitions:

Cost of Hydrogen – Projected cost of capture per mass of H_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of H_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of H_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M, feedstock cost.

Other Parameter Descriptions:

Waste Streams Generated – Mainly negligible quantity of ash that includes less than 1% of unconverted biomass.

Process Design Concept – See Figure 1.

technology advantages

- **High-Purity Hydrogen Production**: The integration of high-temperature hydrogen-selective membranes ensures the production of ultrapure hydrogen, meeting stringent quality standards for various applications.
- **Process Intensification**: Combining gasification and membrane separation in a single, integrated system enhances efficiency and reduces the footprint of the hydrogen production facility.
- **Modular Design**: The technology's modular nature allows for flexible scaling, making it suitable for distributed hydrogen production and facilitating easier integration into existing energy infrastructures.
- **Cost Reduction**: Process intensification and modularization contribute to lower capital and operational costs, improving the economic viability of clean hydrogen production.

R&D challenges

- **Membrane Development**: Creating hydrogen-selective membranes that maintain high performance and durability under high-temperature gasification conditions is a significant technical challenge.
- **System Integration**: Seamlessly integrating the gasifier and membrane units requires careful engineering to ensure optimal performance and reliability.
- **Feedstock Variability**: Biomass feedstocks can vary in composition and properties, necessitating adaptable gasification processes to maintain consistent hydrogen production quality.
- **Economic Feasibility**: Achieving cost targets for hydrogen production involves addressing both technical and economic challenges, including material costs, system efficiency and market factors.

status

Next steps include testing various operational parameters in the two-stage gasifier by using different gasifying agents and catalysts, integrating the gasifier with the membrane reactor, optimizing pyrolysis and other conditions for membrane manufacturing, and optimizing the defect curing step for maximizing selectivity and recovery. Non-isothermal gasifier model, membrane model and CO_2 capture system models are to be completed and validated.

available reports/technical papers/presentations

“Producing Clean Hydrogen Using a Modular Two-Stage Intensified Membrane-Enhanced Catalytic Gasifier,” Debangsu Bhattacharyya, West Virginia University (WVU), 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems - PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Bhattacharyya.pdf*.

An Intensified Process to Transforming the Production of Carbon-Neutral Hydrogen

primary project goal

Clarkson University is demonstrating carbon-neutral hydrogen (H_2) production from biomass gasification based on the use of metallic H_2-selective membrane assisted water-gas shift reactors (MAWGS). As opposed to conventional practice of syngas upgrading/cleaning followed by hydrogen separation, this approach removes the hydrogen gas directly from the WGS reaction zone via the membrane. This results in significant process intensification, reducing the volume of the reactor and catalyst amount and increasing conversion, translating into lower capital, operating and maintenance costs.

technical goals

- Develop a metallic membrane reactor that integrates catalytic gasification and hydrogen separation for efficient, carbon-neutral hydrogen production.
- Enhance process intensification by combining gasification, reforming and hydrogen purification into a single, compact system.
- Achieve high-hydrogen purity and yield while minimizing carbon dioxide (CO_2) emissions through effective membrane separation and catalytic processes.
- Conduct comprehensive modeling, simulation and experimental validation to optimize reactor design and operating conditions.

technical content

Conventionally, hydrogen production by gasification of carbonaceous feedstocks such as coal and biomass starts with gasification, yielding syngas containing H_2 and carbon monoxide (CO) (if oxygen is used in the gasifier, nitrogen content of syngas is negligible). The syngas is shifted by the water-gas shift (WGS) reaction to mostly H_2 and CO_2. Then, H_2 can be separated by a solvent-based process such as Selexol or any suitable pressure swing adsorption method. This is depicted in the top half of Figure 1. However, conventional WGS units require multiple stages for high extent of conversion, plus the solvent-based processes involve high energy penalties.

In contrast, the concept under development involves integrating syngas reforming and hydrogen separation into a single, intensified process unit. The MAWGS process concept (bottom half of Figure 1) combines WGS and hydrogen separation within an integrated reactor. Metallic membranes with high selectivity and permeability for hydrogen are integrated into the reactor, selectively allowing hydrogen molecules to permeate while retaining other gases. This selective permeation results in the continuous extraction of high-purity hydrogen from the reaction zone, driving the gasification and shift reactions toward greater hydrogen

program area:
Gasification Systems

ending scale:
Bench scale prototype (0.2-0.3 kW_{th})

application:
Hydrogen Production

key technology:
Process Intensification for Syngas and Hydrogen

project focus:
Demonstration of metallic H_2-selective membrane assisted water-gas shift reactors (MAWGS)

participant:
Clarkson University

project number:
FE0032205

predecessor projects:
N/A

NETL project manager:
Diane Revay Madden
diane.madden@netl.doe.gov

principal investigator:
Simona Liguori
Clarkson University
sliguori@clarkson.edu

partners:
University of Wisconsin-Madison

start date:
10.01.2022

percent complete:
75%

production due to removal of the product H_2 per Le Chatelier's Principle. Figure 2 illustrates the workings of the MAWGS reactor.

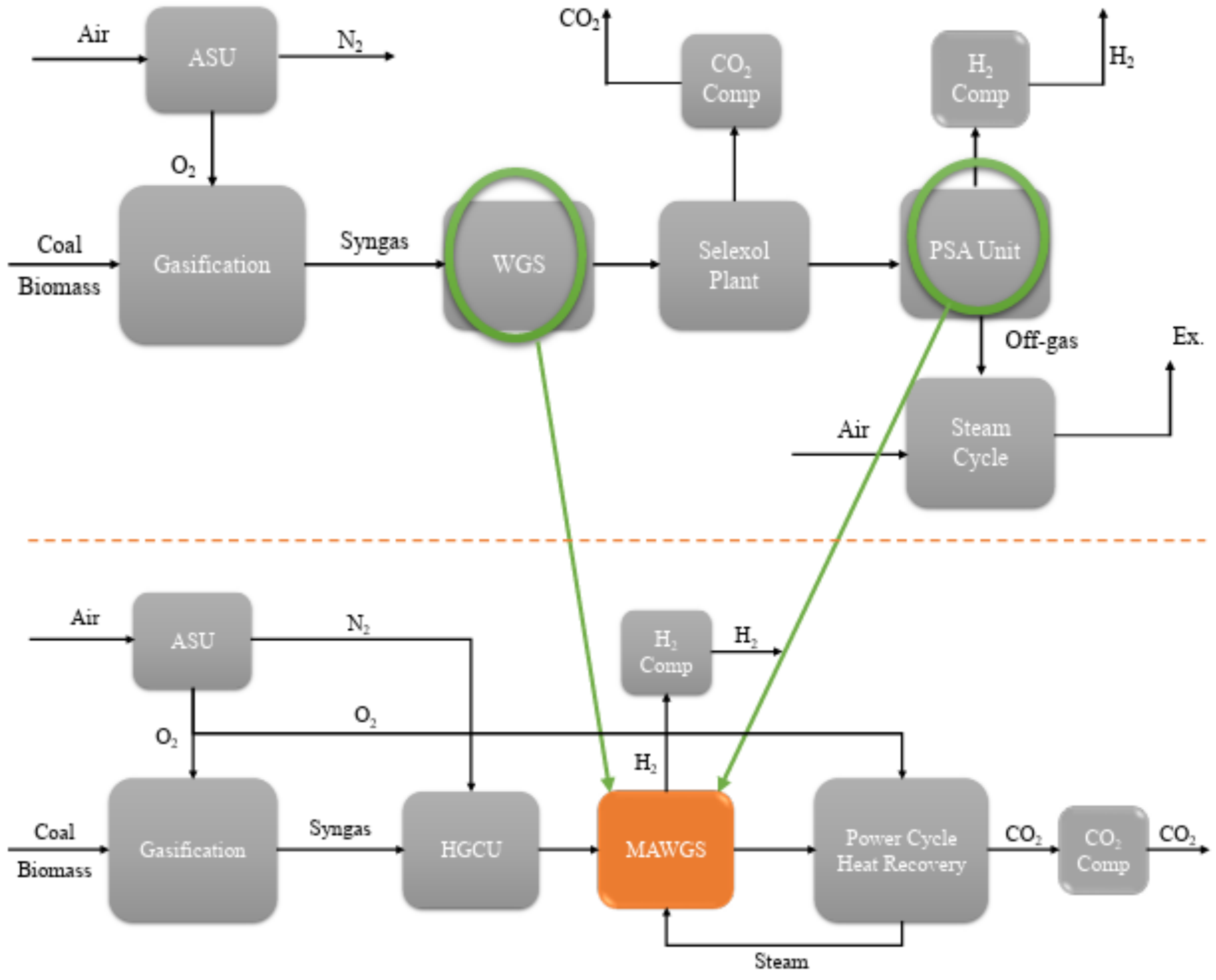


Figure 1: Comparison of conventional versus H_2-selective MAWGS reactor-based H_2 production from gasification.

In the overall process, gasification of biomass is considered, particularly in the context of SunGas or All Power Labs, which specialize in advanced biomass gasification technologies. Among the different gasification methods, a fluidized-bed gasification system is assumed for the techno-economic evaluation of hydrogen production due to its efficiency, scalability and ability to handle a diverse range of biomass feedstocks.

Fluidized-bed gasifiers offer better heat and mass transfer, leading to improved syngas quality and a more uniform temperature distribution within the reactor. This results in higher hydrogen yield, reduced tar formation and increased process efficiency compared to fixed-bed or moving-bed gasifiers. Additionally, the fluidized-bed system is known for its fuel flexibility, allowing for the use of various biomass types, including agricultural residues, wood chips and municipal solid waste, which enhances the economic feasibility of hydrogen production.

The techno-economic evaluation focuses on parameters such as capital and operational costs, hydrogen yield, energy efficiency, and integration with the MAWGS reactor. The synergy between fluidized-bed gasification and advanced hydrogen separation technologies is expected to improve the overall hydrogen recovery rate and process economics, making it a promising approach for sustainable and cost-effective hydrogen production.

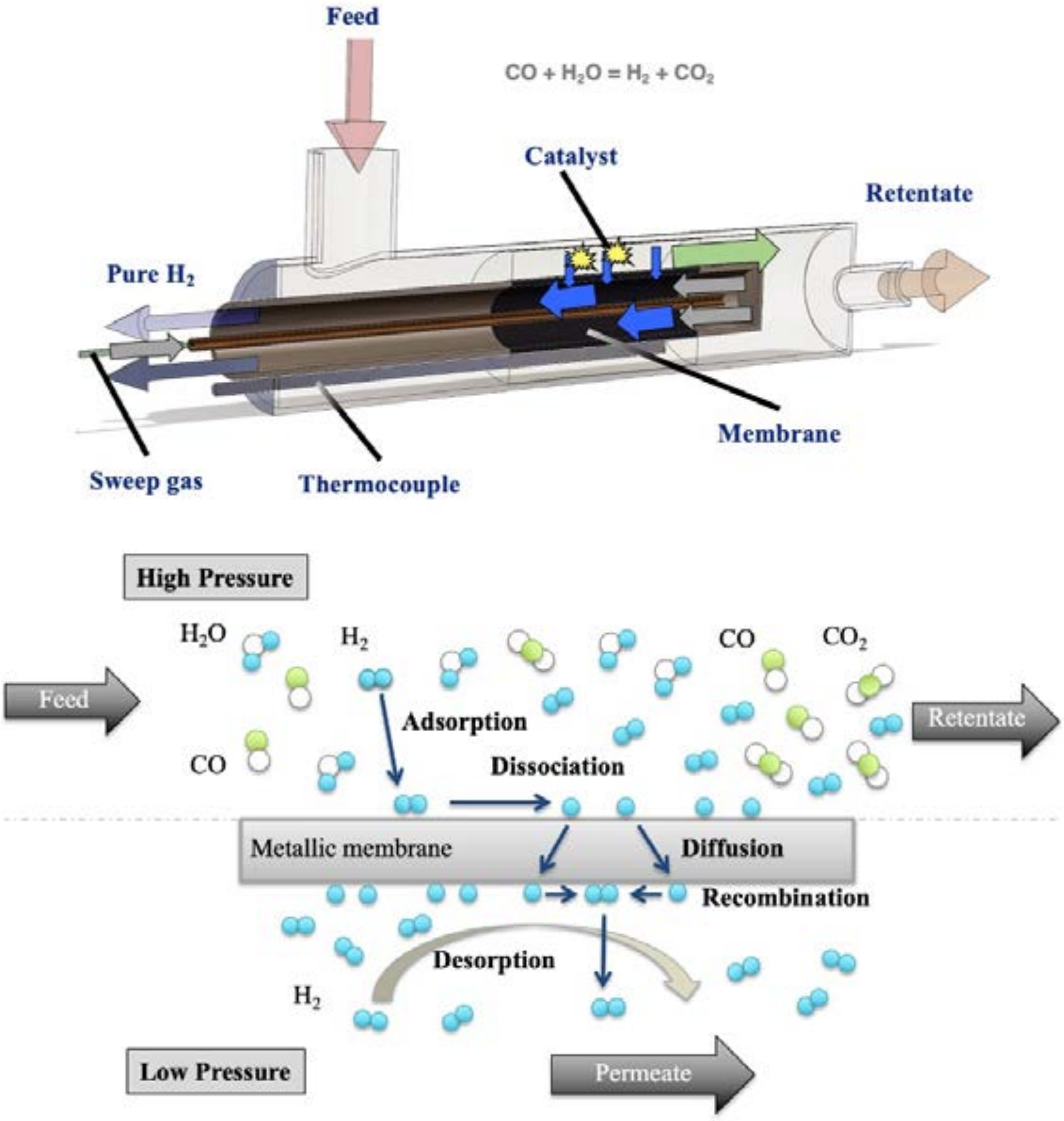
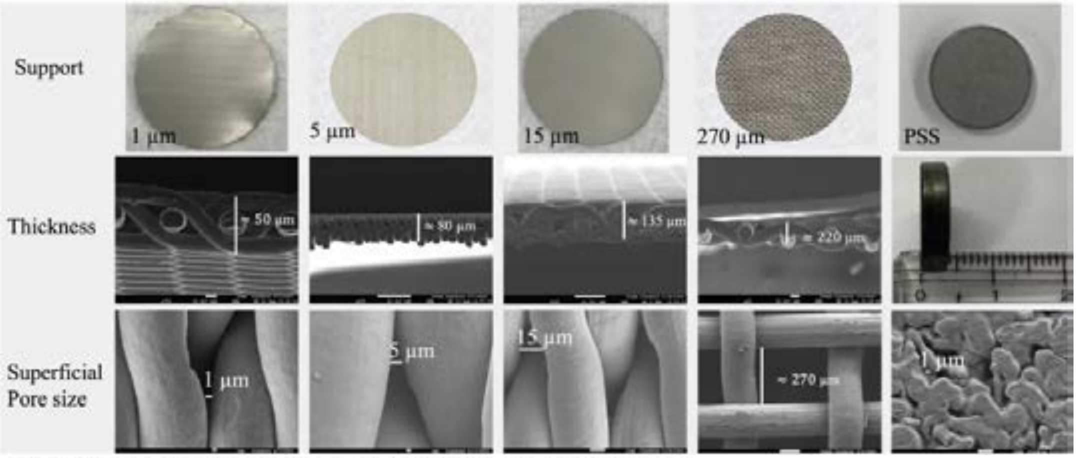


Figure 2: Concept design for H_2-selective MAWGS reactor.

The team conducted a comprehensive study to optimize the reactor design and operating conditions. These efforts have included computational fluid dynamics (CFD) simulations to understand flow patterns, temperature distributions and reaction kinetics within the reactor. Experimental validation is conducted using lab-scale testing (see Figure 3) to assess performance metrics such as hydrogen purity, yield, membrane flux, and durability under operating conditions.



Fabrication and Evaluation of Disc Membranes *(Pd-PSS support)*

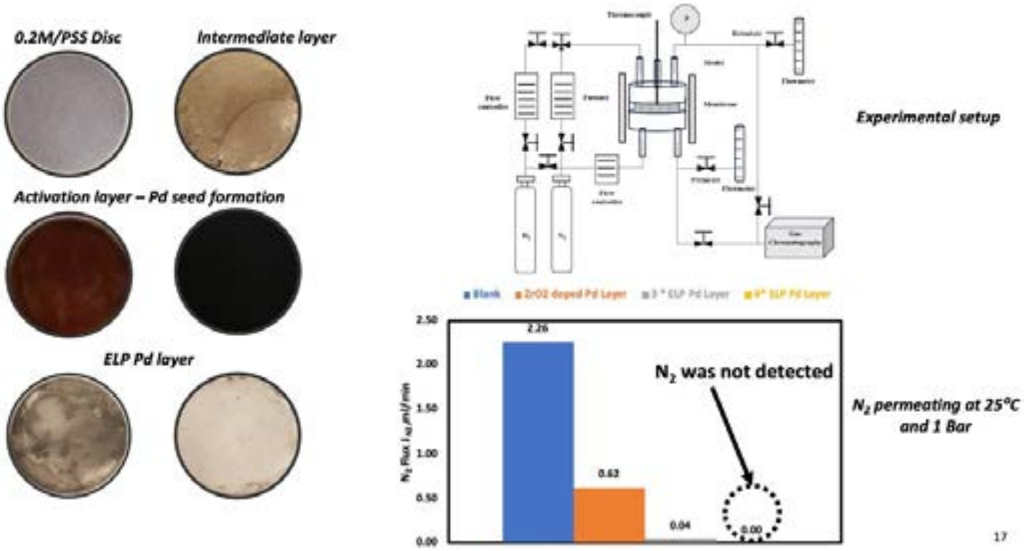


Figure 3: Evaluation of disc membranes using gas chromatography experimental setup.

The team synthesized palladium-based alloy membranes supported by porous stainless steel (PSS) substrates in seeking the best performing H_2 separation membranes for inclusion in the MAWGS reactor. Several disc membranes were characterized at different operating temperatures, including Pd-PSS support, Pd-Au (69-31 w/w%)-PSS support, Pd-Au (69-31 w/w%)-PSS support, and Pd-Au-Ag (70-26-4 w/w%)-PSS support. Testing of these membranes exhibited perfect selectivity for hydrogen, indicating their effectiveness in selectively permeating hydrogen over other gases. The choice of PSS support was crucial; smaller pore sizes led to lower hydrogen flux. Importantly, minimal CO poisoning was demonstrated with only 9% reduction in hydrogen permeation.

Membrane	Permeance, mole/m^2.sec.Pa	Ideal Selectivity
Membrane 0.5M/PSS - 100% Pd	6.95E-07	1500 - 3700
Membrane 0.2M/PSS - 100% Pd	4.14E-07	> 10^7
Binary		
Membrane 0.5M/PSS - 99% Pd, 1% Au	5.49E-07	> 10^7
Membrane 0.2M/PSS - 68.6% Pd, 31.4% Au	3.14E-07	> 10^7
Ternary		
Membrane 0.5M/PSS - 86.8% Pd, 3.1% Ag, 10.1% Au	4.40E-07	> 10^7
Membrane 0.5M/PSS - 63.1% Pd, 23.9% Ag, 13% Au	6.68E-07	> 10^7
Membrane 0.2M/PSS - 70.3% Pd, 3.3% Ag, 26.4% Au	4.96E-07	> 10^7

Table 1: Results from H_2 permeation and selectivity studies of various membrane compositions.

Techno-Economic Analysis

The current estimated results and target research and development (R&D) values for hydrogen production economics are shown in Table 2.

TABLE 2: HYDROGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Hydrogen	\$/kg H_2	2.5 – 2.8	1.8 – 2.3
Capital Expenditures	\$/kg H_2	850 – 1000	700 – 900
Operating Expenditures	\$/kg H_2	1.2 – 1.4	1.1 – 1.2

Definitions:

Cost of Hydrogen – Projected cost of capture per mass of H_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of H_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of H_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M, feedstock cost.

Other Parameter Descriptions:

Waste Streams Generated – CO_2-rich off-gas (from the CO_2 capture unit); ash and char residue (from biomass gasification); spent catalyst (from the membrane reactor).

Process Design Concept – See Figure 1.

technology advantages

- Integration of reforming and hydrogen separation into a single MAWGS reactor enhances efficiency, reduces equipment footprint and simplifies system integration.
- High-purity hydrogen production suitable for various applications, including fuel cells and industrial processes.
- Cost savings by integrating hydrogen production and separation, saving on energy and operational expense, and minimizing emissions.
- Modular and scalable design: The compact reactor design allows for modular deployment, making it adaptable to different scales of hydrogen production needs. And facilitating deployment in various settings including distributed hydrogen production facilities.

R&D challenges

- Maintaining high hydrogen permeability, selectivity and structural integrity of membranes at elevated temperatures is critical.
- Engineering challenges related to thermal management and reaction control.
- Reactor response to changing syngas composition stemming from variations of feedstocks to the upstream gasifier.
- Achieving cost-effective hydrogen production necessitates optimizing materials, processes and system designs to compete with existing technologies.

status

A ternary Pd-based membrane, Pd-Au-Ag (70-26-4 w/w%)-PSS support, shows good performance in terms of hydrogen permeation and ideal selectivity; this membrane underwent several thermal cycles, and it is still stable under reaction environment. Integrated WGS and hydrogen separation demonstration by using tubular membranes remains to be performed.

available reports/technical papers/presentations

“Metallic Membrane Reactors: An Intensified Process to Transforming the Production of Carbon-Neutral Hydrogen,” Simona Liguori, Clarkson University, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems - PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Liguori.pdf*.

“Metallic Membrane Reactors: An Intensified Process to Transforming the Production of Carbon-Neutral Hydrogen,” PI: Simona Liguori, Clarkson University, Project Review Meeting, Dec. 17, 2024.

“Metallic Membrane Reactors: An Intensified Process to Transforming the Production of Carbon-Neutral Hydrogen,” PI: Simona Liguori, Clarkson University, Project Review Meeting, Jan. 21, 2024.

Catalytic Membrane Reactors Based on Carbon Molecular Sieve Hollow Fiber Membranes for Sustainable and Modular Hydrogen Production

primary project goal

State University of New York (SUNY) Buffalo researchers are developing a process-intensification method for modular hydrogen (H_2) production from waste biomass using catalytic membrane reactors (CMRs) incorporating molecular sieve hollow fiber membranes. The CMR would selectively remove H_2 during the high-temperature water-gas shift (WGS) reaction to circumvent thermodynamic limitations on the conversion of carbon monoxide (CO) to carbon dioxide (CO_2) and H_2 in conventional WGS reactors. The work aims to enhance process efficiency, modularity and economic viability of gasification-based hydrogen production from alternative feedstocks such as waste biomass.

technical goals

- Fabricate and optimize carbon molecular sieve (CMS) hollow fiber membranes to achieve a hydrogen permeance of 1,000 GPU and an H_2/CO_2 selectivity of 100 at pressures up to 20 bar and temperatures up to 400°C.
- Create nano-catalysts with high WGS activity and stability under CMR conditions.
- Develop CMRs incorporating the CMS hollow fiber membranes and WGS catalysts and demonstrate high-temperature WGS reactions using simulated and real syngas containing hydrogen sulfide (H_2S), CO and water vapor in a 200-hour continuous bench-scale test.
- Conduct design and techno-economic analysis (TEA) based on the newly developed CMRs in an H_2 production process.

technical content

Conventionally, hydrogen production by gasification of carbonaceous feedstocks such as wastes and biomass starts with gasification, yielding syngas containing H_2 and CO (if oxygen is used in the gasifier, nitrogen content of syngas is negligible). The syngas is shifted by the WGS reaction to mostly H_2 and CO_2. Then, H_2 can be separated by a solvent-based process such as Selexol or any suitable pressure swing adsorption method. However, conventional WGS units require multiple stages for high extent of conversion, plus the solvent-based processes involve high energy penalties.

program area:
Gasification Systems

ending scale:
Bench-Scale Prototype

application:
Hydrogen Production

key technology:
Process Intensification for Syngas and Hydrogen

project focus:
Optimizing catalytic membrane reactors (CMR) for H_2 production

participant:
State University of New York (SUNY)

project number:
FE0032209

predecessor projects:
N/A

NETL project manager:
John Homer
john.homer@netl.doe.gov

principal investigator:
Haiqing Lin
State University of New York
haiqingl@buffalo.edu

partners:
Los Alamos National Lab (LANL)

start date:
10.01.2022

percent complete:
85%

In contrast, the concept under development involves integrating syngas reforming and hydrogen separation into a single, intensified process unit. This unit is termed the CMR, illustrated in Figure 1.

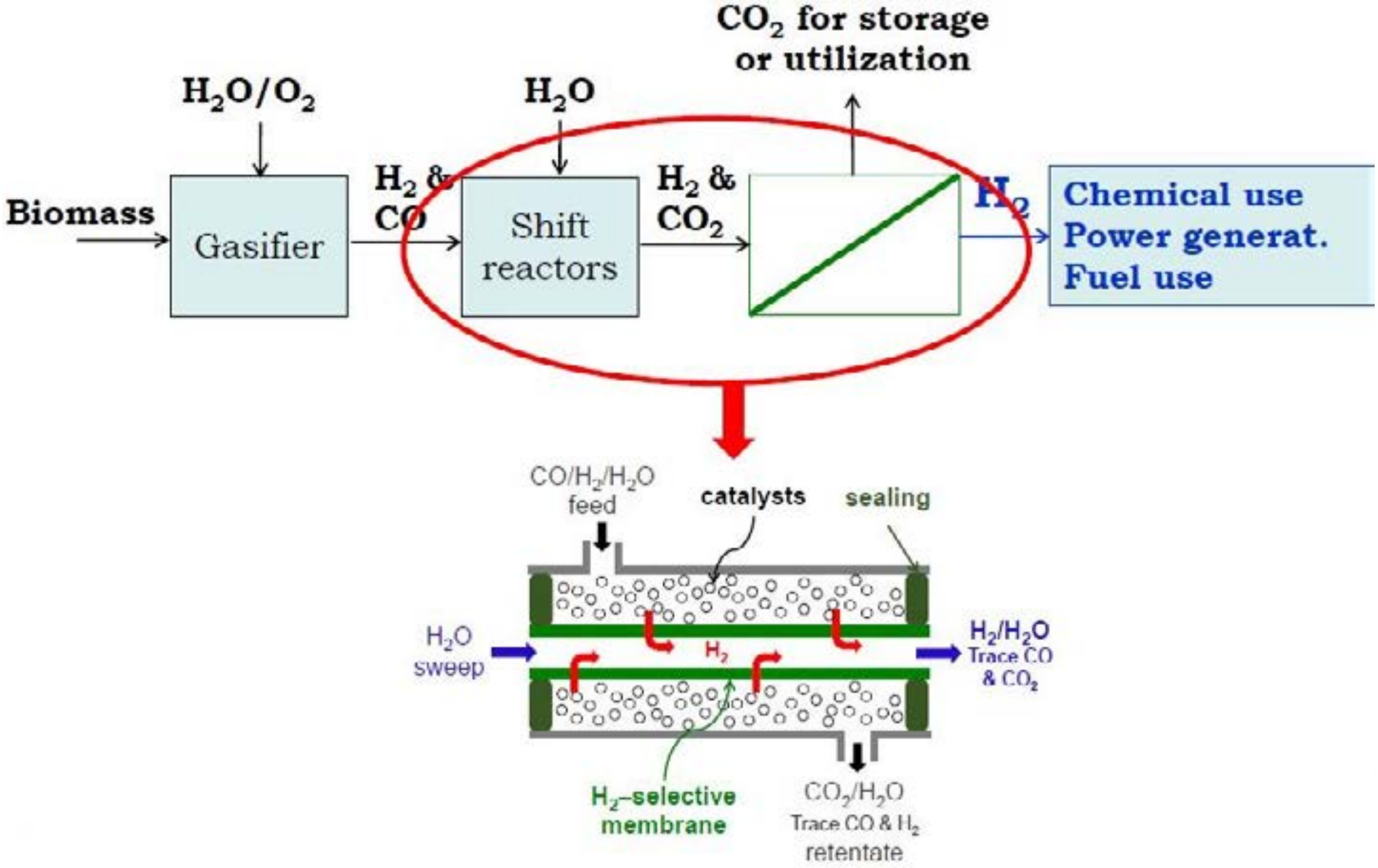


Figure 1: Concept of the catalytic membrane reactor.

The CMR routes unshifted syngas containing CO through packed WGS catalyst surrounding a hollow fiber CMS membrane. These membranes are engineered to achieve high hydrogen permeance and selectivity over CO_2, operating effectively at elevated pressures and temperatures typical of WGS reactions. As the syngas shifts to H_2 and CO_2, H_2 migrates across the membrane and is removed by steam sweep. Given adequate exposure of the syngas to the catalyst bed, CO can be thoroughly converted, leaving a stream consisting of mostly CO_2 for use or storage. The hydrogen stream can be easily dehydrated yielding the desired pure hydrogen product.

Developmental focus has featured design and optimization of the CMS hollow fiber membranes. The fabrication process involves carbonizing polybenzimidazole (PBI) hollow fibers doped with pyrophosphoric acid (PPA), resulting in membranes with a robust selective layer capable of withstanding harsh operating conditions.

Parallel to membrane development, creation of nano-catalysts with high activity and stability for the WGS reaction is essential. A flame aerosol process is being used to synthesize the solid solution nano-catalysts as depicted in Figure 2. Various Fe_2O_3-based nano-catalysts have been synthesized and evaluated, including carbon-promoted Fe_2O_3, silica-supported Fe_2O_3, nickel (Ni)-promoted metal-organic framework (MOF)-derived Fe_2O_3, and copper (Cu)-promoted Fe/SiO_2 catalysts. These catalysts are designed to facilitate efficient conversion of CO and water into hydrogen and CO_2, with a particular emphasis on maintaining performance under the integrated CMR conditions. Figure 3 shows a comparison of one of these, a (FeCrNiCoMn)Ox catalyst, to a commercial WGS catalyst. It achieved a CO conversion of 90% at 450°C after stable 50+ hours operation, much higher than that for the commercial catalyst (45%) at the same temperature.

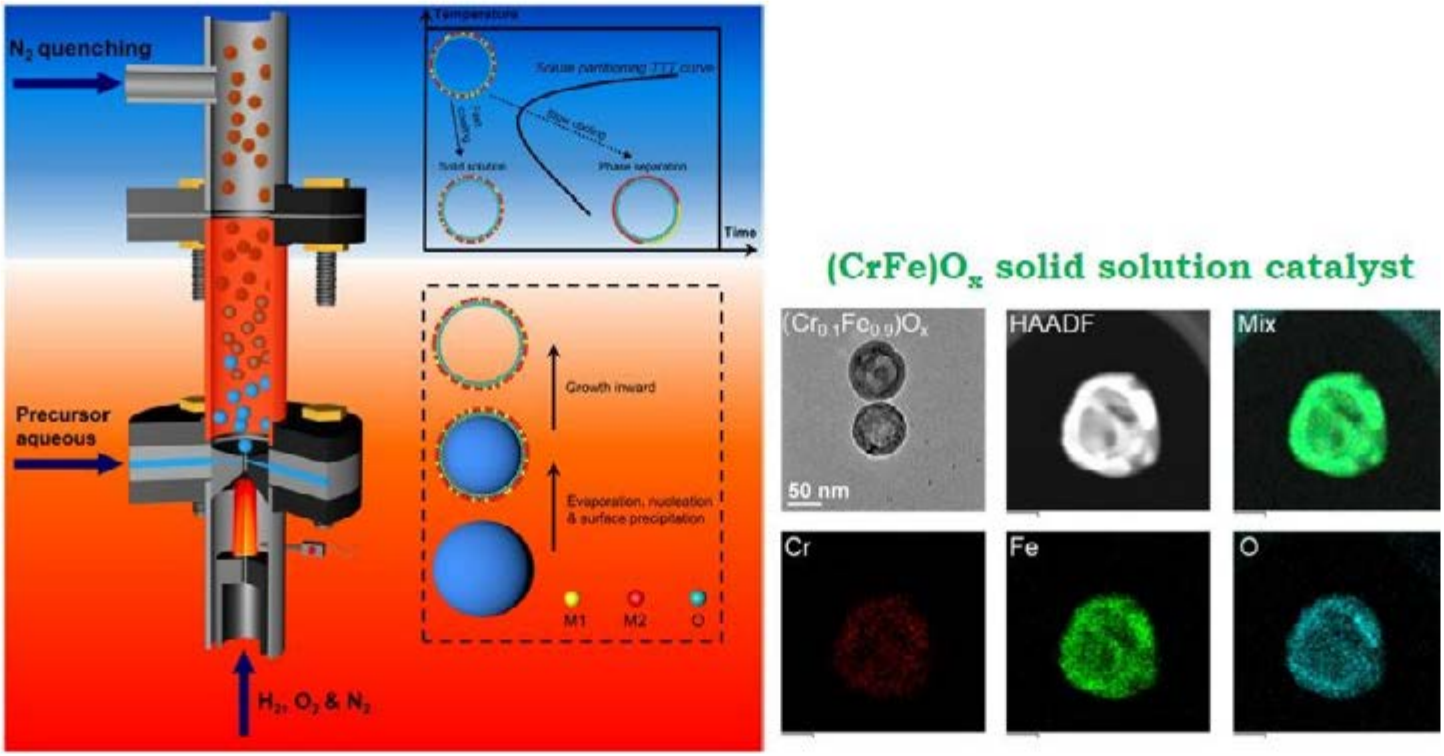


Figure 2: Nano-catalysts for the WGS reaction.

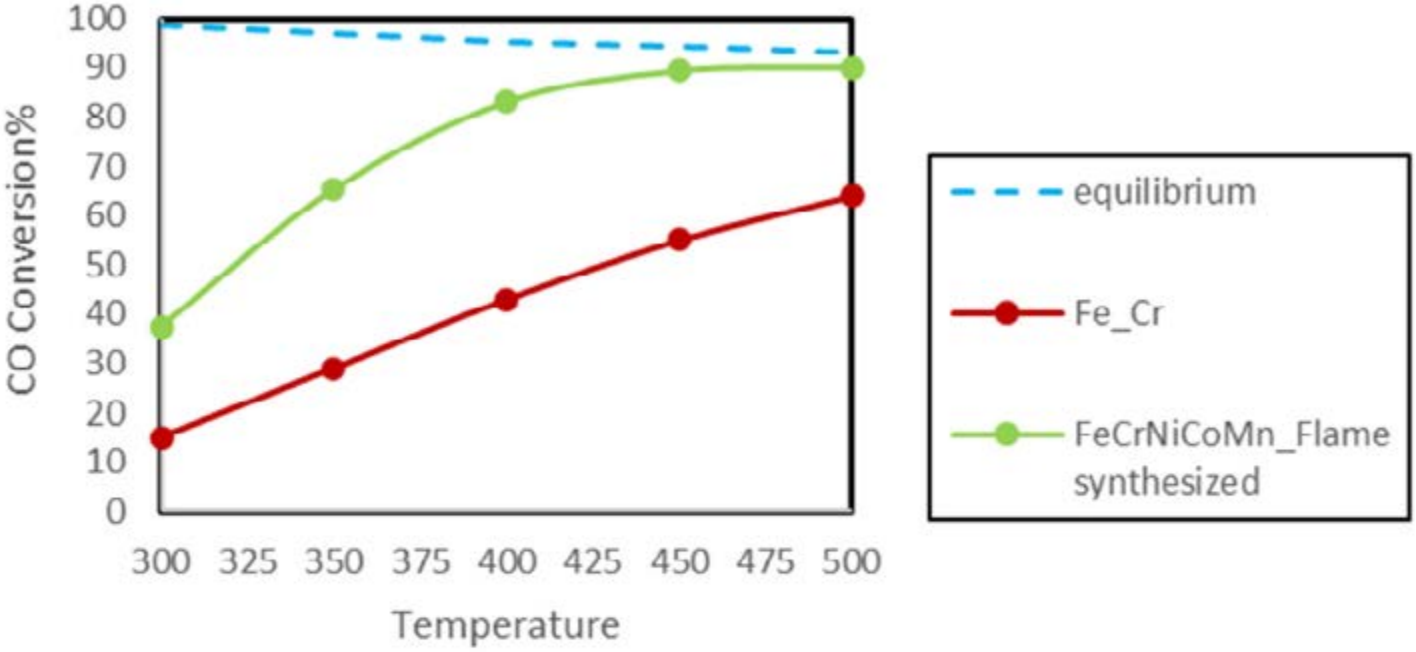


Figure 3: Comparison of a nano-catalyst with commercial WGS catalyst.

The integration of CMS membranes and nano-catalysts within the CMRs is a critical point of technology development. Integration enhances the overall efficiency of the process and enables a more compact reactor design suitable for modular applications.

The unique approach of carbonization of pyrophosphoric acid (PAA)-doped PBI allows for a hollow fiber membrane with enhanced properties. Preliminary data indicate that CMRs utilizing tubular membranes demonstrate higher CO conversion rates compared to traditional packed-bed reactors (PBRs) (see Figure 4). Simulations show that the primary advantage of CMRs is the ability to increase the dry gas hourly space velocity (DGHSV), indicating a smaller reactor volume requirement for a given hydrogen production rate. This suggests that CMRs can achieve higher throughput and efficiency, making them advantageous for scalable hydrogen production systems.

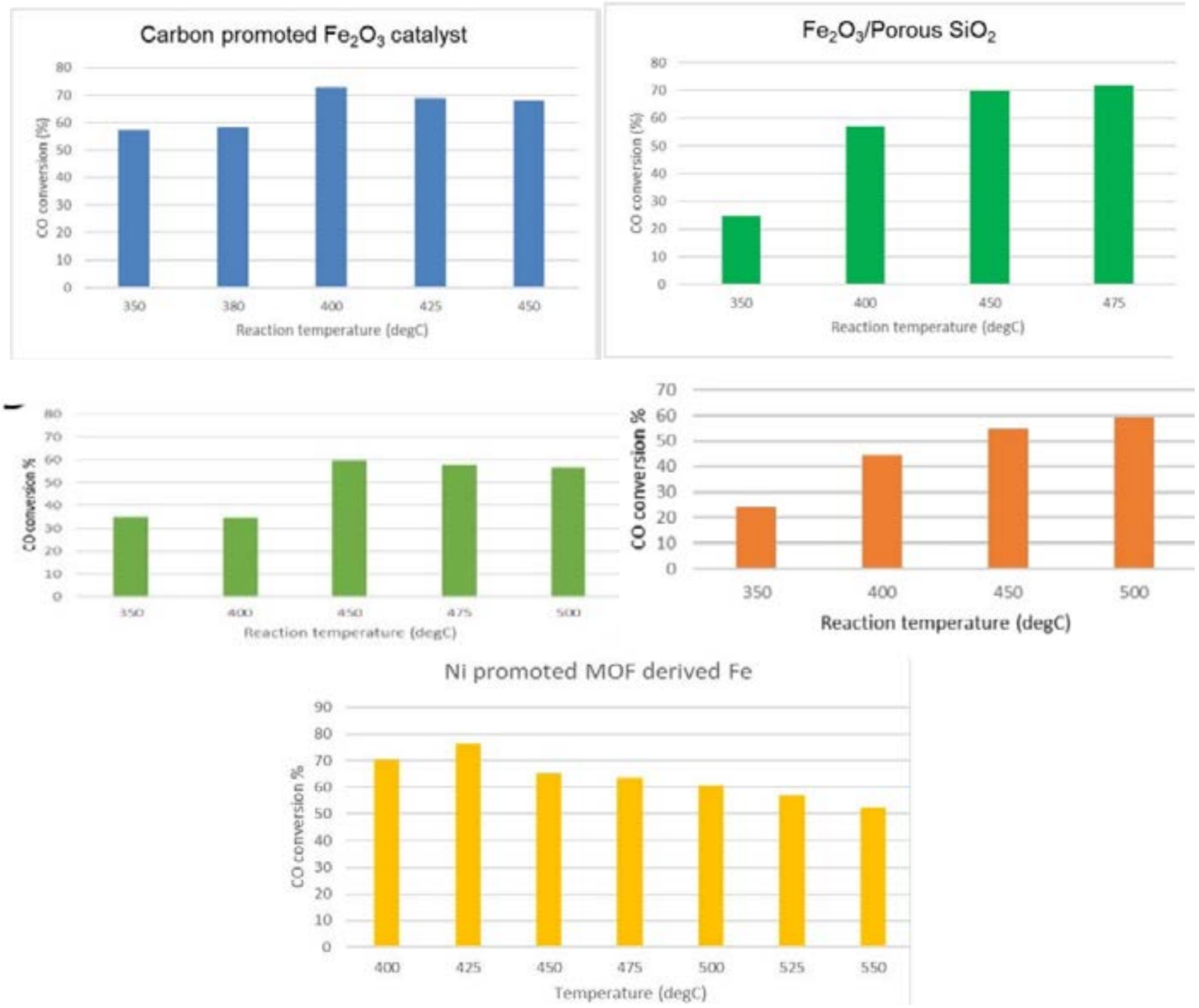


Figure 4: Results from catalyst testing, with CO conversion reaching as high as 78%.

Techno-Economic Analysis

TEA will be conducted to assess the cost-effectiveness of the integrated system, considering factors such as membrane and catalyst performance, reactor design, and operational parameters.

The current estimated results and target research and development (R&D) values for hydrogen production economics are shown in Table 1.

TABLE 1: HYDROGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Hydrogen	$/kg H_2	TBD	TBD
Capital Expenditures	$/kg H_2	TBD	TBD
Operating Expenditures	$/kg H_2	TBD	TBD

Definitions:

Cost of Hydrogen – Projected cost of capture per mass of H_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of H_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of H_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M, feedstock cost.

Other Parameter Descriptions:

Waste Streams Generated – None specified.

Process Design Concept – See Figure 1.

technology advantages

- **Process Intensification**: Integrating reaction and separation within a single reactor enhances efficiency and reduces the system footprint.
- **High-Performance Membranes**: CMS hollow fiber membranes offer high hydrogen permeance and selectivity, operating effectively under high-temperature and high-pressure conditions.
- **Advanced Catalysts**: Nano-catalysts with high WGS activity and stability improve reaction kinetics and overall hydrogen yield.
- **Modular Design**: The compact and efficient design of CMRs facilitates modular deployment, enabling scalable hydrogen production from distributed biomass sources.

R&D challenges

- **Membrane Fabrication**: Developing CMS membranes that maintain high performance and structural integrity under harsh operating conditions is a significant challenge.
- **Catalyst Integration**: Ensuring compatibility and optimal performance of nano-catalysts within the CMR environment requires careful design and testing.
- **System Integration**: Achieving seamless integration of membranes and catalysts within the reactor to optimize reaction and separation processes poses engineering challenges.
- **Economic Viability**: Conducting comprehensive TEAs to ensure the developed technology is cost-competitive with existing hydrogen production methods.

status

CMS hollow fiber membranes have been demonstrated with excellent H_2/CO_2 separation performance, meeting the target. Various Fe_2O_3-based nano-catalysts exhibit high CO conversion, and CMRs using tubular membranes should demonstrate higher CO conversions than PBRs according to simulations. Next steps include preparing multifiber membrane modules, requiring scaling up catalyst production, as well as preparing and characterizing an operable bench-scale CMR.

available reports/technical papers/presentations

"Catalytic Membrane Reactors Based on Carbon Molecular Sieve Hollow Fiber Membranes for Sustainable And Modular H_2 Production," Haiqing Lin, SUNY Buffalo, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems - PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Lin.pdf*.

"Catalytic Membrane Reactors Based on Carbon Molecular Sieve Hollow Fiber Membranes for Sustainable and Modular H_2 Production, Haiqing Lin, SUNY Buffalo, DOE Project Review Meeting, Oct. 17, 2024.

Hydrogen Production From Modular CO_2-Assisted Oxy-Blown Gasification of Waste Blends

primary project goal

Auburn University, in collaboration with Research Triangle Institute (RTI), is developing a process to produce hydrogen (H_2) from blended feedstock wastes via carbon dioxide (CO_2)-assisted oxy-blown gasification. The goal is the integration of this gasification method with novel, modular technologies for syngas cleanup and conditioning, including RTI's fixed-bed warm desulfurization process (FBWDP), trace contaminant removal process (TCRP), and advanced fixed-bed water-gas shift (AWGS).

technical goals

- Develop a process for producing high-purity (99.97%) hydrogen from blended feedstocks, including legacy waste coal, forest residues, and the organic fraction of municipal solid waste (OFMSW), via CO_2-assisted oxy-blown gasification.
- Understand the flow properties and energy requirements for preprocessing blended feedstocks to optimize gasification performance.
- Investigate the gasification behavior of these mixtures to assess syngas composition and identify potential contaminants.
- Evaluate syngas conditioning and cleanup catalysts/sorbents to ensure high-quality hydrogen production.
- Develop process models to estimate hydrogen production costs.

technical content

The technology being developed is for the production of hydrogen through CO_2-assisted oxy-blown gasification of blended feedstocks, including legacy waste coal, forest residues and OFMSW. The United States generates approximately 292 million tons of municipal solid waste (MSW) annually, with about 146 million tons landfilled and only around 10% of plastics recycled. Additionally, legacy waste coal piles, such as those in Alabama, present environmental challenges and potential energy resources. Utilizing these waste materials simultaneously addresses environmental concerns while producing clean hydrogen.

Project activities demonstrate the integration of CO_2-assisted oxy-blown gasification with novel, modular technologies for syngas cleanup and conditioning, including RTI's FBWDP, TCRP and AFWGS. These novel processes have specifically been developed for the 5–50 megawatt-electrical (MWe) scale, and thus are anticipated to reduce the cost of producing high-purity H_2 from high-volume

program area:
Gasification Systems

ending scale:
Bench scale (1 kg/hr feedstock)

application:
Hydrogen Production

key technology:
Process Intensification for Syngas and Hydrogen

project focus:
Integrate CO_2-assisted oxy-blown gasification with RTI's novel syngas cleanup technology

participant:
Auburn University

project number:
FE0032214

predecessor projects:
N/A

NETL project manager:
Richard Dalton
richard.dalton@netl.doe.gov

principal investigator:
Sushil Adhikari
Auburn University
sushil.adhikari@auburn.edu

partners:
Research Triangle Institute (RTI) International

start date:
03.01.2023

percent complete:
85%

waste materials and biomass compared with state-of-the-art conventional technologies that rely on economies of scale at very large unit sizes.

Feedstock Characterization and Preprocessing

Adequate characterization of feedstocks and feedstock preprocessing are essential for the formulation of suitable feedstock blends that can be reliably fed to the gasifier. Characterization includes proximate and ultimate analyses to determine moisture content, ash composition, calorific value and elemental composition. For instance, legacy waste coal samples have shown varying ash content (10.86% to 37.05%) and higher heating values (9,229 to 13,201 Btu/lb; see Table 1 below). Understanding these properties is crucial for optimizing gasification performance.

Property	Method	Sample 1	Sample 2	Sample 3
Ash, %	D3174	10.86	37.05	23.71
VM, %	D3175	32.11	19.90	25.27
FC, %	D3172	57.03	43.05	51.02
Sulfur, %	D4239	1.30	0.49	0.60
HHV, Btu/lb	D5865	13201	9229	11577

Source: Ray Robbins. Talladega Foundry & Machine Co Inc

Table 1: Legacy waste coal compositions.

Gasification Behavior

Carbon dioxide-assisted oxy-blown gasification enhances hydrogen yield by converting some of the CO_2 through the Boudouard reaction. Experiments helped determine optimal operating conditions for the gasifier, such as temperature, pressure and gasifying agent ratios, to maximize hydrogen production and minimize impurities from the blended feedstocks in this gasification regime. Results for syngas composition studies are displayed in Figure 1.

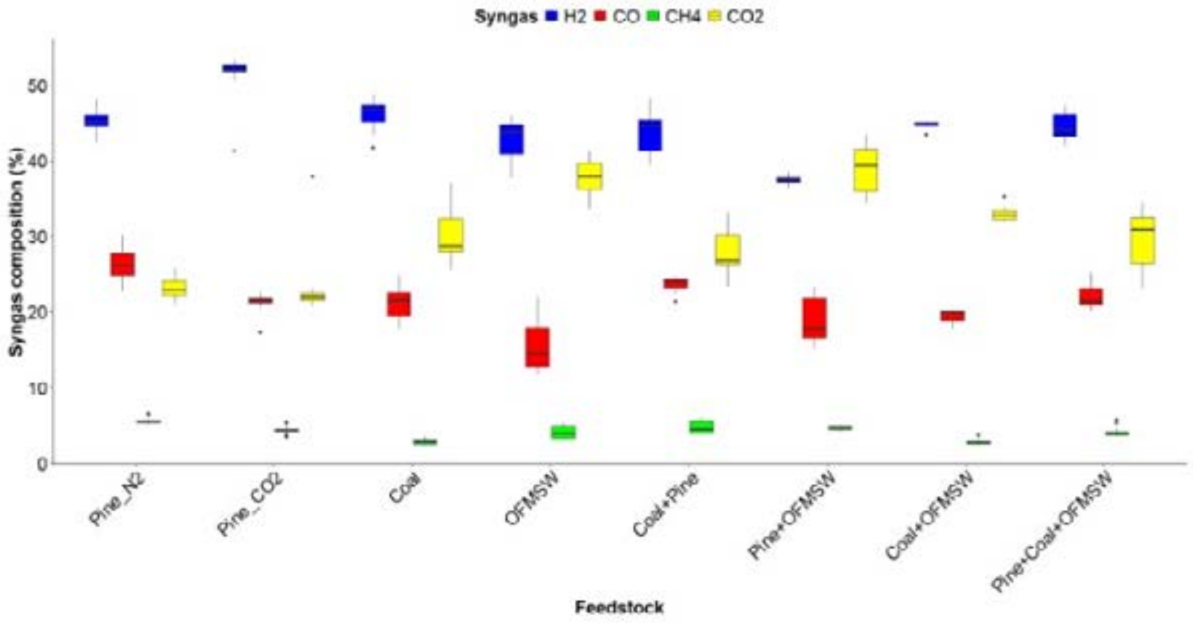


Figure 1: Syngas composition data for various feedstocks.

Syngas Conditioning and Cleanup

The gasification process yields syngas that contains contaminants such as tar, ammonia (NH_3), hydrogen sulfide (H_2S), carbonyl sulfide (COS), hydrogen chloride (HCl) and trace metal contaminants. Various catalysts and sorbents for syngas conditioning and cleanup have been evaluated for enabling high-quality hydrogen production. Techniques such as FBWDP for sulfur removal, TCRP for trace metals removal, and AFWGS reactors for syngas conditioning are tailored for syngas compositions derived from the gasification of selected feedstocks. These techniques overcome the process inefficiencies of the conventional syngas cleanup and conditioning technologies and help reduce the cost of hydrogen production.

Recent work has evaluated the performance of syngas cleanup and conditioning technologies, and has derived design parameters for integration with gasifiers for waste blends. Performance of RTI's proprietary regenerable sorbents for FBWDP and TCRP, and a commercially available water-gas shift (WGS) catalyst for syngas conditioning, have been studied to optimize the design parameters for syngas cleanup and conditioning process.

FBWDP uses a proprietary regenerable sorbent for sulfur removal at high temperatures (450–650°C), which are closer to gasifier outlet temperatures and thus can be easily integrated with the biomass gasification process. The desulfurization of sour syngas effectively eliminates up to 99% of sulfur compounds present, including H_2S and COS. The sorbent employed in the adsorber can be regenerated at temperatures of 600°C using a mixture of air and nitrogen (N_2) or the regenerator off-gas (ROG) as a diluent, maintaining near-ambient pressures. ROG leaving the sorbent regenerator contains sulfur dioxide (SO_2) that can be converted to elemental sulfur or treated using caustic scrubbing to produce gypsum. Figure 2 shows the baseline testing data curves for the sorbent sulfidation (Figure 2a) and regeneration (Figure 2b) steps involved in FBWDP syngas desulfurization cycle. Baseline testing exhibited greater than 90% sulfur removal. RTI is currently working to optimize the sorbent synthesis recipe to achieve up to 99% sulfur removal.

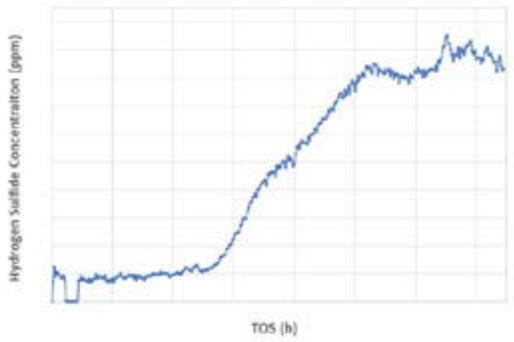


Figure 2a: FBWDP sorbent sulfidation curve.

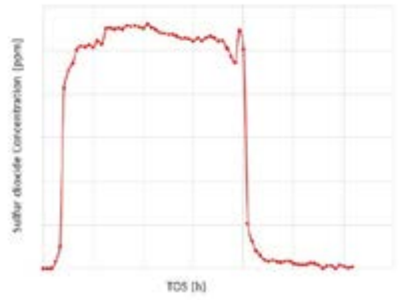


Figure 2b: FBWDP sorbent sulfidation curve.

A commercial WGS catalyst was evaluated at different feed syngas compositions (2:1 and 3: 1 steam to carbon monoxide [CO] ratio) as a function of reaction temperature (300–425°C) to identify the optimum reaction conditions to achieve high activity and stability for high-temperature shift reaction. Activity tests were conducted over a range of reaction temperatures by studying each temperature data point for four to eight hours. Stability tests were conducted for a specific syngas composition, reaction temperature and pressure for 100 hours on stream to achieve a steady catalyst performance. Figures 3 and 4 summarize the high-temperature shift and medium-temperature shift catalyst testing results for the activity and stability tests. These results indicate the trade-off between higher catalyst lifetime at steam-to-CO ratio of 5:1 that can help lower catalyst replacement cost, but also higher cost for shift steam at steam-to-CO ratio of 5:1.

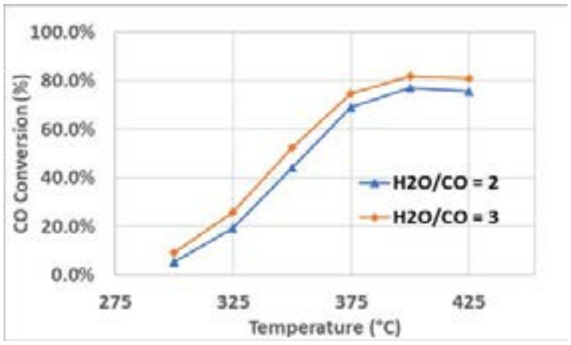


Figure 3a: High-temperature shift stability testing results at 400°C and 100 psig.

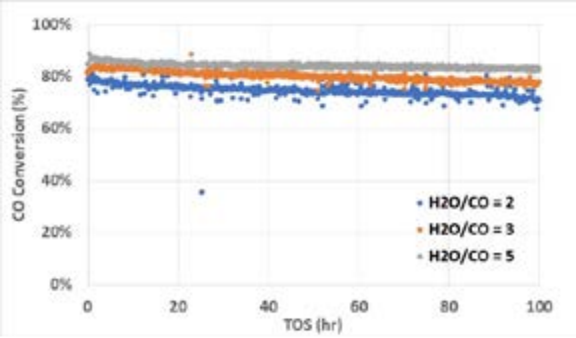


Figure 3b: High-temperature shift stability testing results at 400°C and 100 psig.

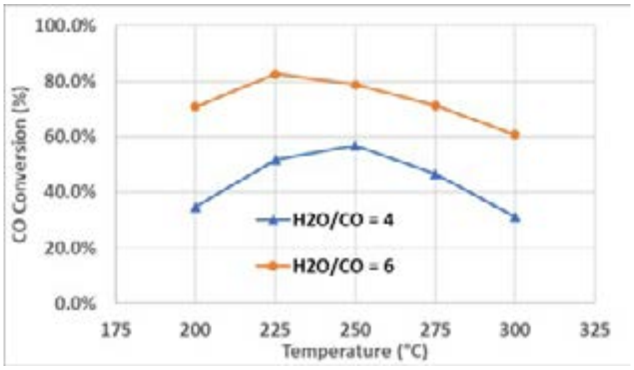


Figure 4a: Medium-temperature shift activity testing results at 100 psig.

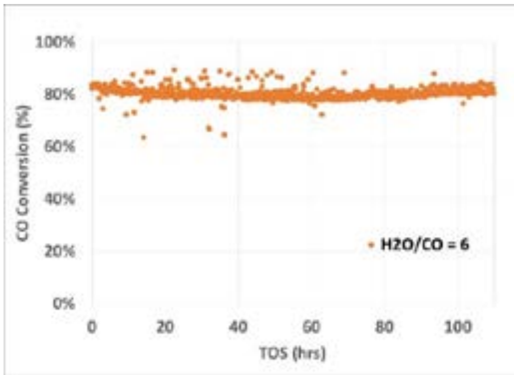


Figure 4b: Medium-temperature shift stability testing results at 225°C and 100 psig.

Mercury retention capacity was determined for TCRP candidate sorbents at an exposure temperature of 200°C using a reducing atmosphere containing simulated syngas components. The candidate sorbents included Supelco FSTM, which is an iodinated charcoal previously marketed to determine mercury emissions from stationary sources using U.S. Environmental Protection Agency (EPA) methodology. For TCRP applications to syngas, the mercury present is anticipated to be in the elemental form because of the reducing environment of the syngas and efficient capture, or removal, at elevated temperatures is highly desirable to preserve the value of the gas produced. Figure 5 presents the mercury removal breakthrough curve for FSTM sorbent. The removal efficiency reached 99.5%, which was the greatest efficiency that could be calculated based on the 20-minute QC cartridge sampling time, but there was a lag of about 1,500 minutes at the beginning of the exposure before that efficiency was realized.

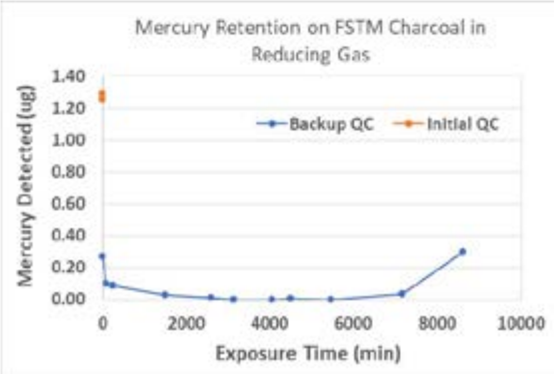


Figure 5: Mercury breakthrough curve for FSTM exposed to mercury in reducing gas.

RTI synthesized and characterized five sulfur sorbents, with pending testing and optimization of the conditions for sulfur removal. RTI studied the advanced WGS reaction using the Shift Max 120 catalyst, identifying an optimal temperature of 400°C and a steam-to-CO ratio of 3:1. Further optimization regarding the pressure effect is still needed. RTI compared the mercury removal performance of two sorbents at 200°C, finding that Supelco FSTM iodinated charcoal achieved more than 99% removal, outperforming Carulite. Auburn University screened tar reforming catalysts for MSW raw syngas cleanup and plans further tests. Both Auburn University and RTI are collaborating effectively to develop a methodology for syngas cleanup, targeting 99.97% hydrogen purity.

Techno-Economic Analysis

Techno-economic analyses (TEA) compares clean hydrogen production from conventional processes with the proposed process using waste blends. The analyses consider factors such as capital and operating costs (CAPEX and OPEX), feedstock availability, and hydrogen market prices. Results suggest emerging technologies can achieve about 16% reduction in hydrogen production cost (2.94$/kg to 2.47$/kg), approximately 22% reduction in CAPEX, and approximately 23% reduction in OPEX (fixed and variable). Feedstock cost was identified as a significant impactor of hydrogen production cost. Future analyses will involve sensitivity analysis to capture the impact of various cost components on the cost of hydrogen. Feedstock Cost: Biomass — $40/ton, Plastics — $100/ton, Coal — $36/ton production (COP).

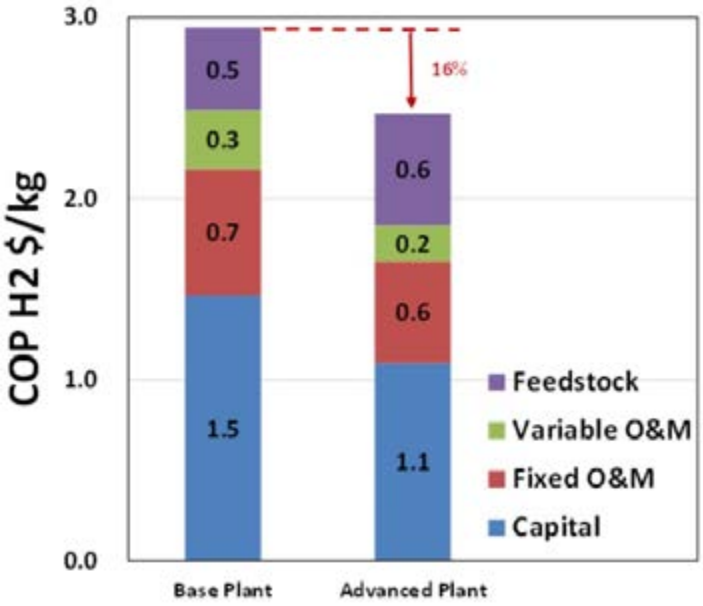


Figure 6: Relative price contributions based on TEA.

The current estimated results and target research and development (R&D) values for hydrogen production economics are shown in Table 2.

TABLE 2: HYDROGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Hydrogen	$/kg H_2	2.47	2.00
Capital Expenditures	$/kg H_2	1.09	0.87
Operating Expenditures	$/kg H_2	1.38	1.13

Definitions:

Cost of Hydrogen – Projected cost of capture per mass of H_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of H_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of H_2 produced. It could be split into variable operations and maintenance (O&M), fixed O&M, and feedstock cost.

Other Parameter Descriptions:

Waste Streams Generated – Tar is generated in the gasification, causing quick deactivation of the WGS and TMRP, yet this is speculation and has not been worked on the integrated system. The team is evaluating several commercial tar reforming catalysts for addressing the tar issue.

Process Design Concept – The proposed gasification and syngas-to-hydrogen is shown in Figure 7.

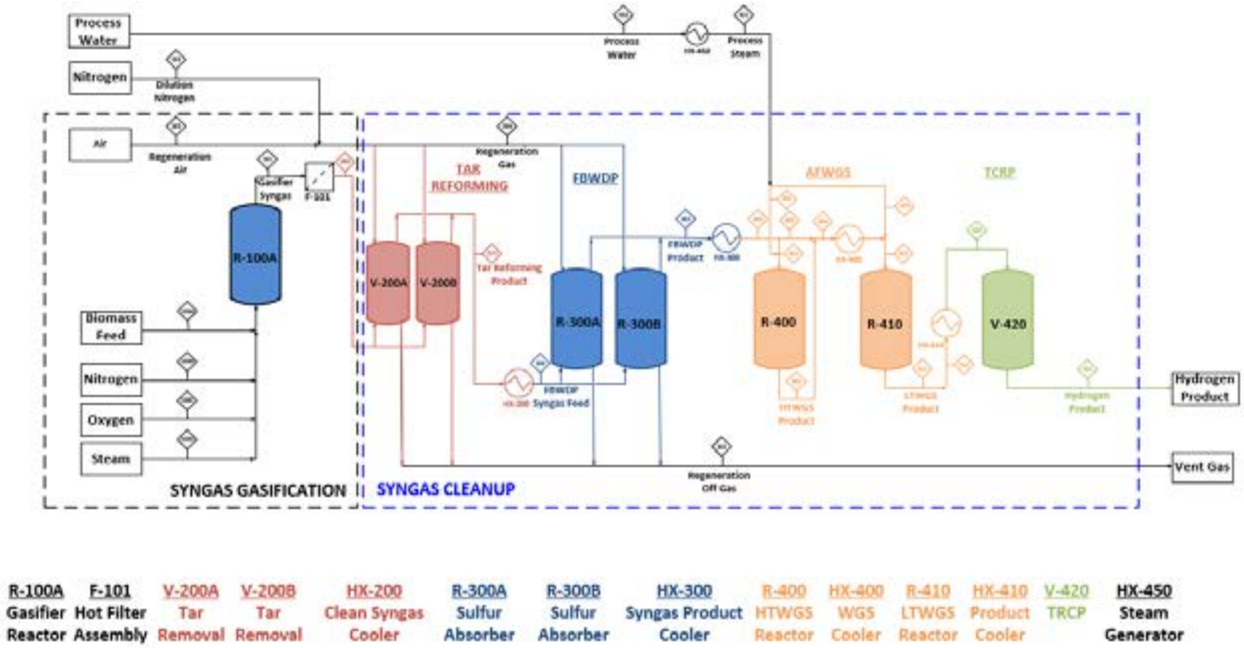


Figure 7: Process flow diagram for biomass-to-hydrogen process.

Technology advantages

- Waste Utilization: The process converts various waste materials, including legacy waste coal and MSW, into valuable hydrogen, addressing environmental concerns and reducing landfill usage.
- CO_2-Assisted Gasification: Utilizing CO_2 in the gasification process can enhance hydrogen yield and improve carbon efficiency, contributing to greenhouse gas reduction efforts.
- Integrated Syngas Cleanup: The development of tailored catalysts and sorbents for syngas conditioning ensures the production of high-purity hydrogen suitable for various applications.
- Economic Potential: By leveraging low-cost, abundant waste feedstocks, the process has the potential to produce hydrogen at a competitive cost, supporting the goal of $1 per kilogram of clean hydrogen.

R&D challenges

- Feedstock Variability: The heterogeneous nature of waste materials poses challenges in maintaining consistent gasification performance and syngas quality.
- Contaminant Management: Effectively removing contaminants such as sulfur compounds, tar and particulates from the syngas stream is critical to prevent catalyst deactivation and ensure high-purity hydrogen production.
- Process Optimization: Identifying optimal operating conditions for the CO_2-assisted oxy-blown gasification process requires extensive experimentation and modeling to balance hydrogen yield, efficiency and economic viability.
- Scale-Up and Integration: Transitioning from laboratory-scale experiments to commercial-scale operations involves addressing engineering challenges related to reactor design, heat integration and process control.

status

Ten feedstock blends have been synthesized by varying ratios of waste coal, organic fraction of municipal solid waste (OFMSW), and pine residues, and gasification experiments that optimized hydrogen levels in the raw syngas have been conducted. Additionally, RTI tested proprietary catalysts for sulfur removal. RTI has identified the optimal temperature (400°C) shift for the advanced WGS reaction for the shift max-120 catalyst. RTI's investigations showed that Supelco FSTM iodinated charcoal effectively removed more than 99% of mercury from syngas. Studies have demonstrated that integrating gasification with effective syngas cleanup can enhance hydrogen purity beyond 99%, leading to a more sustainable hydrogen production process. The anticipated outcomes include achieving continuous operation for 100 hours at a feedstock processing rate of 1 kg per hour, significantly contributing to the efficiency and sustainability of hydrogen production.

available reports/technical papers/presentations

Hydrogen Production from Modular CO_2 Assisted Oxy-Blown Gasification of Waste Blends, Sushil Adhikari, Auburn University, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems - PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Adhikari.pdf*.

Advanced Air Separation Unit (ASU) for Low-Cost H_2 Production via Modular Gasification

primary project goal

TDA Research is developing a high-purity oxygen (O_2) separation process based on novel sorbents that will be utilized in a two-stage, modular, vacuum pressure swing adsorption (VPSA) and pressure swing adsorption (PSA) system.

technical goals

- Develop a modular, sorbent-based air separation unit (ASU) to produce high-purity oxygen (target of greater than 99.5%) for efficient hydrogen production via gasification.
- Synthesize and optimize advanced sorbents for nitrogen and argon (Ar) removal to enable oxygen purification.
- Design, fabricate and validate a prototype capable of producing 10 kg/day of high-purity oxygen.
- Demonstrate durability of the sorbent in process context over 10,000 cycles.
- Design a system suitable for use with 5-to-50-megawatt (MW) gasification systems for hydrogen production at reduced costs and compare against cost of conventional cryogenic air separation systems.

technical content

The technology under development is an advanced ASU that utilizes a two-stage adsorption process to produce high-purity oxygen, essential for efficient hydrogen production through modular gasification of biomass and waste materials (see Figure 1). In the first stage, a VPSA unit operation generates oxygen with a purity of 93% to 95%. TDA Research has previously developed a VPSA system for medical oxygen applications, utilizing layered beds of silver-exchanged lithium low-silica X (AgLiLSX) and lithium low-silica X (LiLSX) zeolites. This configuration enhances nitrogen adsorption capacity, resulting in a 15% to 20% improvement in performance compared to traditional systems. The second stage increases oxygen purity to greater than 98% up to 99.5% by removing argon and other impurities. This is achieved through a PSA process using silver zeolite (AgZ) to selectively adsorb Ar, and carbon molecular sieve (CMS) or zeolite sorbent for selective O2 adsorption.

program area:
Gasification Systems

ending scale:
Bench Scale (2 kg oxygen sorbent)

application:
Hydrogen Production

key technology:
Air Separation Technology

project focus:
Advancing TDA's two-stage oxygen separation technology

participant:
TDA Research Inc.

project number:
FE0032328

predecessor projects:
N/A

NETL project manager:
John Homer
john.homer@netl.doe.gov

principal investigator:
Gökhan Alptekin
TDA Research Inc.
galptekin@tda.com

partners:
University of Alberta

start date:
10.01.2023

percent complete:
80%

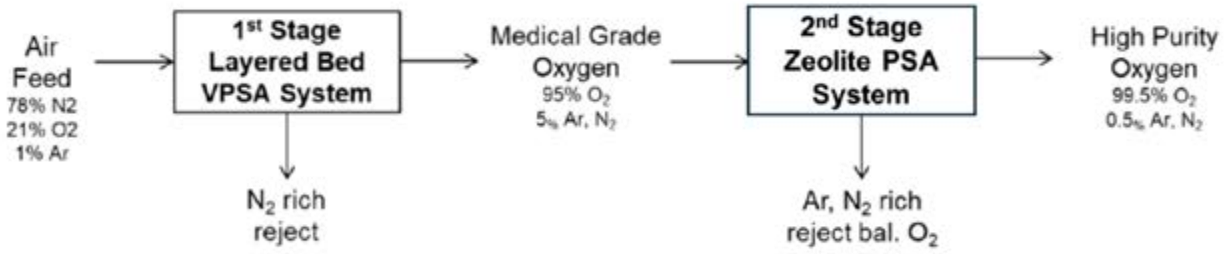


Figure 1: Two-stage adsorption process developed by TDA Research.

Sorbent Synthesis and Optimization

Sorbents are being developed with tailored pore sizes to maximize nitrogen and argon selectivity, thereby enhancing the efficiency of both VPSA and PSA processes. The sorbent's pore size is meticulously tuned to selectively adsorb oxygen over argon, leveraging the slight differences in molecular diameters (O_2: 3.5 Å; Ar: 3.7 Å). TDA is working on reproducing results from the literature on synthesizing reduced pore zeolite (RPZ) materials. The pore sizes of RPZ materials can be tuned via the choice of halogen atoms in the crystal structure at bridging O7 crystallographic sites (see Figure 2). This creates a molecular sieving effect based on the size of the halogen (fluorine [F], chlorine [Cl] and iodine [I]) and the size of the adsorbate molecule.

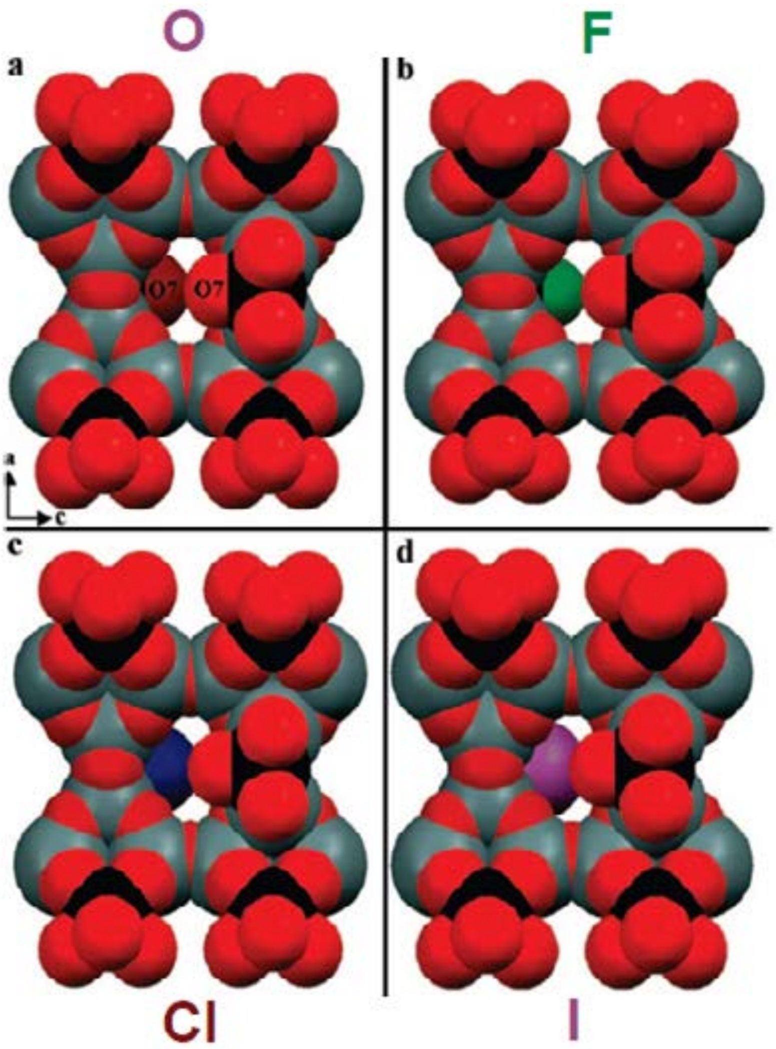


Figure 2: RPZ pore size tuning enabling gas selectivity.

RPZs are crystallized from combining their components into a homogeneous gel followed by thermal treatment at around 200°C for at least 16 hours. TDA synthesized a barium-exchanged RPZ containing both Cl and I at the O7 bridge, termed Ba RPZ-2. This sorbent was found to have satisfactory gas selectivity of greater than 10.4 (compared against a benchmark CMS selectivity of 7.8).

Prototype Design and Fabrication

ASU cycling was optimized by process simulations. A four-step processing cycle was modeled (see Figure 3) for purification of oxygen by removal of Ar.

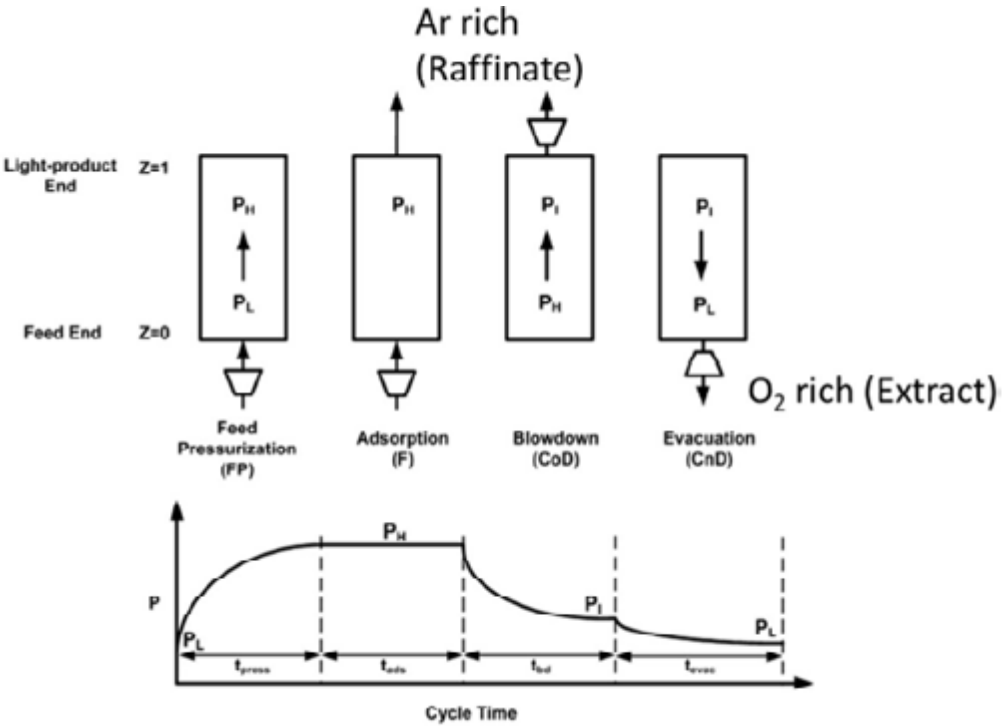


Figure 3: Four-step cycle for oxygen purification.

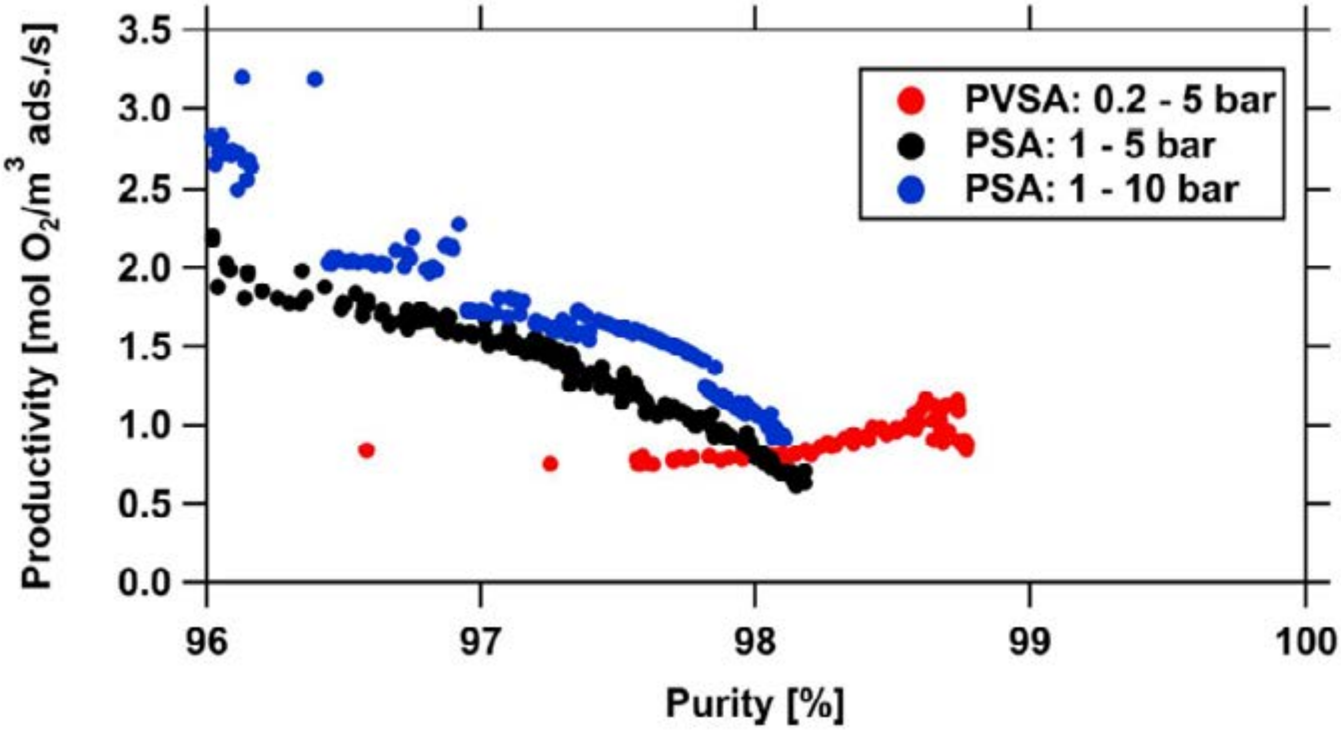


Figure 4: Oxygen productivity versus purity for four-step cycle.

Productivity values of approximately 1 mol O_2/m^3s for VPSA 0.2–0.5 bar indicate that greater than 98% pure oxygen could be produced in the optimized cycle (see Figure 4). Using the best adsorbent Ba RPZ-2 with current performance characteristics would require a 3.6 L sorbent bed size (1.8 kg of Ba RPZ-2) for a 10 kg/day prototype.

Techno-Economic Analysis (TEA)

Evaluating the economic feasibility of the developed ASU involves comparison to conventional cryogenic air separation systems, considering factors such as capital expenditure (CAPEX), operational expenditure (OPEX) and overall cost of oxygen production. Preliminary TEA results indicate that TDA's two-stage adsorption approach offers a significant reduction in oxygen production costs, estimated at $55 per ton, compared to $115 per ton for traditional cryogenic systems. Additionally, the modular design of the ASU is projected to reduce the facility footprint by more than 20% at a 30-ton/day oxygen production scale, aligning with the needs of a 5-MW gasifier module.

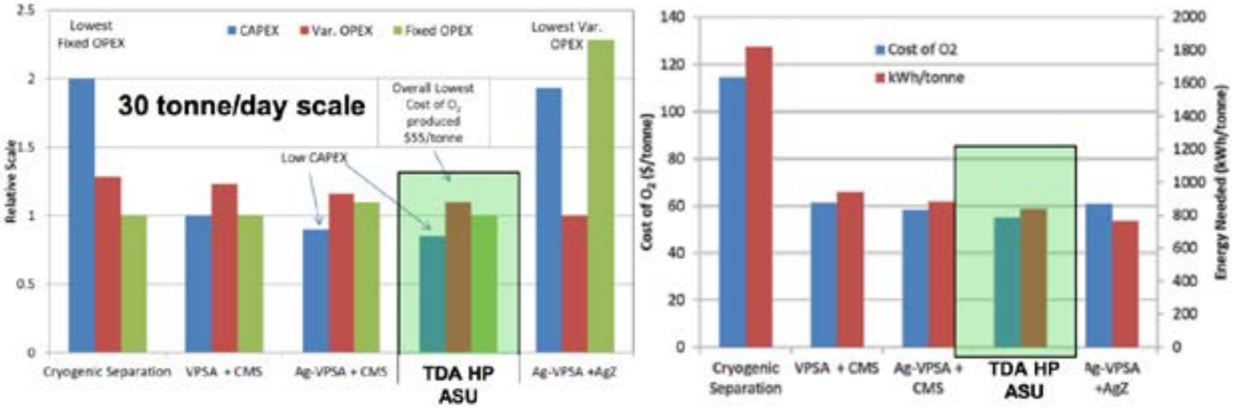


Figure 5: Results from preliminary TEA.

The current estimated results and target research and development (R&D) values for oxygen production economics are shown in Table 1.

TABLE 1: OXYGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Oxygen	$/kg O_2	TBD	TBD
Capital Expenditures	$/kg O_2	TBD	TBD
Operating Expenditures	$/kg O_2	TBD	TBD

Definitions:

Cost of Oxygen – Projected cost of capture per mass of O_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of O_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of O_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M.

Other Parameter Descriptions:

Waste Streams Generated – None specified.

Process Design Concept – See Figure 1.

technology advantages

- The sorbent-based ASU offers a lower CAPEX and OPEX compared to cryogenic systems, reducing the overall cost of oxygen production.
- The compact and scalable design allows for flexible integration with various gasification systems, accommodating different production scales and facilitating distributed hydrogen production.
- The adsorption-based process consumes less energy than cryogenic distillation, contributing to a more sustainable and economical operation.
- The system's design enables quicker startup times, enhancing operational flexibility and responsiveness to demand fluctuations.

R&D challenges

- Creating sorbents with optimal pore structures that maintain high selectivity and capacity over extended cycles is critical for sustained performance.
- Balancing adsorption and desorption parameters to maximize efficiency while minimizing energy consumption requires precise control and understanding of the process dynamics.
- Ensuring seamless integration of the ASU with existing gasification units involves addressing engineering challenges related to pressure management, flow rates and thermal compatibility.

status

Durability testing is still needed to demonstrate sorbent stability and performance over 10,000 adsorption-desorption cycles, ensuring long-term operational viability. Complete full-scale system design is in process, involving designing a scalable, modular ASU system suitable for integration with 5-to-50-MW gasification units, facilitating flexible deployment across various hydrogen production facilities.

available reports/technical papers/presentations

"Advanced Air Separation Unit (ASU) for Low-Cost H_2 Production via Modular Gasification," Ambal Jayaraman, TDA Research, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems - PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Jayaraman.pdf*.

"Advanced Air Separation Unit (ASU) for Low-Cost H_2 Production via Modular Gasification," Gökhan Alptekin, TDA Research, Annual Briefing, Oct. 18, 2024.

High-Purity Oxygen Generation Through Modular Structured Rapid Pressure Swing Adsorption (RPSA)

primary project goal

Susteon Inc. is developing a novel, single-stage dual-layer advanced air separation technology for a modular oxygen production system. The technology is based on a microporous, nitrogen (N_2)-selective lithium-exchanged X-type (LiX) zeolite-containing fiber adsorbent layered with an argon-selective carbon molecular sieve (CMS)-structured fiber adsorbent to separate nitrogen and argon from air via rapid pressure swing adsorption (RPSA), yielding high-purity oxygen.

technical goals

- Develop a novel RPSA process to produce high-purity oxygen (greater than 95%) at a cost of less than $45 per ton.
- Fabricate fiber-structured adsorbents to enhance adsorption efficiency and reduce pressure drop.
- Integrate a two-layer fiber RPSA architecture in a module delivering the required oxygen purity.

technical content

Susteon's technology development is focusing on innovations over commercial vacuum pressure swing adsorption (VPSA) based on LiX zeolite beads. VPSA operates by exposing a bed of sorbent to air at pressure; the sorbent adsorbs mainly nitrogen, leaving a stream of relatively pure oxygen. When saturated, the sorbent bed is cycled under vacuum to expel the adsorbed nitrogen, and small amounts of water and carbon dioxide (CO_2) (see Figure 1). VPSA units, typically ranging from 5 to 250 TPD, are well-suited for smaller and modular applications that conventional cryogenic air separation units (ASUs), with their typical size range of 1,000 to 4,000 TPD, cannot accommodate. However, commercial VPSA oxygen (O_2) production is limited to approximately 90%-pure O_2, with costs of $50-$80/ton. Power consumption from the large pressure swings required is significant, contributing to approximately 50% of O_2 production cost; moreover, these units suffer from poor operational reliability.

In contrast, Susteon is providing a technological alternative in the form of fiber-structured adsorbents, specifically zeolite and CMS adsorbents in fiber form for VPSA units. Fiber adsorbents reduce pressure drop, attrition and dusting that occur with conventional zeolite beaded bed systems (see Figure 2). The fibrous structure allows for rapid adsorption cycles, enhancing throughput and efficiency. This is termed the RPSA process.

program area:
Gasification Systems

ending scale:
Bench scale pilot (10 kg oxygen production per day)

application:
Hydrogen Production

key technology:
Air Separation Technology

project focus:
Develop novel air separation technology for clean syngas

participant:
Susteon Inc.

project number:
FE0032335

predecessor projects:
N/A

NETL project manager:
John Homer
john.homer@netl.doe.gov

principal investigator:
Dr. James Zhou
Susteon Inc.
sjz@susteon.com

partners:
Georgia Institute of Technology

GENERON USA

start date:
10.01.2023

percent complete:
60%

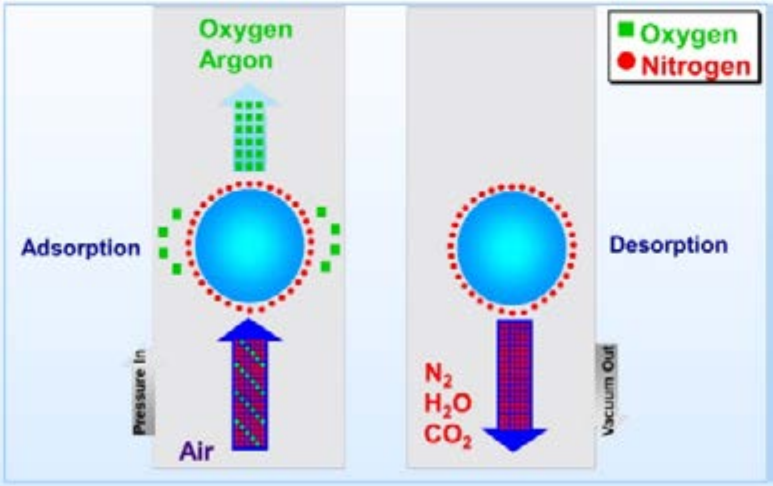


Figure 1: Commercial vacuum pressure swing adsorption.

Figure 2: VPSA commercial beaded sorbents (left) versus innovative fiber-based (right).

The RPSA technology under development incorporates two-layer fiber adsorbents to increase the purity of O_2 produced (see Figure 3). The first layer utilizes LiX zeolite fibers to adsorb nitrogen, while the second layer employs adsorbents such as AgX zeolite or CMSs to selectively remove argon. This layered approach effectively increases O_2 purity by targeting specific impurities (mainly argon). Preliminary laboratory testing demonstrated that the single-fiber RPSA system could achieve high than 90% O_2 purity with a bed size factor of 360 lb/ton per day and an O_2 recovery rate of 67.4%. However, by combining LiX and CMS fibers into the two-fiber configuration, O_2 purity up to 98.4% could be achieved with a bed size factor of 141 lb/ton per day and an O_2 recovery rate of 58.3%.

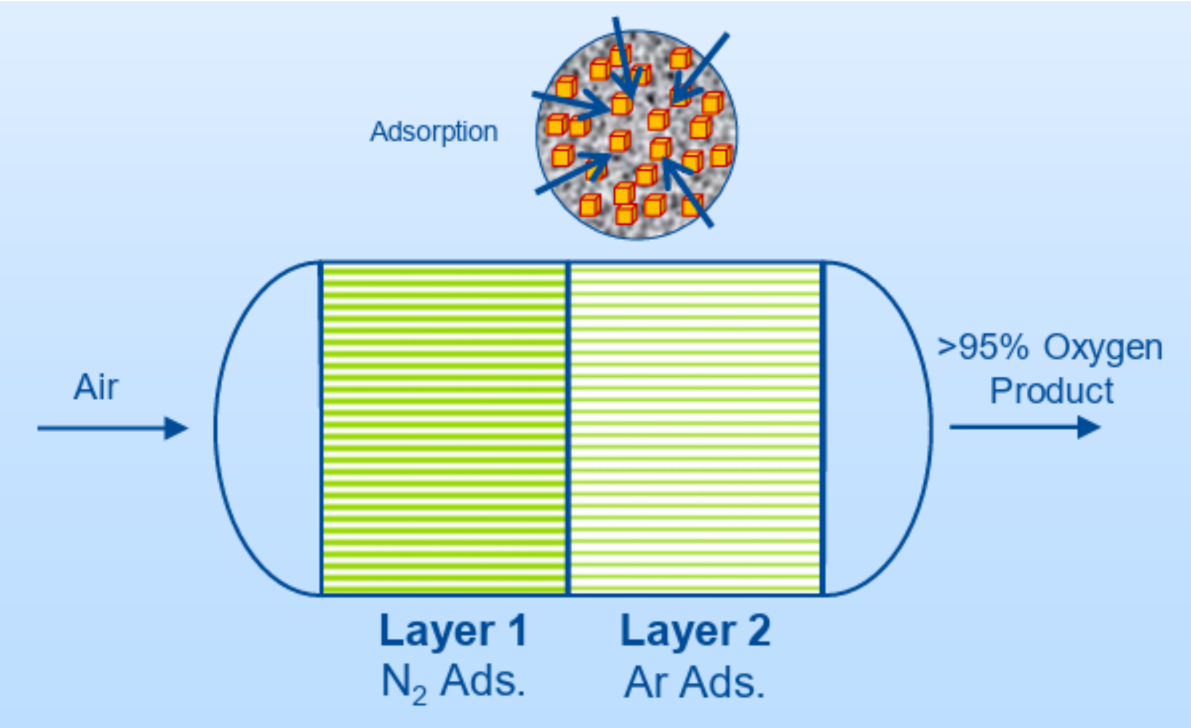


Figure 3: High-purity O_2 through two-layer fiber RPSA.

Efforts have been made to develop and optimize cost-effective polymer binders for the fiber adsorbents. Although Matrimid has proven effective, its high cost prompted the investigation of alternative polymers. Hybrid polymer binders combining cheaper polymers with small amounts of Matrimid have shown promising performance. This approach has shown to reduce the overall fiber production costs by more than 90% without compromising adsorption efficiency. Multiple LiX-polymer fibers were successfully prepared in the lab with LiX ≥ 80 wt%. Both LiX/P-1 and LiX/(P-2 + Matrimid) fibers show promising N_2 uptakes, N_2/O_2 selectivity, and thermal stability (see Figure 4). Hybrid polymer binders with addition of small amounts of Matrimid enhances performance, which can significantly reduce the overall fiber adsorbents cost. The LiX fiber adsorbent is currently being scaled up to kilogram scale using a pilot spinning line at GENERON.

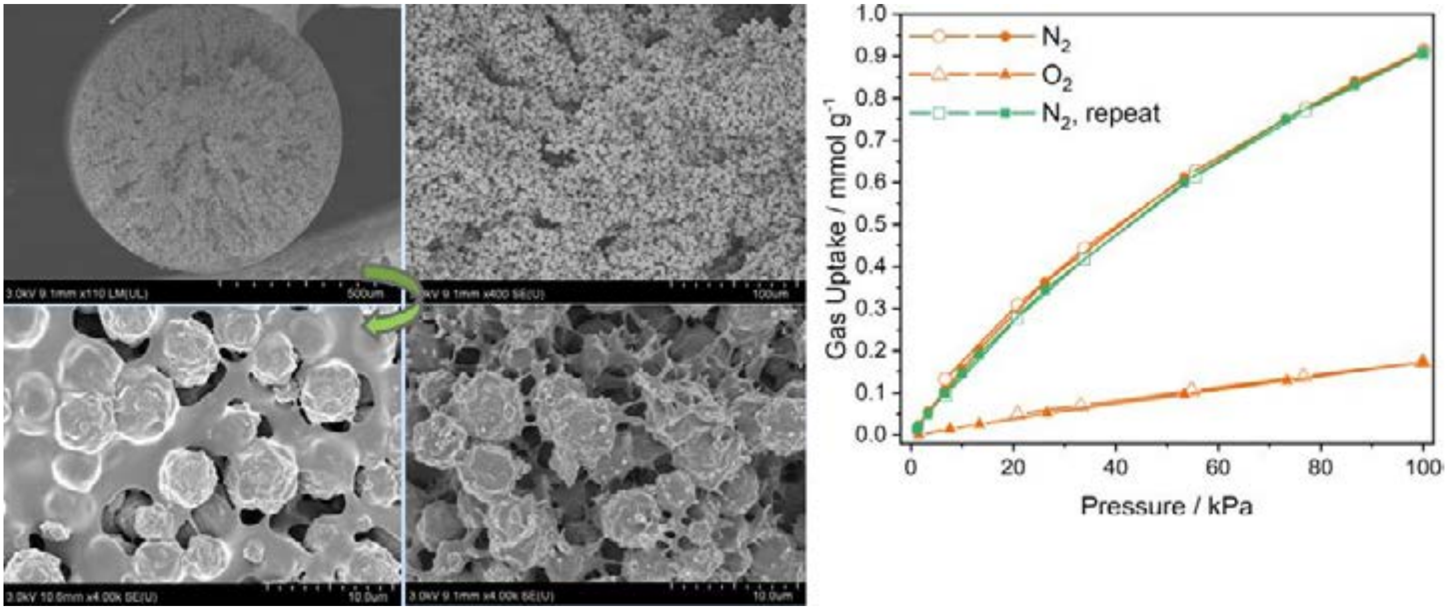


Figure 4: LiX fiber with improved hybrid polymers.

While the LiX fiber adsorbent forms the first layer of the two-layer bed for N_2 adsorption, the CMS fiber adsorbent forms the second layer for Argon (Ar) adsorption to achieve greater than 95% O_2 production. Susteon investigated the starting materials, such as cellulose acetate (CA) and microcrystalline cellulose (MCC), and pyrolysis conditions such as pyrolysis temperature profiles, for the optimization CMS fiber adsorbent. After iterations of starting materials, pyrolysis temperatures and time variations, the optimized CMS fiber adsorbent made from MCC showed excellent Ar/O_2 selectivity of 1.3 (as illustrated in Figure 5). This is almost 20% better than the Ar/O_2 selectivity of 1.1 for AgX zeolite.

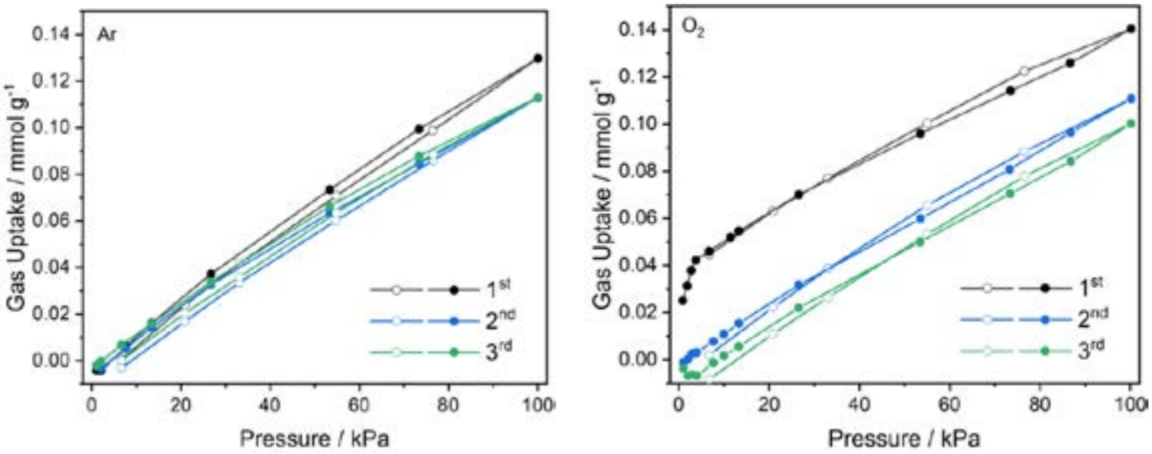


Figure 5: Ar and O_2 adsorption uptake for CMS fiber adsorbent made from MCC, showing Ar/O_2 sorption selectivity of approximately 1.3.

Techno-Economic Analysis

A preliminary techno-economic analysis (TEA) examined commercial viability of the developed RPSA process. The analysis considered factors such as active LiX content, voidage, bed size factor, recovery rates and fiber production costs. Preliminary results suggest that optimizing these parameters can lead to breakeven oxygen production costs below $45 per tonne, meeting the project's economic targets (as shown in Figure 6).

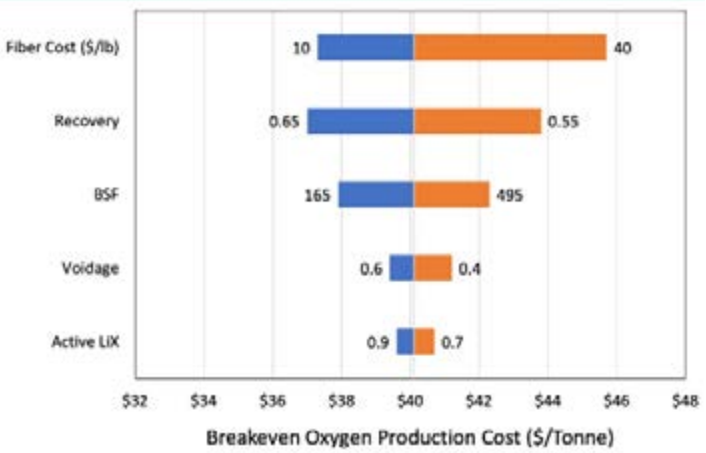


Figure 6: Tornado chart highlighting results from TEA.

The current estimated results and target research and development (R&D) values for oxygen production economics are shown in Table 1 for a nominal 50 tonne/day O_2 unit.

TABLE 1: OXYGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Oxygen	$/kg O_2	$4.48	$4.00
Capital Expenditures	$/kg O_2	$6.82	$6.21
Operating Expenditures	$/kg O_2	$2.99	$2.45

Definitions:

Cost of Oxygen – Projected cost of capture per mass of O_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of O_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of O_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M.

Other Parameter Descriptions:

Waste Streams Generated – N_2, water vapor, and CO_2 mixed stream.

Process Design Concept – The process flow diagram of the two-layer structured adsorbent RPSA system is shown in Figure 7.

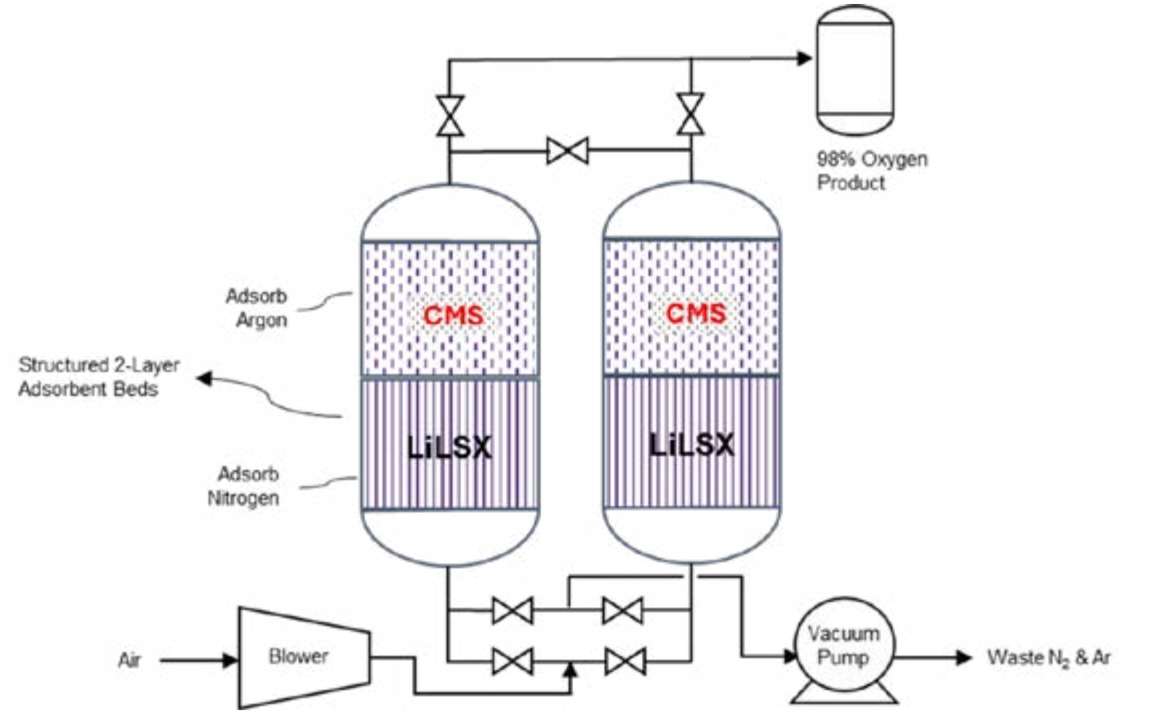


Figure 7: Process flow diagram of the two-layer structured adsorbent RPSA system.

In this fiber adsorbent-based RPSA system, approximately 90%-pure O_2 is produced in the first layer of adsorbent. By adding a second layer structured adsorbent based on Ar-selective CMS adsorbent, high-purity O_2 (greater than 95%) can be achieved in the final product by removing Ar from the stream exiting the first stage/layer. The modular, structured and compact system design enables significantly lower pressure drop through the adsorbent beds, facilitates faster heat and mass transfer, and reduces the bed size factor and hence compensates for the additional capital cost of the second stage/layer and the cost of the adsorbent materials.

technology advantages

- Reduces the pressure drop, attrition and dusting of the current beaded bed system for oxygen production by VPSA by using fibrous-structured adsorbent (order of magnitude lower ∆P).
- Enables rapid cycles in PSA using fiber-structured beds — greater than 30% lower bed size factor (equivalent to higher throughput).
- Maximizes adsorption capacity and rate through optimized fiber manufacturing with suitable polymer binders.
- Produces greater than 95%-pure O_2.

R&D challenges

- Manufacturing of high-performance fiber adsorbents at low cost.
- Stringent pyrolysis conditions require precise control during CMS fiber sorbent production.

status

Design and fabrication of a 10-kg/day oxygen production prototype is in process.

available reports/technical papers/presentations

“High Purity Oxygen Generation through Modular Structured Rapid Pressure Swing Adsorption (RPSA),” Jian Zheng, Susteon, Inc., 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Zheng.pdf*.

“High Purity Oxygen Generation through Modular Structured Rapid Pressure Swing Adsorption (RPSA),” Dr. James Zhou, Susteon Inc., Semi Annual Project Review, Sept. 12, 2024.

Electrochemically Mediated Air Separation Modules (EM-ASM)

primary project goal

RTX Technology Research Center (RTRC) is developing a novel sorbent/electrochemical looping technology based on electrochemical flow cells fed tailored transition metal (TM) complexes. The approach involves computational methods to rapidly identify promising TM complexes, synthesis and rapid screening of promising TM complex sorbents, design/build/test of small reactors for oxygen production, and evaluation of a scaled-up oxygen separation module in the context of a gasification process.

technical goals

- Advance the technology readiness of a novel, scalable, efficient, cost-effective and durable electrochemically mediated oxygen separation technology.
- Generate oxygen of sufficient purity to enable high-quality syngas production and efficient precombustion carbon capture for hydrogen production from gasification of biomass and wastes.

technical content

RTRC is developing the innovative electrochemically mediated air separation module (EM-ASM) technology, designed to efficiently produce high-purity oxygen for use in biomass and waste gasification systems. The production of oxygen via electrochemical methods addresses critical needs for scalable, energy-efficient oxygen generation to enhance syngas quality and facilitate precombustion carbon capture in hydrogen production processes.

The EM-ASM system leverages recent advancements in electro-swing sorption technologies for carbon dioxide (CO_2) capture. These technologies use electrochemical reduction and oxidation cycles to selectively bind and release CO_2 molecules. Central to the process that RTRC is developing are transition metal complexes that undergo reversible chemical changes to capture oxygen from air during the reduction phase and release it during the oxidation phase. This mechanism eliminates the need for traditional cryogenic or pressure swing adsorption (PSA) methods, offering a potentially lower energy alternative.

Figure 1 depicts an earlier successful electrochemically mediated gas separations approach for extracting CO_2, illustrating the concept. It leverages the capacity of quinones to be rapidly electrochemically reduced to hydroquinone in aqueous solutions that can bind CO_2 at the cathode. After returning to the anode, hydroquinone is oxidized back to quinone releases pure CO_2.

program area:

Gasification Systems

ending scale:

Bench scale (6 g/hr oxygen, 2.5 W)

application:

Hydrogen Production

key technology:

Air Separation Technology

project focus:

Developing a novel sorbent/electrochemical looping technology for oxygen production

participant:

RTX Technology Research Center

project number:

FE0032348

predecessor projects:

N/A

NETL project manager:

Drew O'Connell
andrew.oconnell@netl.doe.gov

principal investigator:

Robert Darling
robert.darling@rtx.com

partners:

University of California Davis; University of California Irvine; Massachusetts Institute of Technology

start date:

10.01.2023

percent complete:

65%

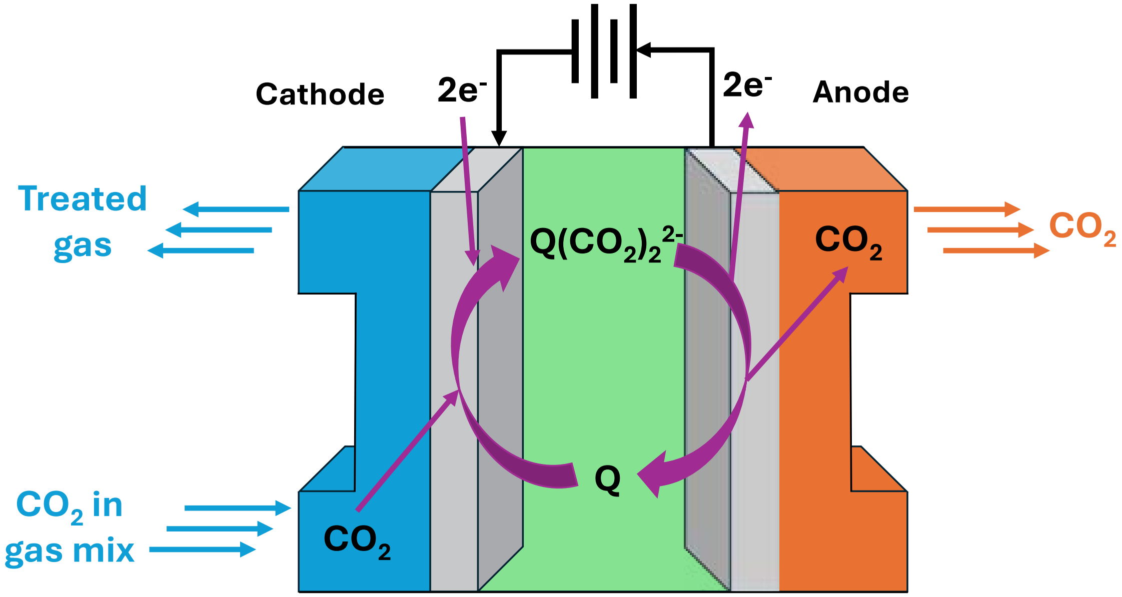


Figure 1: Concept for electrochemically mediated CO_2 separation, an analogue for EM-ASU.

Applying this gas separations approach to air separation requires oxygen capture molecules. Several reduced transition metal complexes reversibly bind oxygen (O_2) with equilibrium constants ranging from 10 to 100. These values would allow O_2 capture from air. The oxidized versions of these complexes are not known to bind O_2, making them good candidates for reversible O_2 binding and release. These macrocycles are easily functionalized to modify electronic properties that will impact their reduction potentials, oxygen binding capabilities and solubilities. Some examples of these transition metal complexes are illustrated in Figure 2.

Iron(II) porphyrin

Co(II)(salen)

Ni(II)(tetraimine)

Figure 2: Examples of transition metal complexes possibly useful in the oxygen electro-swing sorption.

University of California, Davis (UC Davis) is employing machine learning and molecular modeling to identify and design a library of more than 1 million candidate oxygen-binding molecules. They are screening these candidates for their binding strength, energy efficiency and durability. The modeling process aims to pinpoint compounds capable of delivering optimal performance under operational conditions. University of California, Irvine (UC Irvine) synthesized a family of substituted Co(II)-salens and evaluated their binding with oxygen, solubility and redox potentials. Parameters such as binding enthalpy and reaction kinetics were carefully evaluated to select the most promising materials for further testing. UC Irvine identified functional groups favoring $M^n(L)\text{-}O_2$ (superoxo) and $[M^n(L)]_2\text{-}O_2$ (μ-peroxo) binding (see Figure 3). Promising synthesized samples were scaled-up to gram-scale quantity and sent to the Massachusetts Institute of Technology (MIT) for small-reactor (sub-scale) testing. Ensuring consistency in performance across synthesis scales is a critical aspect of this phase.

Figure 3: Co(salen)s as electro-swing O_2 capture molecules.

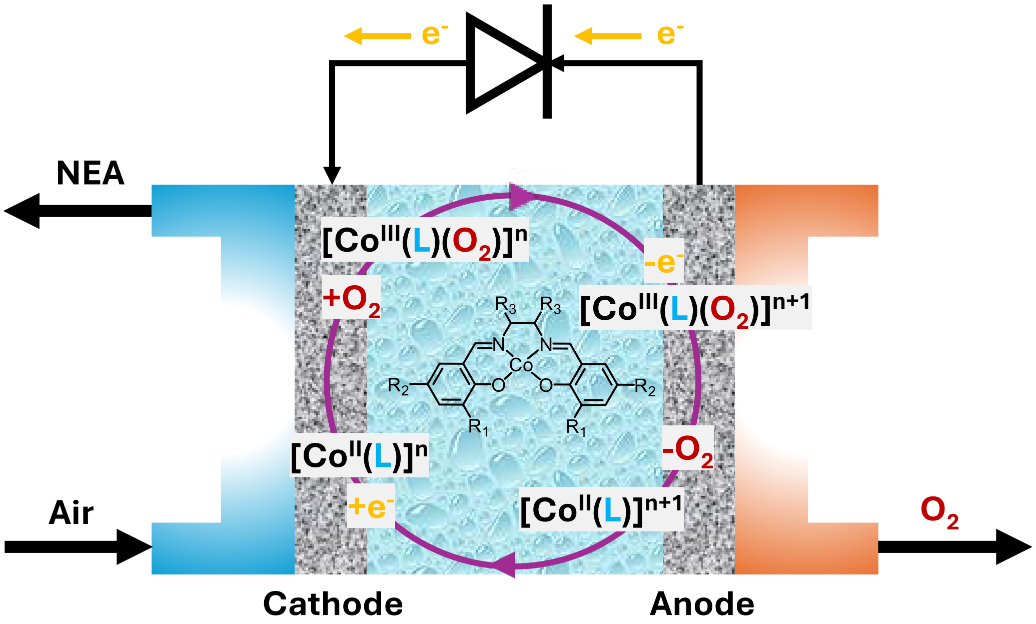


Figure 4: Electrochemically mediated air separation scheme using functionalized Co(II)-salens assuming superoxo bonding of oxygen. (NEA refers to nitrogen-enriched air.)

MIT has been constructing a series of sub-scale EM-ASM reactors to evaluate the synthesized electro-swing capture materials under realistic operating conditions. These reactors are designed to simulate industrial-scale performance while allowing for precise control and monitoring of operational parameters. Metrics such as oxygen purity, separation efficiency, energy consumption and material degradation are closely monitored. Preliminary results indicate that the electrochemical approach can achieve oxygen purity exceeding 95% with significantly lower energy input compared to traditional methods.

An unfunctionalized Co(II)-salen was evaluated for cyclic voltammetry by MIT using a three-electrode cell, and showed a well-defined, quasi-reversible Co(II)/Co(III) redox peak under argon (Ar) and O_2 (see Figure 5). Cell polarization between 0 and 0.4 V was studied on the cell, showing minimal hysteresis between forward and reverse polarization scans, and modest degradation after aging for one month, indicating that both Co(II) and Co(III) states are reasonably stable (see Figure 6). The performance of the test cell is limited by low concentrations of the salens and a thick electrolyte separator gap.

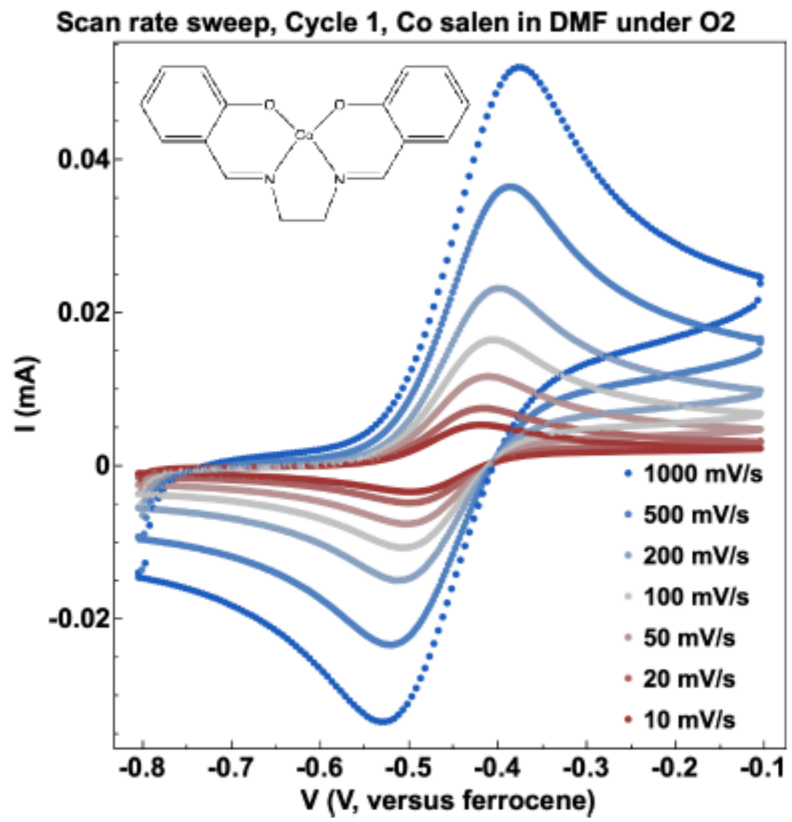


Figure 5: Representative cyclic voltammetry of Co(salen) in DMF.

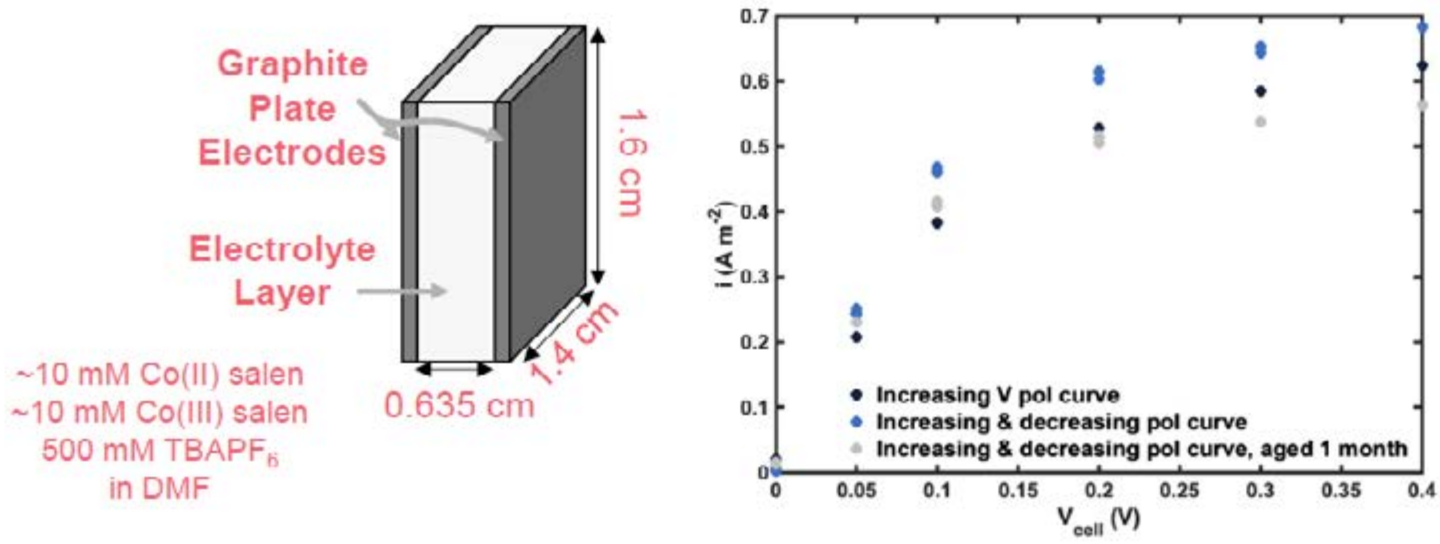
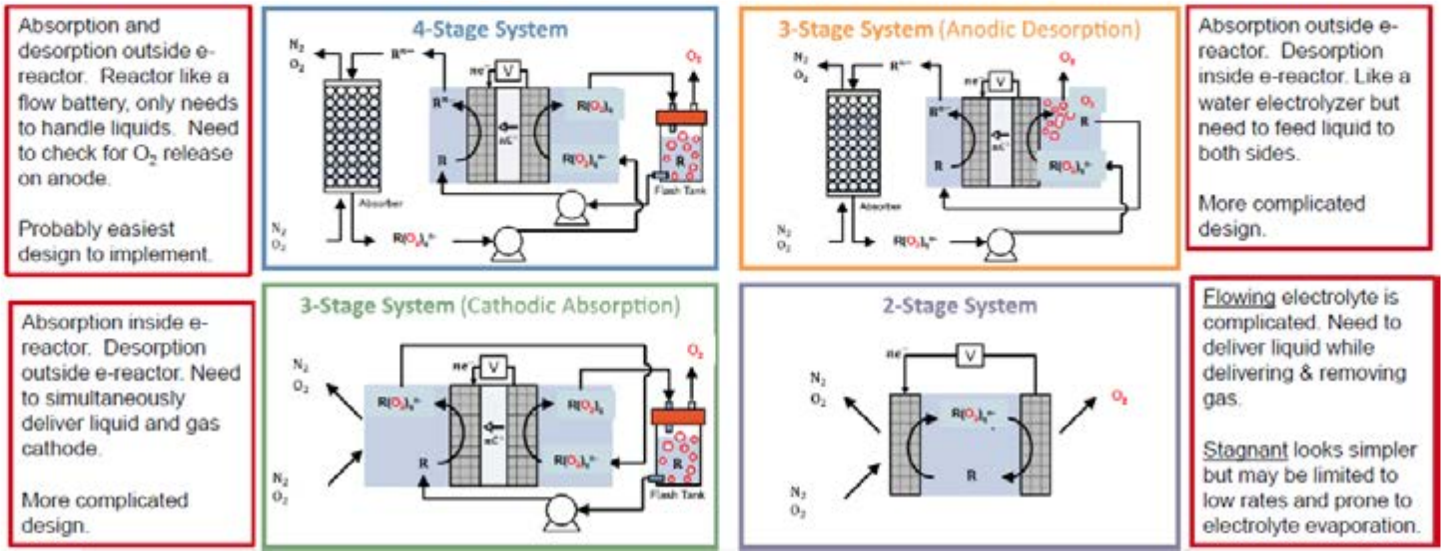


Figure 6: Electrochemical cell polarization scans.

Using data from sub-scale testing, predictive models are being developed to guide the design of scaled-up systems, with various numbers of stages in the systems possible (see Figure 7). A tenfold scale-up is targeted, with engineering designs aimed at maintaining performance consistency. Computational fluid dynamics (CFD) and reactor modeling are employed to optimize flow dynamics, thermal management and electrochemical efficiency. A critical focus is on maintaining oxygen purity while minimizing energy losses and material wear during continuous operation.



Absorption and desorption outside e-reactor. Reactor like a flow battery, only needs to handle liquids. Need to check for O_2 release on anode.

Probably easiest design to implement.

Absorption outside e-reactor. Desorption inside e-reactor. Like a water electrolyzer but need to feed liquid to both sides.

More complicated design.

Absorption inside e-reactor. Desorption outside e-reactor. Need to simultaneously deliver liquid and gas cathode.

More complicated design.

Flowing electrolyte is complicated. Need to deliver liquid while delivering & removing gas.

Stagnant looks simpler but may be limited to low rates and prone to electrolyte evaporation.

Figure 7: Four process designs considered for scale up at RTRC.

These various process designs have been modeled. Specifically, preliminary electro-swing tests were run to simulate a four-stage reactor to inform model development. Assumptions of the same reactants at anode and cathode, no standard voltage difference, and aqueous electrolyte were made. Concentrations of reactants were varied. Fast reaction kinetics were noted, but slower mass transport was observed than had been expected.

From analysis and modeling results completed so far, a three-stage EM-ASU with anodic desorption appears to be the preferred approach.

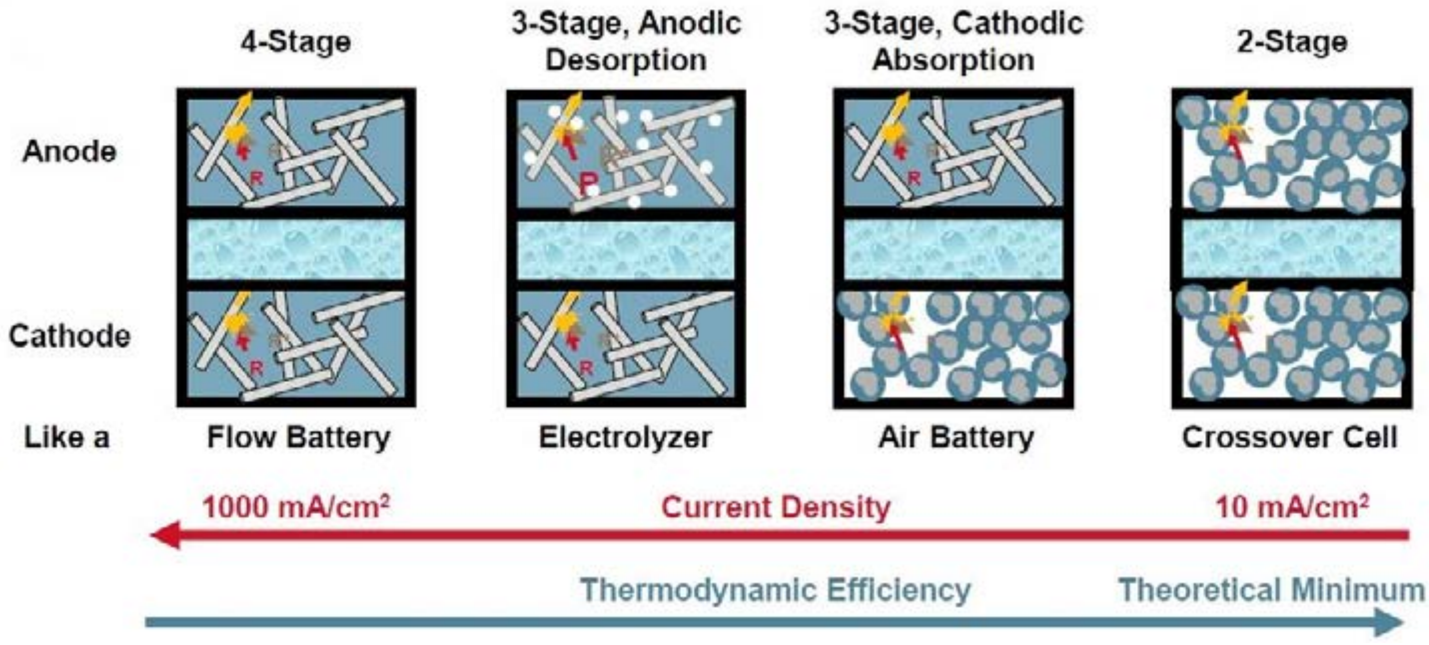


Figure 8: Reactor configurations.

RTRC will conduct a techno-economic analysis (TEA) to evaluate the cost competitiveness of the EM-ASM system against established oxygen separation technologies such as cryogenic distillation and PSA. The TEA includes detailed cost breakdowns for materials, fabrication, energy consumption and operational expenses. Additionally, a life cycle analysis assesses the environmental impact of the system, focusing on energy efficiency and greenhouse gas emissions. Preliminary findings suggest that EM-ASM technology has the potential to reduce oxygen production costs to below $45 per ton while achieving substantial energy savings.

The current estimated results and target research and development (R&D) values for oxygen production economics are shown in Table 1.

TABLE 1: OXYGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Oxygen	$/kg O_2	0.202	0.055
Capital Expenditures	$/kg O_2	0.096	0.019
Operating Expenditures	$/kg O_2	0.107	0.036

Definitions:

Cost of Oxygen – Projected cost of capture per mass of O_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of O_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of O_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M.

Other Parameter Descriptions:

Waste Streams Generated – No major waste streams identified.

Process Design Concept – See Figure 7.

technology advantages

- **Energy Efficiency**: The electrochemical process is designed to operate with low specific energy consumption, potentially reducing operational costs compared to conventional oxygen separation methods.
- **Scalability**: The modular nature of the EM-ASM technology allows for flexible scaling, accommodating various production capacities, and facilitating integration into different industrial settings.
- **High-Purity Oxygen Production**: The technology aims to produce oxygen of sufficient purity to enhance syngas quality and improve the efficiency of precombustion carbon capture processes.
- **Cost-Effectiveness**: By reducing energy requirements and system complexity, the EM-ASM technology has the potential to lower the overall cost of oxygen production.

R&D challenges

- **Material Stability**: Ensuring the long-term stability and durability of the transition metal complexes under operational conditions is critical for sustained performance.
- **System Integration**: Effectively integrating the electrochemical modules into existing gasification and carbon capture systems requires careful engineering to maintain process efficiency.
- **Scale-Up Validation**: Demonstrating consistent performance during scale-up from laboratory- to industrial-scale applications is essential to validate the technology’s feasibility.
- **Economic Viability**: Conducting comprehensive TEAs to confirm that the EM-ASM technology can compete with existing oxygen separation methods in terms of cost and performance.

status

Further work is needed at UC Davis in molecular modeling, including solubility predictions, redox desorption estimates for Co-salen and functionalized analogs, and binding energy predictions for other oxygen capture macrocycles, along with synthesis and screening of a final optimal novel salen at UC Irvine for testing at MIT. Regarding small-reactor work at MIT, all steps of the O_2 capture/release cycle need to be demonstrated with the substituted salen molecules made by UC Irvine. Also, design for scaled-up testing at 25-cm^2 scale is in process, supporting ultimate TEA and maturation.

available reports/technical papers/presentations

“Electrochemically Mediated Air Separation Modules (EM-ASM),” Robert Darling, RTX Technology Research Center, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Darling.pdf*.

“Electrochemically Mediated Air Separation Modules (EM-ASM),” Mid-Project Review with U.S. DOE, National Energy Technology Lab (NETL), October 24, 2024.

Oxygen-Integrated Unit for Modular Biomass Conversion to Hydrogen (OXYIUM)

primary project goal

SRI is developing a novel oxygen (O_2) sorbent technology, consisting of a durable porous polymer with chemically bonded cobalt(II) (Co^{2+}) complexes that capture O_2 reversibly by vacuum pressure swing adsorption (VPSA). High specific surface area (greater than 100 m^2/g) and pore tuning of mesopores between 10 to 100 nanometers (nm) in size will enable rapid rates of gas transport, bulk diffusion and high O_2 uptake.

technical goals

- Design and synthesize a high-capacity (greater than 6 wt%) oxygen sorbent capable of capturing oxygen from air at ambient conditions.
- Demonstrate the sorbent's performance in a fixed-bed reactor, achieving reversibility with a cycle time of approximately two minutes and long lifetime/stability.
- Scale up sorbent production to more than 25 grams and integrate it into a bench-scale prototype system for oxygen production.
- Show lower cost of oxygen production than the state of the art, at a scale supporting 5 to 50-megawatt-electric (MWe) hydrogen production plants.

technical content

SRI is developing technology to address the challenge of cost-effective oxygen production at the small, modular scales at which state-of-the-art cryogenic air separation is not economical or practicable. The concept under development leverages PARC's past success in polyamine aerogels, originally synthesized for the purpose of carbon dioxide (CO_2) capture (Figure 1). The polyamine aerogels have high surface areas (greater than 100 m^2/g) and tunable porosity, facilitating rapid gas transport and bulk diffusion.

program area:

Gasification Systems

ending scale:

Bench scale (54 g/hr oxygen production using 30 g sorbent)

application:

Hydrogen Production

key technology:

Air Separation Technology

project focus:

Developing a reversible O_2 sorbent for pressure swing adsorption

participant:

SRI/Palo Alto Research Center (PARC)

project number:

FE0032350

predecessor projects:

FE0031951

NETL project manager:

Sarah Pfeiffer
sarah.pfeiffer@netl.doe.gov

principal investigator:

Koyel Bhattacharyya
koyel@sri.com

partners:

SIMACRO LLC

start date:

10.01.2023

percent complete:

65%

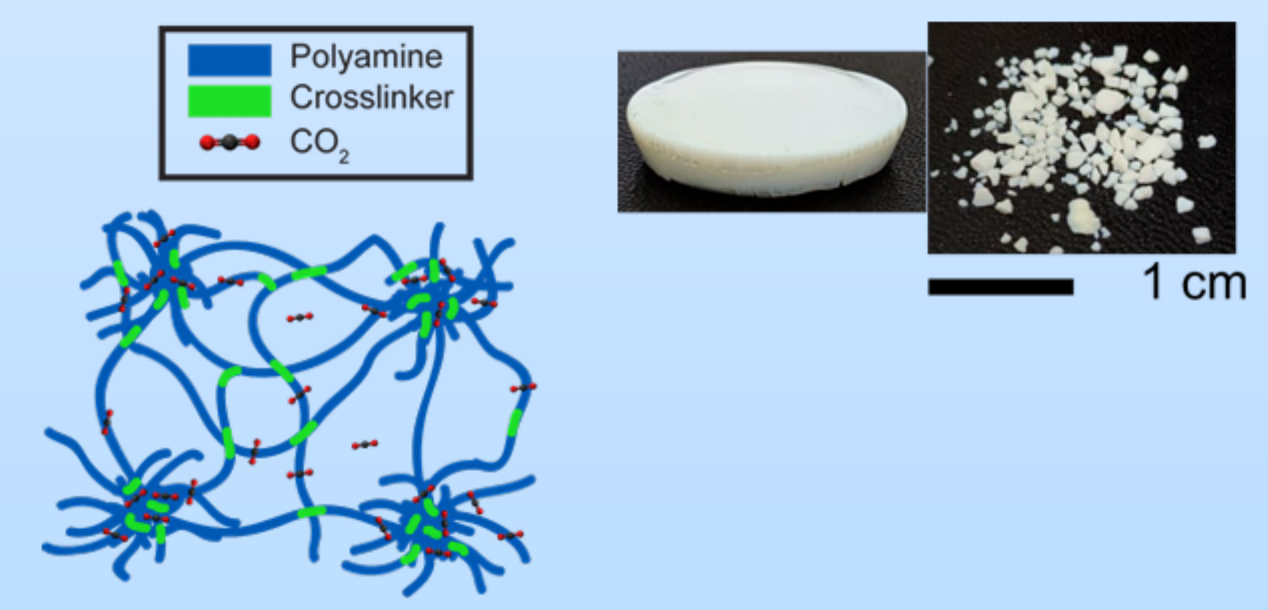


Figure 1: PARC polyamine aerogel for gas separations.

Central to the OXYIUM system is the development of a high-capacity, reversible oxygen sorbent based on SRI's patented amine aerogel platform. The sorbent design involves chemically binding Co^{2+} complexes to the amine groups within the aerogel matrix. This configuration forces a 1:1 carbon monoxide (CO):O_2 stoichiometry, doubling the potential oxygen capacity compared to traditional 2:1 ratios observed in other cobalt materials. Figure 2 illustrates the sorbent synthesis pathway. A tetramine ligand (N_4) is first chelated to the cobalt center, then incorporating the CoN_4 complex into the amine polymer. In this modified form, the sorbent can reversibly incorporate oxygen. Measurement of oxygen and nitrogen isotherms demonstrated that the addition of CoN_4 significantly improves both oxygen capacity and selectivity with respect to nitrogen versus either bare sorbent or sorbent embedded with cobalt alone. PARC polymers adsorbed approximately two times more cobalt than commercial resin for the same amine content due to its superior porosity. The addition of cobalt to the sorbent maintained the high porosity of the bare sorbent, enabling the high levels of oxygen capacity needed for superior performance.

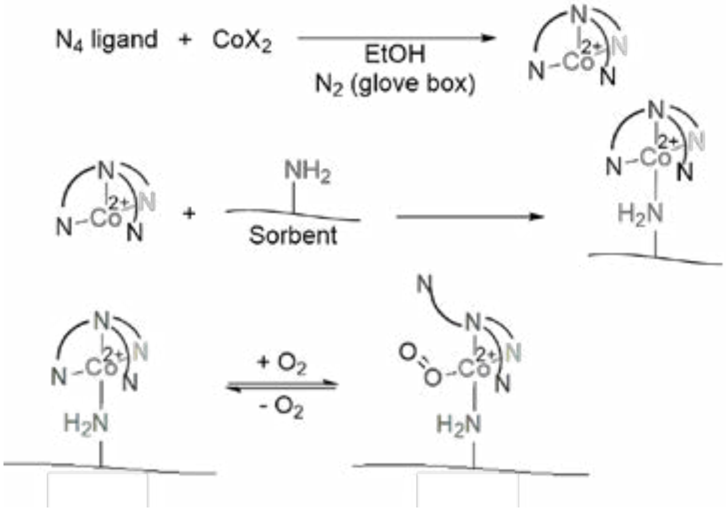
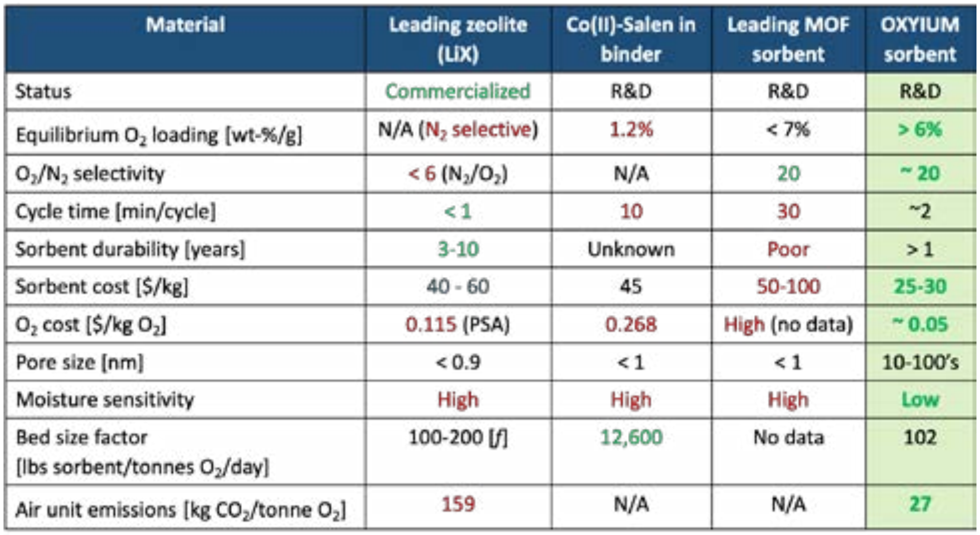


Figure 2: Pathway for oxygen sorbent synthesis.

The envisioned operation of the sorbent involves a VPSA system, adsorbing oxygen from air at ambient conditions and desorbing under vacuum. The CoN_4-sorb material was successfully scaled and tested in fixed-bed reactor tests, demonstrating efficient oxygen capture and release cycles. Per oxygen isotherm measurements, the sorbent retained stability over at least three cycles with an oxygen capacity of 2 wt%, indicating a long operational lifetime potential. The mesoporosity of the sorbent contributes to a rapid cycle time, enhancing the efficiency of the oxygen production process. Table 1 compares the performance goals of the SRI OXYIUM sorbent with commercially available and state-of-the-art sorbents reported in the literature, quantifying benefits in several parameters, including cycling time, cost and moisture sensitivity.

TABLE 1: COMPARISON OF OXYIUM SORBENT EXPECTED PERFORMANCE TO STATE-OF-THE-ART OXYGEN SORBENTS



Material	Leading zeolite (LiX)	Co(II)-Salen in binder	Leading MOF sorbent	OXYIUM sorbent
Status	Commercialized	R&D	R&D	R&D
Equilibrium O_2 loading [wt-%/g]	N/A (N_2 selective)	1.2%	< 7%	> 6%
O_2/N_2 selectivity	< 6 (N_2/O_2)	N/A	20	~ 20
Cycle time [min/cycle]	< 1	10	30	~2
Sorbent durability [years]	3-10	Unknown	Poor	> 1
Sorbent cost [$/kg]	40 - 60	45	50-100	25-30
O_2 cost [$/kg O_2]	0.115 (PSA)	0.268	High (no data)	~ 0.05
Pore size [nm]	< 0.9	< 1	< 1	10-100's
Moisture sensitivity	High	High	High	Low
Bed size factor [lbs sorbent/tonnes O_2/day]	100-200 [f]	12,600	No data	102
Air unit emissions [kg CO_2/tonne O_2]	159	N/A	N/A	27

Figure 3 contextualizes the current best OXYIUM material to literature results in terms of oxygen uptake and O_2/N_2 selectivity. Note that the industry standard (Li-LSX) selects for N_2 (not O_2), requiring further downstream purification of O_2. Even though several metal-organic frameworks (MOFs) show better uptake than projected results for the current OXYIUM sorbent system, the cost, scale-up, water stability and fixed-bed reactor usability of these materials are much worse than projected for the envisioned SRI OXYIUM system.

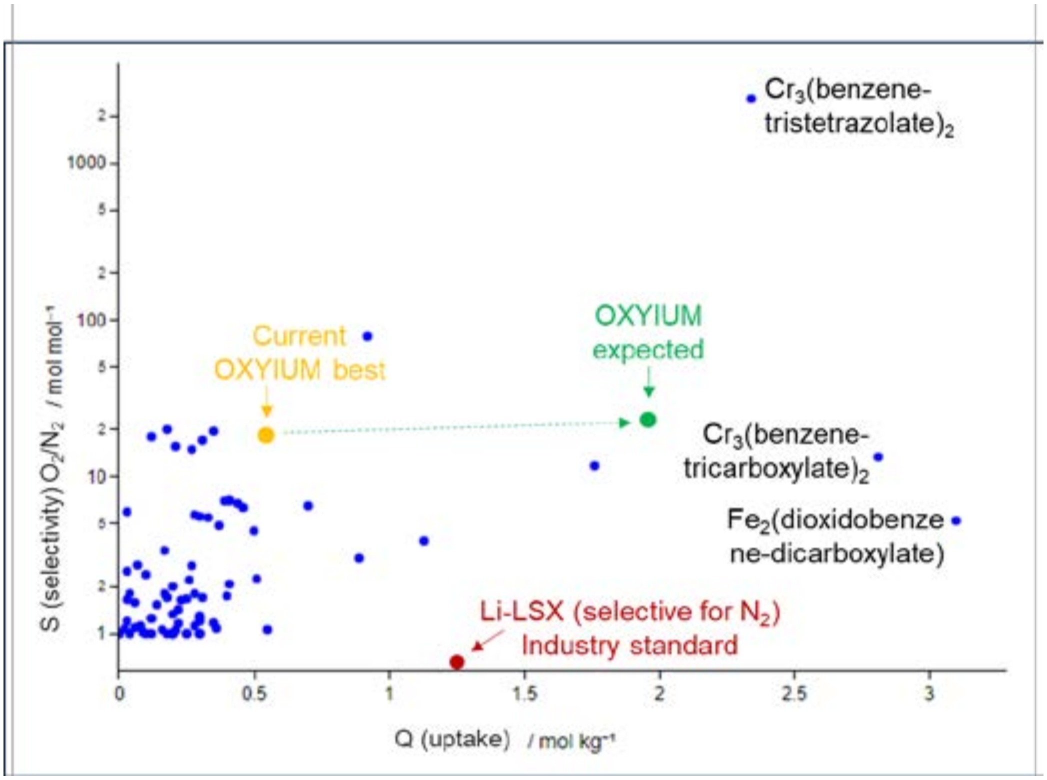


Figure 3: Comparison of OXYIUM current sorbent material to literature results.

Techno-Economic Analysis

Modeling is planned to simulate oxygen production process dynamics, refine system design, and evaluate integration with biomass gasifiers. These models will inform system optimization and scalability while supporting the development of detailed techno-economic and life cycle analyses (TEAs and LCAs). The TEA will assess the system's cost competitiveness relative to existing oxygen production technologies, and the LCA will evaluate its environmental impact, particularly in terms of carbon neutrality and energy efficiency. These efforts collectively aim to prepare the technology for commercial deployment while ensuring economic and environmental feasibility.

The current estimated results and target research and development (R&D) values for oxygen production economics are shown in Table 2.

TABLE 2: OXYGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Oxygen	\$/kg O_2	50.00	0.05
Capital Expenditures	\$/kg O_2	20.00	0.0425
Operating Expenditures	\$/kg O_2	30.00	0.0075

Definitions:

Cost of Oxygen – Projected cost of capture per mass of O_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of O_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of O_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M.

Other Parameter Descriptions:

Waste Streams Generated – CO_2 (27 kg/ton O_2).

Process Design Concept – Simplified diagram below demonstrating use of SRI OXYIUM sorbent in air separation unit (ASU), as part of a gasification plant for conversion of biomass waste to hydrogen with incorporated CO_2 capture.

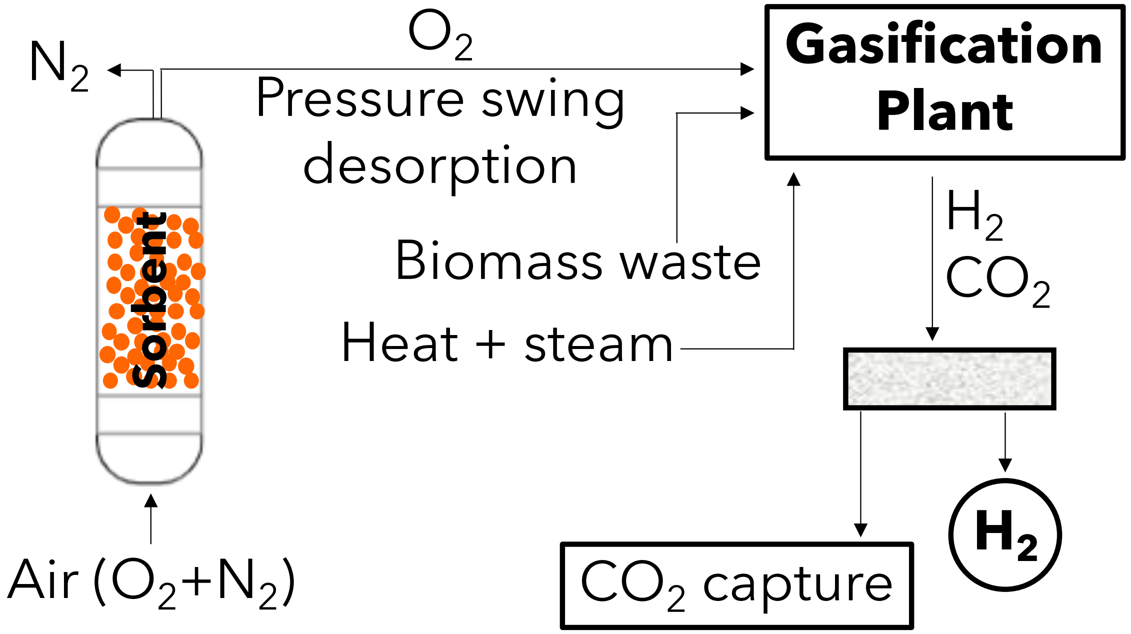


Figure 4: Process integration of the OXYIUM ASU with a biomass gasification cycle.

technology advantages

- **High Oxygen Capacity**: SRI (PARC) sorbent design should achieve an oxygen capacity exceeding 6 wt%, enhancing the efficiency of the oxygen production process.
- **Rapid Cycle Time**: Mesoporous structure of the sorbent will enable a cycle time of approximately two minutes, allowing for quick adsorption and desorption cycles.
- **Ambient Conditions**: The sorbent will operate effectively at ambient temperature, reducing energy requirements and simplifying system design.
- **Scalability**: The technology is deployable in small-scale biomass gasification units, supporting distributed hydrogen production.

R&D challenges

- Ensuring the long-term stability and durability of the sorbent under repeated adsorption/desorption cycles is critical for sustained performance. Issues such as cobalt retention, etc.
- Transitioning from laboratory-scale synthesis to larger-scale production while maintaining sorbent performance presents engineering challenges.
- Effectively integrating the oxygen production unit into existing biomass gasification systems requires careful design to optimize performance and efficiency.

status

An amine sorbent has been synthesized with up to 14 mmol amine per gram sorbent, exceeding a milestone of 4.5 mmol N/g. Cobalt complex-containing CoN_4-sorb has been synthesized on 32-g scale with at least 3.7 mmol cobalt per gram sorbent, exceeding a milestone of 2 mmol Co/g. Reversible oxygen adsorption/desorption has been demonstrated for the base sorbent, sorbent containing simple cobalt ions, and sorbent containing tetramine cobalt complexes, and the target material demonstrates a clear orders-of-magnitude improvement in both oxygen capacity and selectivity.

A fixed-bed reactor was built and verified using commercial nitrogen sorbent material; this will be used for conducting enhanced fixed-bed testing to evaluate the sorbent’s long-term durability and performance under extended operation and varied conditions. This will confirm the material’s suitability for industrial applications.

available reports/technical papers/presentations

“OXYIUM: Oxygen Integrated Unit for Modular Biomass Conversion to Hydrogen,” Koyel Bhattacharyya, PARC (SRI), 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Bhattacharyya_2.pdf*.

“OXYIUM: Oxygen Integrated Unit for Modular Biomass Conversion to Hydrogen,” Koyel Bhattacharyya, PARC (SRI), Project Semi-annual Update Presentation, Nov. 5, 2024.

Optimization and Scale-Up of Molecular-Sieve Membranes With Record Air Separation Performance

primary project goal

Osmoses Inc. is developing membranes made of hydrocarbon ladder polymers with ultrahigh selectivity for gas separations. The polymer membranes feature thermal stability up to 250°C, resistance to humidity/water vapor, and operability under high pressure. The polymer membranes are targeted for incorporation in membrane modules for modular air separation units (ASUs) at low production cost and low energy consumption.

technical goals

- Develop a novel membrane system capable of producing enriched oxygen (O_2) from air for integration into modular gasification systems aimed at low-cost hydrogen production.
- Optimize polymer formulations and thin-film composites to enhance membrane oxygen permeance and O_2/nitrogen (N_2) selectivity.
- Scale up thin-film composite formulations to produce 100 m^2 of membrane area.
- Advance the Technology Readiness Level (TRL) from 2 to 5.

technical content

Osmoses Inc. is developing advanced molecular-sieve membranes for modular air separation application. The technical focus is on optimization of polymer formulations and thin-film composite membrane structures to improve oxygen permeance and air separation performance relative to state-of-the-art membrane-based ASU technologies.

Osmoses' membranes are based on novel polymers that exhibit size-selectivity due to their contorted ladder backbone structures, resulting in gas-size pores that facilitate efficient gas separations. The molecular structures involved in the polymer membranes are illustrated in Figure 1. Here, porosity dimensions, if precisely controlled, can allow passage of smaller O_2 molecules while blocking the slightly larger N_2 molecules, providing a basis for O_2/N_2 selectivity of this membrane in an ASU.

program area:
Gasification Systems

ending scale:
Bench Scale

application:
Hydrogen Production

key technology:
Air Separation Technology

project focus:
Developing hydrocarbon ladder polymer membranes for air separation

participant:
Osmoses Inc.

project number:
FE0032352

predecessor projects:
N/A

NETL project manager:
Diane Revay Madden
diane.madden@netl.doe.gov

principal investigator:
Katherine Rodriguez
katmiz@osmoses.com

partners:
Gas Technology Institute

start date:
10.01.2023

percent complete:
40%

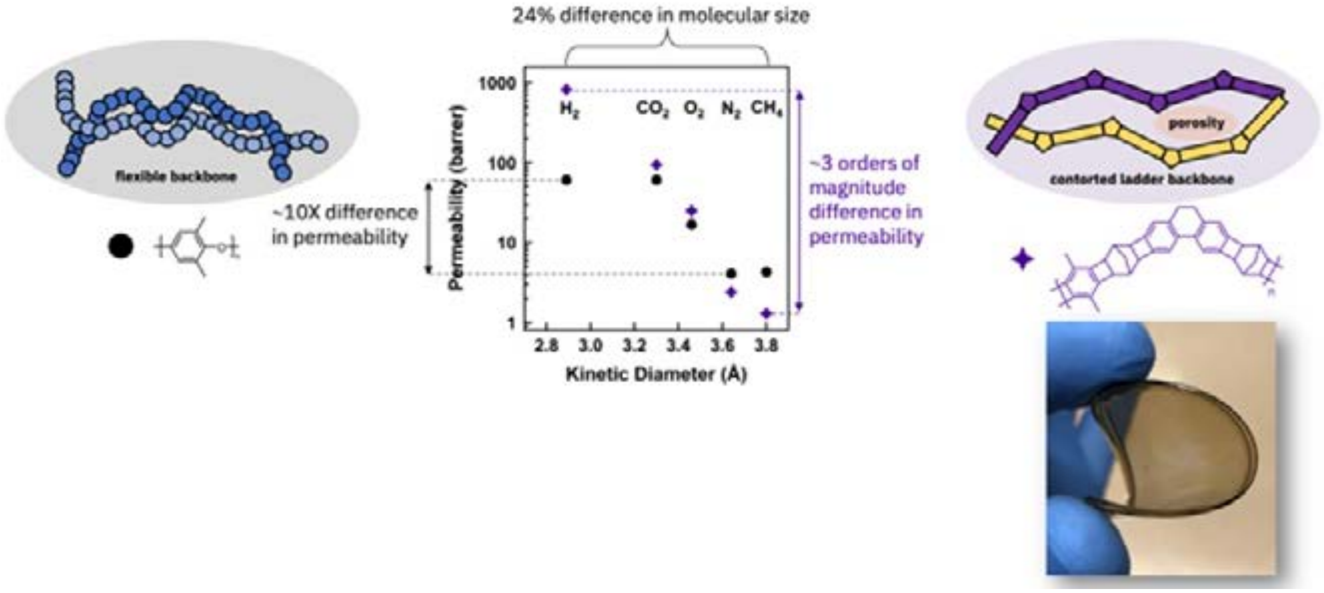


Figure 1: Diagram and results demonstrating size-selectivity of Osmoses polymers.

Techno-Economic Analysis

A significant component of the project involves developing process and techno-economic models to evaluate the integration of membrane systems in 5-to-50-megawatt-electric (MWe) biomass-fueled gasifiers for hydrogen production with purity levels exceeding 99%. This includes comparing the performance and cost-effectiveness of membrane-based air separation using the Osmoses technology, against conventional methods.

The current estimated results and target research and development (R&D) values for oxygen production economics are shown in Table 1.

TABLE 1: OXYGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Oxygen	$/kg O_2	TBD	TBD
Capital Expenditures	$/kg O_2	TBD	TBD
Operating Expenditures	$/kg O_2	TBD	TBD

Definitions:

Cost of Oxygen – Projected cost of capture per mass of O_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of O_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of O_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M.

Other Parameter Descriptions:

Waste Streams Generated – None specified.

Process Design Concept – See Figure 2.

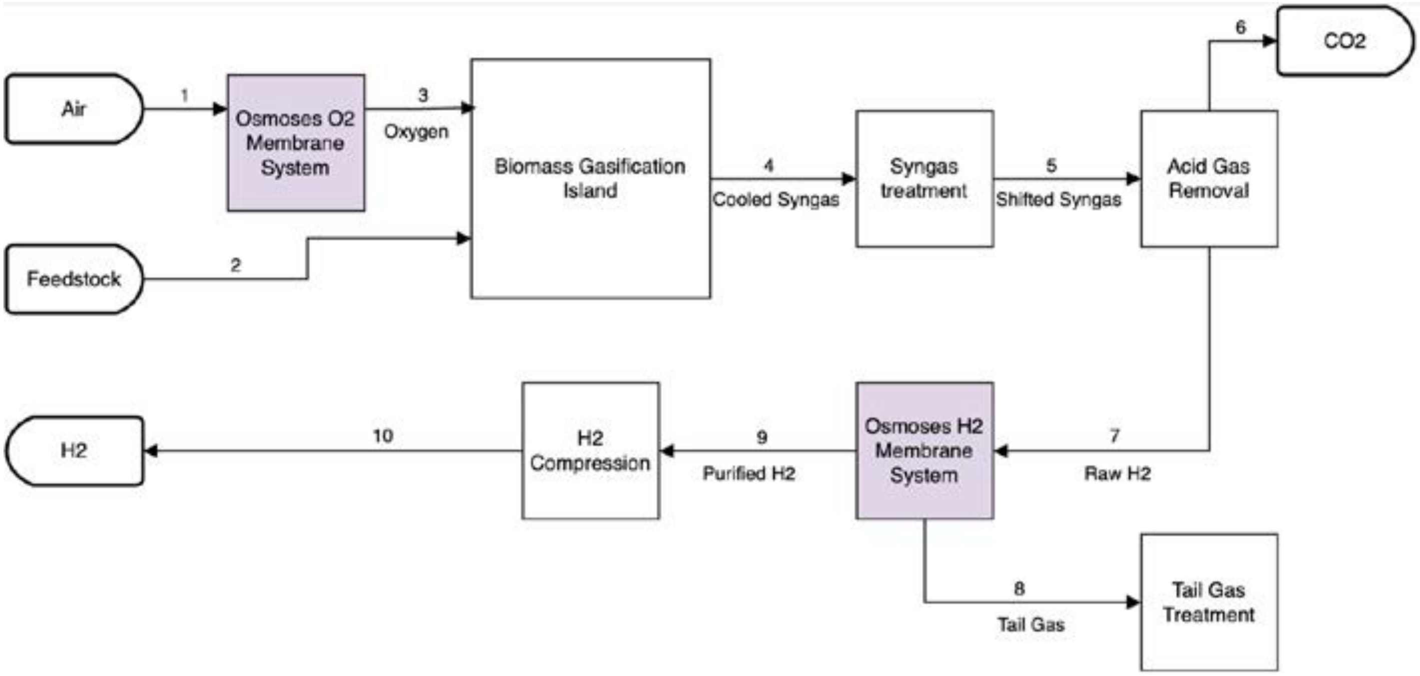


Figure 2: Process cycle incorporating Osmoses ASU.

technology advantages

- **Exceptional Size-Selectivity**: The contorted ladder backbone of the polymers results in gas-sized pores, providing a significant difference in permeability between oxygen and nitrogen, leading to high O_2/N_2 selectivity.
- **Thermal Stability**: The membranes are chemically stable up to 250°C, making them suitable for various industrial applications.
- **Chemical Resistance**: The membranes are nonreactive in the presence of water, hydrogen sulfide (H_2S), and other contaminants, ensuring durability and longevity in harsh environments.
- **High-Pressure Performance**: External tests have demonstrated high CO_2/methane (CH_4) selectivity at 60 bar, indicating the membranes' capability to perform well under high-pressure conditions.

R&D challenges

- **Polymer Optimization**: Identifying and synthesizing polymers that offer the optimal balance between oxygen permeance and O_2/N_2 selectivity.
- **Scale-Up Manufacturing**: Ensuring consistent quality and performance of the membranes during the scale-up process to 100-m^2 production.
- **Long-Term Performance**: Evaluating the membranes' long-term performance and aging rates to ensure durability and reliability over extended periods.

status

Current work is focusing on polymer synthesis and membrane fabrication. Promising polymers are synthesized in small quantities, enough to form membranes suitable for testing of permeance and selectivity. Best-performing polymers are synthesized at a larger scale, with additional testing results on temperature and pressure dependence of the membranes for air separation. Later, long-term testing (1,000 hours is planned) and scaling of the membranes to 100 square meters scale will underpin evaluation of quality control and manufacturing performance potential.

available reports/technical papers/presentations

"Optimization and Scale-Up of Molecular-Sieve Membranes with Record Air Separation Performance," Holden Lai, Osmoses, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Lai.pdf*.

"23598 GTI Energy Update," Project Status Update, 11.20.24.

An Advanced Modular Redox Air Separation System for Cost-Effective, Net-Zero Hydrogen Production

primary project goal

North Carolina State University (NCSU) is developing a redox-based air separation unit (ASU) taking advantage of selected perovskite oxygen sorbents enabling continuous oxygen exchange, steam resistance, flexible thermodynamic properties and fast kinetics. Development work targets identifying superior performing sorbent formulations and testing them for long-term operational efficacy and durability, plus process modeling and techno-economic analysis (TEA) to determine systems feasibility.

technical goals

- Develop and demonstrate a redox-based modular ASU capable of high-purity oxygen (greater than 95%) production.
- Synthesize advanced, steam-resistant oxygen sorbents with an oxygen capacity exceeding 2 wt% and minimal deactivation over extended cycles.
- Design and operate a sub-pilot ASU system capable of producing 20 kg of oxygen per day, integrating the developed sorbents.

technical content

NCSU and partners are developing an advanced air separation system tailored for small-scale gasification oxygen needs. The system aims to produce oxygen efficiently for use in modular gasifiers capable of generating low-cost, clean hydrogen, especially in the size range where traditional cryogenic air separation methods would not be practicable or cost-effective.

A key innovation in this project is the development of high-performance oxygen sorbents designed to operate in a cyclic redox process (see Figure 1). These materials enable selective oxygen capture and release, allowing for efficient air separation in small-scale, decentralized applications. Perovskite oxides are the focus of this developmental work.

program area:
Gasification Systems

ending scale:
Bench scale, 20 kg/day oxygen production

application:
Hydrogen Production

key technology:
Air Separation Technology

project focus:
Developing a redox-based air separation unit for modular gasification

participant:
North Carolina State University (NCSU)

project number:
FE0032355

predecessor projects:
N/A

NETL project manager:
Sarah Pfeiffer
sarah.pfeiffer@netl.doe.gov

principal investigator:
Dr. Fanxing Li
fli5@ncsu.edu

partners:
Acadian Research & Development LLC;
Gas Technology Institute (GTI);
Massachusetts Institute of Technology (MIT)

start date:
10.01.2023

percent complete:
65%

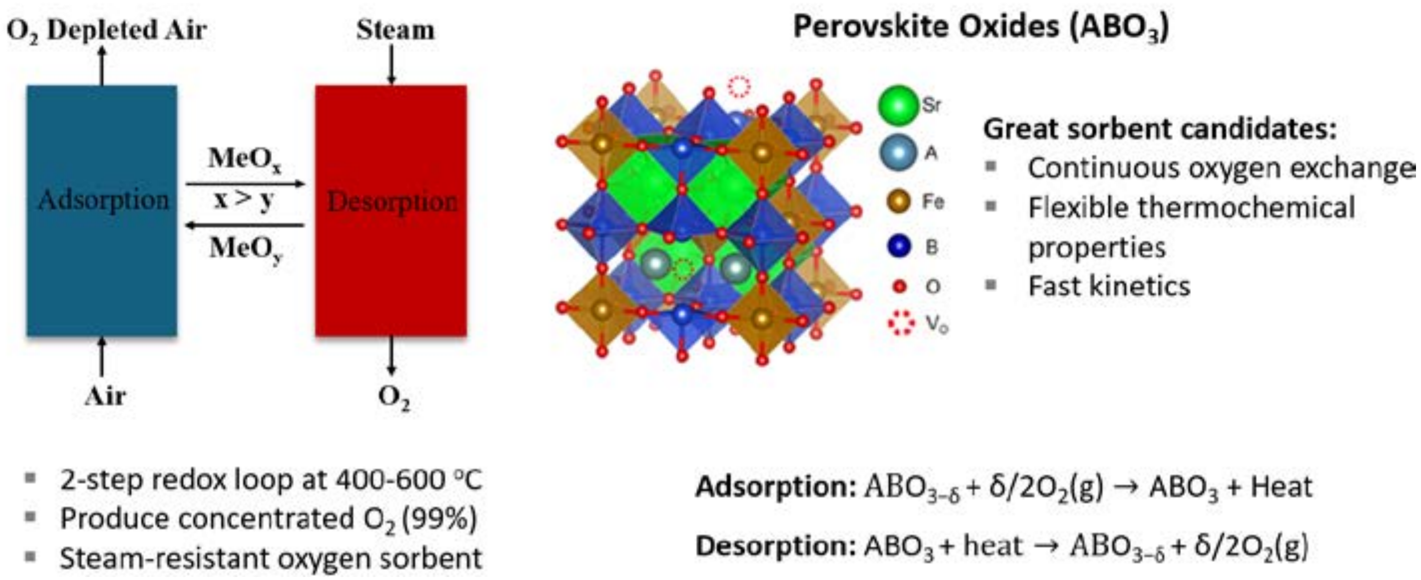


Figure 1: Redox loop (left) and perovskite oxides (right) basis for oxygen separation.

Intended development of the ASU requires high-performance oxygen sorbents having high capacity, stability and resistance to steam degradation. Using advanced modeling techniques such as density functional theory (DFT) and machine learning, the team identified promising perovskite oxide-based sorbent materials for cyclic oxygen capture and release. Among the candidates, a $Sr_xCa_{1-x}Fe_yCo_{1-y}O_{3-\delta}$ (SCFC) composition exhibited superior performance, achieving oxygen capacities seven times higher than a baseline material $SrFeO_{3-\delta}$. See Figure 2 for oxygen capacities of the baseline SF, SCFC and CSFN sorbents. The SCFC sorbent demonstrated stable performance over 10,000 redox cycles, suggesting high durability and long-term operational potential. CSFN exhibited superior oxygen capacity to SCFC at lower temperatures (400°C), maintaining an isothermal oxygen capacity of 2.2 wt% over 20 cycles. However, at such low temperatures, kinetics are limited, which requires longer desorption time.

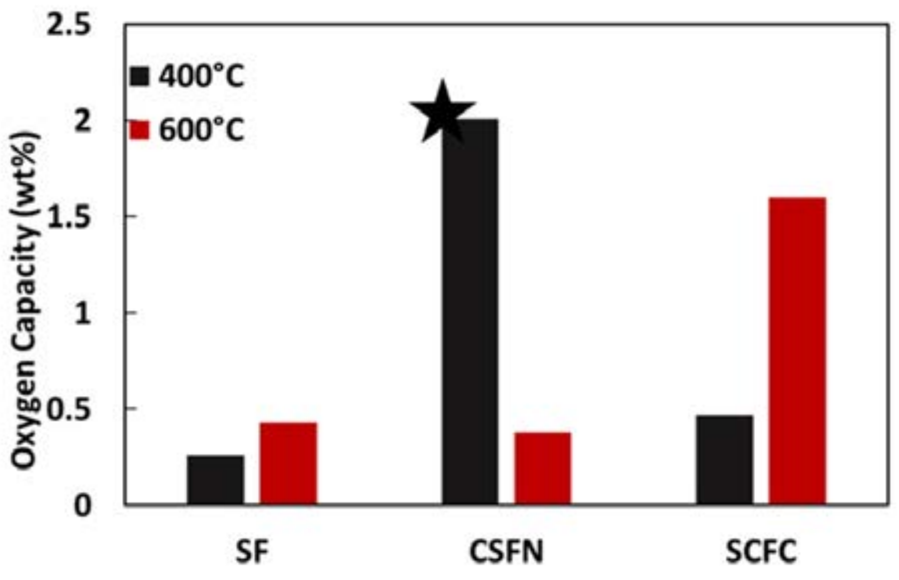


Figure 2: Isothermal oxygen capacities of sorbents under pressure swing between 20% O_2 and 1% O_2.

In addition to material development, process simulations are being utilized to determine the performance of an ASU system. The ASU system modeled is depicted in Figure 3.

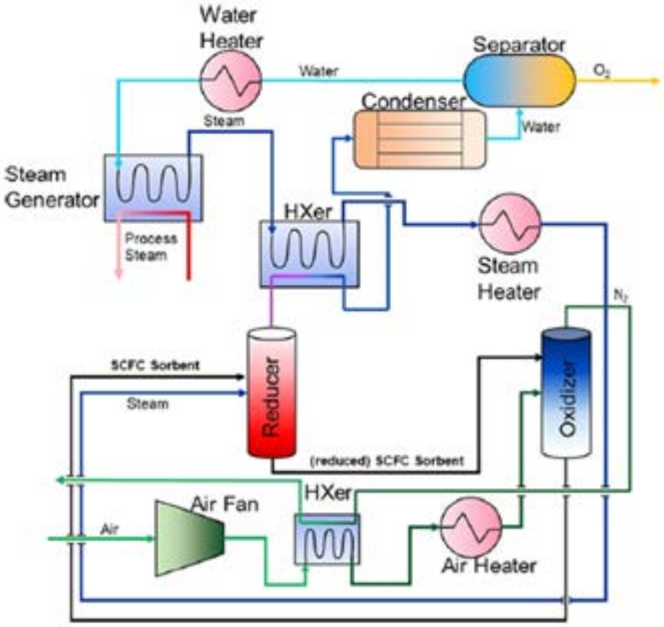


Figure 3: ASU system for process analysis.

Simulations indicate that the system could achieve a 30.8% reduction in energy consumption compared to traditional cryogenic air separation methods, using the SCFC sorbent (see Figure 4). Further efficiency improvements can potentially be achieved with the newly developed SCFN sorbents.

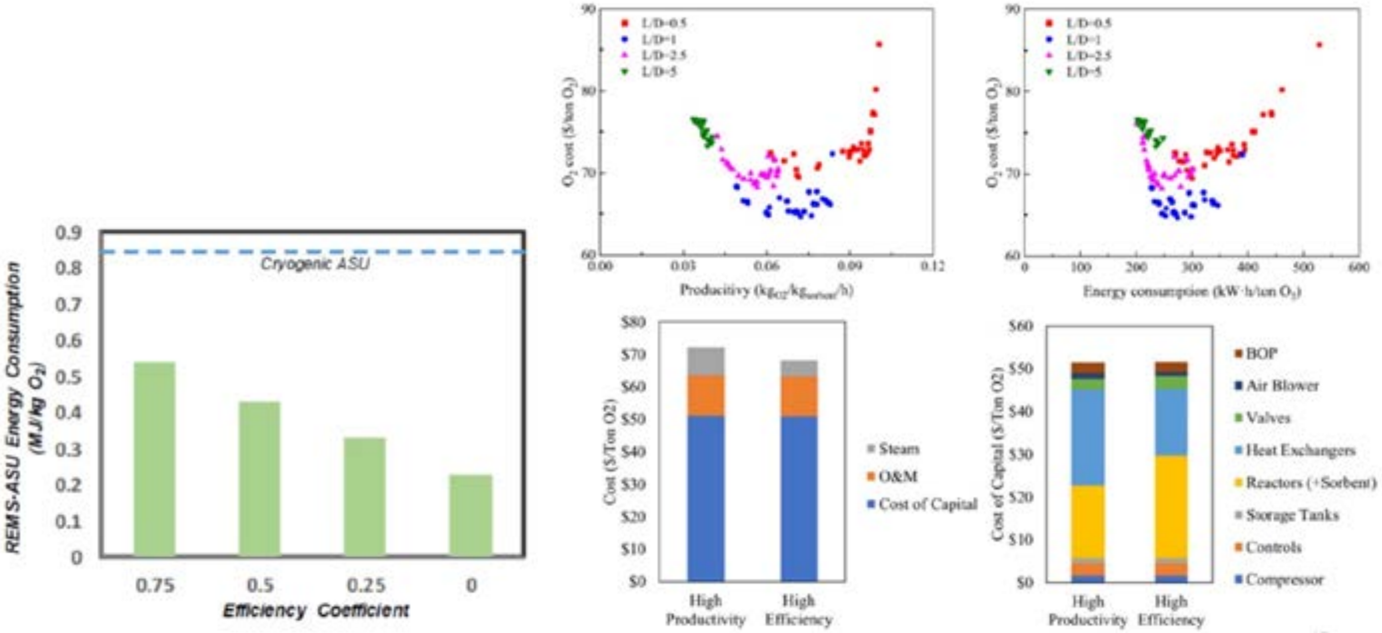


Figure 3: Energy consumption results and preliminary cost analysis.

A TEA will evaluate the cost-competitiveness of the redox ASU system against established oxygen separation technologies, such as cryogenic distillation and pressure swing adsorption. The TEA includes detailed cost breakdowns for materials, fabrication, energy consumption and operational expenses. Additionally, a life cycle analysis assesses the environmental impact of the system, focusing on energy efficiency and greenhouse gas emissions.

The current estimated results and target research and development (R&D) values for oxygen production economics are shown in Table 1.

TABLE 1: OXYGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Oxygen	\$/kg O_2	\$0.085/kg	\$0.07/kg
Capital Expenditures	\$/kg O_2	\$0.05	\$0.045
Operating Expenditures	\$/kg O_2	\$0.035/kg	\$0.025/kg

Definitions:

Cost of Oxygen – Projected cost of capture per mass of oxygen (O_2) produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of O_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of O_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M.

Other Parameter Descriptions:

Waste Streams Generated – Most of the water will be recycled, so wastewater amount resulting would be limited.

Process Design Concept – See Figure 3.

technology advantages

- The redox ASU is designed to consume less energy than traditional cryogenic ASUs, making it more suitable for small-scale applications.
- Sorbent bed-based ASUs have intrinsic modularity and reasonable unit capital costs per module, allowing for easy integration with small, distributed gasifiers, providing flexibility in deployment, scalability and cost-effectiveness.
- The redox ASU system can recuperate waste heat from the gasifier, leading to even higher process efficiency.
- Enables the production of high-purity oxygen (greater than 95%), enhancing the efficiency of downstream gasification processes.

R&D challenges

- Ensuring the long-term stability and performance of the perovskite sorbents under operational conditions, particularly in the presence of steam, is critical.
- System integration of an ASU with a gasification system requires careful engineering to maintain process efficiency and reliability.
- Scaling up from sub-pilot scale to commercial-scale systems involves challenges in maintaining performance, managing heat integration and ensuring economic viability.

status

Optimization of high-performance oxygen sorbents is underway to improve durability and efficiency under real-world ASU operating conditions. The ASU system is to be validated through additional experimental testing, specifically targeting 20 kg/day oxygen production capacity in the test bed.

available reports/technical papers/presentations

"An Advanced Modular Redox Air Separation System for Cost-Effective, Net-Zero Hydrogen Production," Kevser (Hilal) Bektas, North Carolina State University, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Bektas.pdf*.

Advancing Entrained-Flow Gasification of Waste Materials and Biomass for Hydrogen Production

primary project goal

The University of Utah is partnering with Ensyn Technologies and Linde to develop a high-pressure, slurry-fed, oxygen-blown entrained-flow system to enable co-gasification of pulverized coal, biomass pyrolysis liquids and liquefied plastic oil. Gasification performance of the most promising slurry mixtures is being evaluated in the University of Utah's pilot-scale pressurized oxygen-blown gasifier with Linde's hot oxygen burner (HOB) installed.

technical goals

- Determine compositions of coal-biomass-plastic mixtures that produce a stable slurry suitable for pumping to high pressure.
- Create blended feedstock slurries by mixing various combinations of coal, bioliquid and plastic oil, ranging from 25% to 60% biomass on a heating value basis.
- Design and test a novel burner to effectively atomize the mixed feedstock slurry in a pressurized gasifier.
- Acquire first-of-a-kind performance data for pressurized, oxygen-blown entrained-flow gasification of slurred blends of coal, biomass and plastic.

technical content

The most efficient and cost-effective gasifiers are the entrained flow type, using slurried or fine powder feed, which can be easily prepared from traditional solid fuels like coal and petcoke. Entrained flow gasifiers react feedstock with pure oxygen at high pressure and temperature to produce high-quality, relatively clean syngas with high conversion. However, low-density heterogeneous solid feedstocks such as biomass and wastes are difficult to feed into pressurized entrained flow gasifiers. Conventional gasification of wastes and biomass is therefore performed in non-pressurized fixed bed or fluidized bed gasifiers, which can accept bulky, moderately size-reduced materials such as chips and pellets. But these types of gasifiers are difficult or impracticable to pressurize, and operate at comparatively low temperatures that result in low conversion. Moreover, the resulting syngas is lower in quality and usually contaminated with tar, requiring expensive downstream cleanup.

The proposition of this work is to enable use of biomass and waste feedstocks in entrained flow gasifiers by converting those feedstocks to liquids that can be readily slurried and fed using conventional slurry feeding methods for these

program area:
Gasification Systems

ending scale:
Small Pilot, 1.4 TPD (275-335 kW_{th})

application:
Hydrogen Production

key technology:
Novel Technologies for Chemicals & Fuels

project focus:
Biomass and waste slurry feedstock entrained flow gasification

participant:
University of Utah

project number:
FE0032175

predecessor projects:
N/A

NETL project manager:
Sarah Pfeiffer
sarah.pfeiffer@netl.doe.gov

principal investigator:
Kevin J. Whitty
University of Utah
kevin.whitty@utah.edu

partners:
Ensyn Technologies Inc.;
Linde Inc.

start date:
01.01.2023

percent complete:
85%

gasifiers. Key features of the University of Utah process concept include conversion of biomass to pyrolytic bioliquid and conversion of mixed plastic waste to plastic oil, then blending of these with solid materials such as coal or char to prepare slurry suitable for pumping into a high-pressure entrained flow gasification system. This is illustrated in Figure 1.

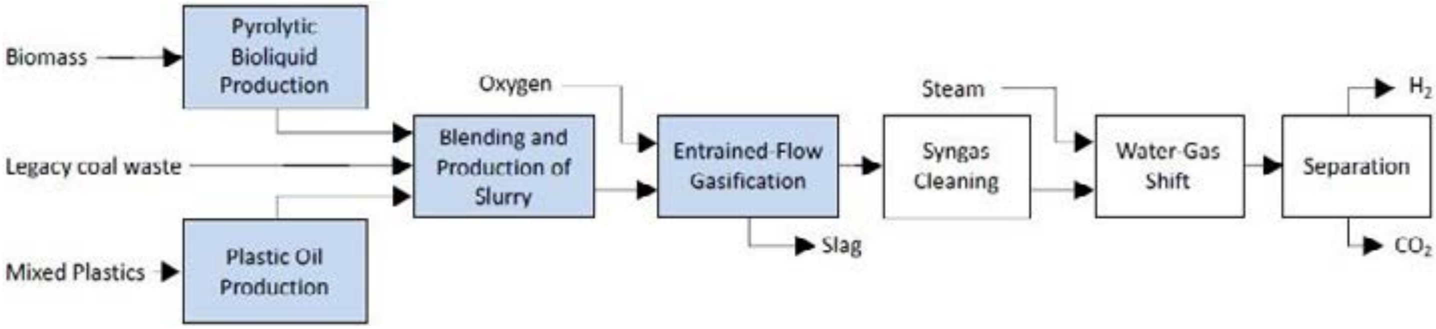


Figure 1: Process concept for high-pressure entrained flow gasification of waste and biomass derived feedstocks.

Specifically, the feedstock preparation utilizes (1) Ensyn's rapid thermal treatment technology for converting biomass into so-called bio-liquid, a stable emulsion of approximately 1,200 kg/m^3 density, similar to appearance to crude oil though having high water and oxygen content; and (2) thermal decomposition of waste plastic to produce plastic oil of approximately 800 kg/m^3 density and comparable to diesel in appearance and properties. Leveraging these technologies in slurry preparation is illustrated in Figure 2.

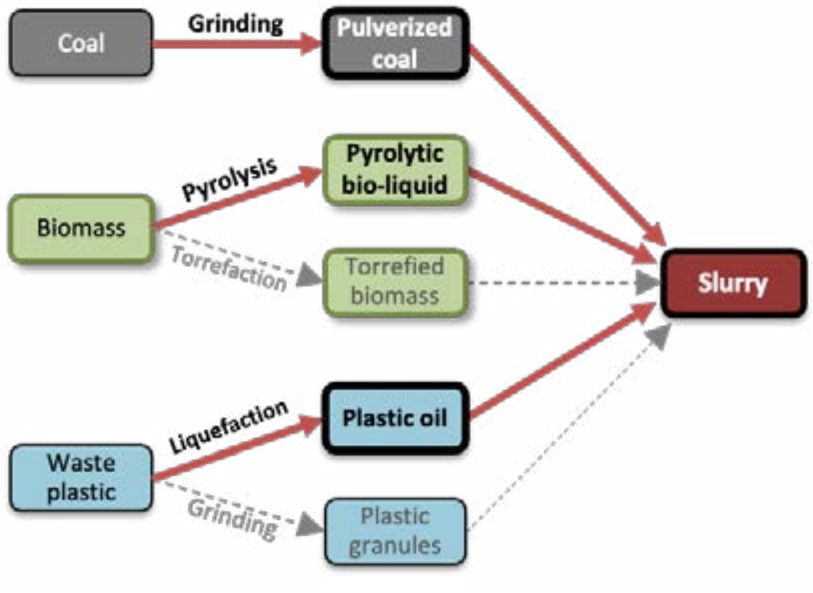


Figure 2: Details on waste and biomass processing associated with blending and production of slurry.

Emulsion stability and viscosity of the slurries made from these unusual components are important considerations, as separation of slurry into separate phases and excessively high viscosity make gasifier feeding problematic or impossible. The University of Utah investigated wide ranges of component mixtures and found that best slurry properties were attained with less than 45 wt% coal and less than 20 wt% plastic oil. Influence of coal and plastic oil on slurry viscosity was quantified, showing a predictable viscosity doubling as coal fraction increases from 10% to 20%, and doubling again from 20% to 30%. This is illustrated in Figure 3.

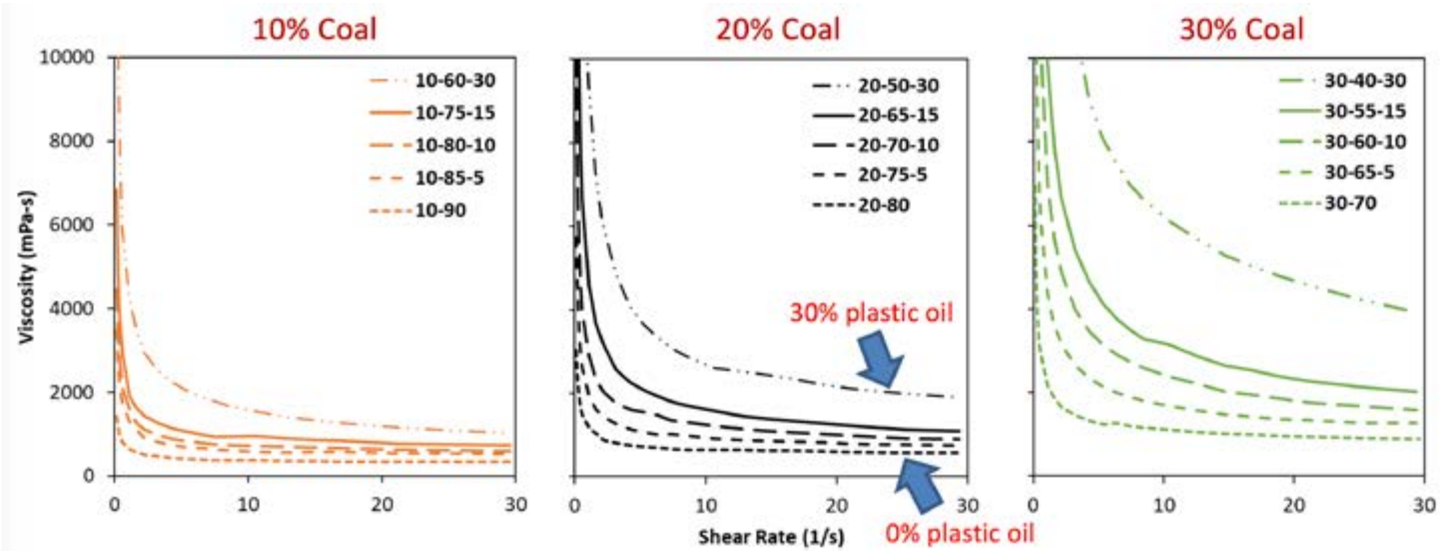


Figure 3: Influence of coal and plastic oil on viscosity.

Pressurized Entrained Flow Gasifier

Gasification testing utilizes the pressurized entrained flow gasifier located at the University of Utah's Advanced Energy Systems Research Facility, with feed capacity of 1-2 tons/day, maximum 500 kilowatt (kW) thermal input, operation at a maximum temperature of 3,000°F (1,650°C) and pressure up to 400 pounds per square inch (psi; (28 atm) with pressurized oxygen supply available for oxygen-fired operation. This is depicted in Figure 4.

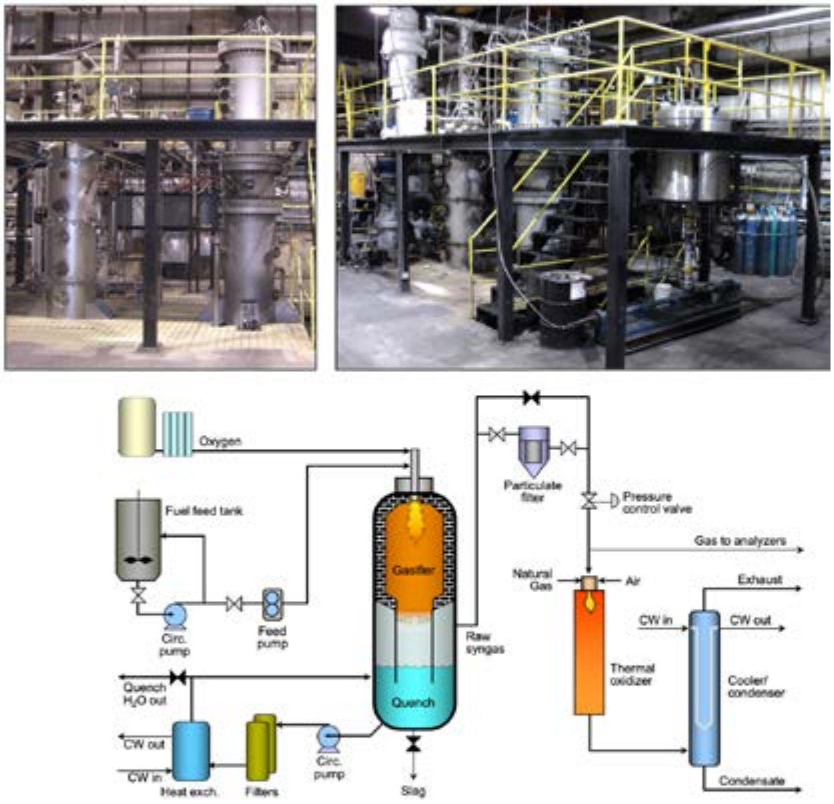
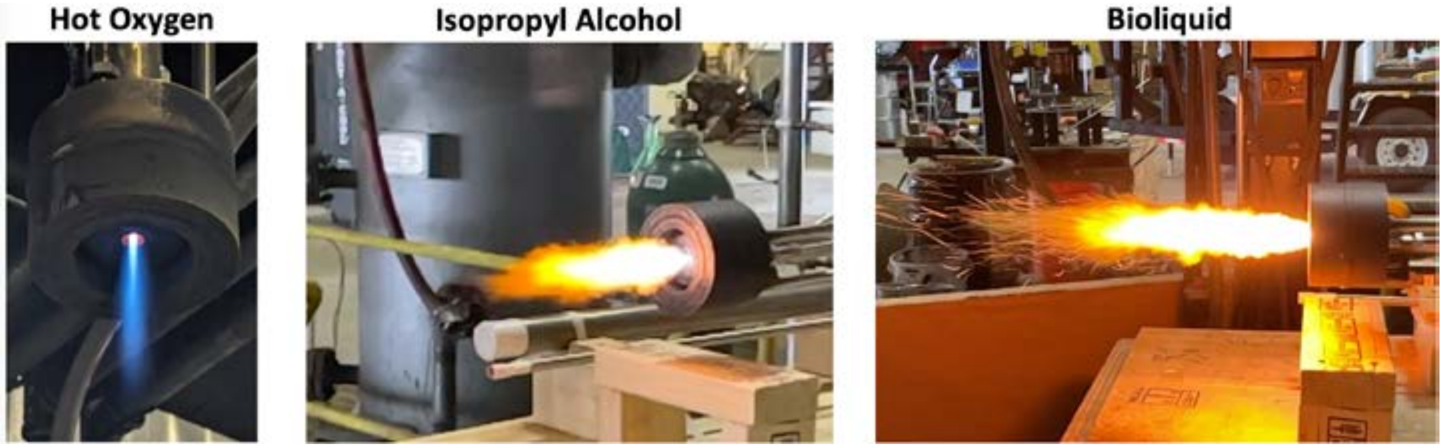


Figure 4: Pressurized entrained flow gasifier at University of Utah.

Hot Oxygen Burner

Liquid feedstock atomization is a challenge for oxygen blown entrained flow gasification, given low gas volumes available in the case of pressurized oxygen gas supply. The HOB is a viable solution, based on the commercially available Linde HOB, but in this case customized specifically for the Utah gasifier. Oxygen is preheated to achieve high velocity, reactivity and mixing. Initial testing has resulted in good performance. The Utah gasifier HOB in operation on various fuels is illustrated in Figure 5. Note the HOB has been metal 3-D printed; this allowed more flexible design.


Hot Oxygen

Isopropyl Alcohol

Bioliquid

Figure 5: Hot oxygen burner.

Techno-Economic Analysis

The current estimated results and target research and development (R&D) values for hydrogen production economics are shown in Table 1.

TABLE 1: HYDROGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Hydrogen	$/kg H_2	5.00	3.02
Capital Expenditures	$/kg H_2	2.50	1.14
Operating Expenditures	$/kg H_2	2.50	1.88

Definitions:

Cost of Hydrogen – Projected cost of capture per mass of hydrogen (H_2) produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of H_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of H_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M, feedstock cost.

Other Parameter Descriptions:

Waste Streams Generated – Slag, quench water.

Process Design Concept – See Figures 1 and 2.

technology advantages

- Facilitate leveraging extensive technology base for high-efficiency, pressurized entrained flow gasifiers for alternative feedstocks such as biomass and wastes (plastics, etc.).
- Syngas quality superior to that from gasifier types normally chosen for biomass and wastes (avoiding tar by-product).
- Slagging gasifier operation better allows ash and impurities management and allows wider feedstock range.
- Leverages relatively technologically advanced biomass and waste conversion technologies (e.g., Ensyn pyrolysis).
- Linde HOB technology component boosts efficiency.
- Advances clean hydrogen production technology toward the goal of achieving $1/kg of H_2 per Hydrogen Shot goals.

R&D challenges

- Keeping costs and energy consumption for biomass and wastes conversion to slurry ingredients down.
- Liquid feedstock atomization.

status

Stable and pumpable slurry compositions of solids and liquids (bio-liquid, pyrolysis oil) are now well understood. Gasification testing is showing good conversion and syngas quality. The Linde HOB is achieving high conversion, good syngas and little soot.

available reports/technical papers/presentations

"Advancing Entrained-Flow Gasification of Waste Materials and Biomass for Hydrogen Production," Kevin J. Whitty and David R. Wagner, The University of Utah, Project Update Presentation for DOE/NETL, August 26, 2024.

"Advancing Entrained-Flow Gasification of Waste Materials and Biomass for Hydrogen Production," David R. Wagner, The University of Utah, 2024 FECM/NETL Spring R&D Project Review Meeting, 23-25 April 2024, Pittsburgh, PA. *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Wagner.pdf*.

Fluidized Bed Gasification for Conversion of Biomass and Waste Materials to Renewable Hydrogen

primary project goal

Gas Technology Institute (GTI) is advancing an approach for efficient gasification of biomass, waste plastic and municipal solid waste (MSW) feedstock blends. The gasifier basis is the GTI U-GAS® fluidized bed gasification technology. Project focus was on understanding the chemical kinetics and gasification behavior of biomass and waste material feedstock blends, plus developing a safe and reliable feeding mechanism for those blends into GTI's U-GAS pilot-scale gasifier. Findings informed a prefeasibility study of a hydrogen (H_2) production plant concept.

technical goals

- Develop a gasification system to efficiently convert biomass and waste materials into renewable hydrogen with a target cost of $1 per kilogram.
- Address challenges associated with feedstock variability, including composition, ash content and handling issues, to ensure robust operation.
- Advance the process to Technology Readiness Level (TRL) 5 with the potential for scalable deployment.
- Optimize feedstock blends and gasification conditions to achieve high-hydrogen yields and low tar production.

technical content

In a fluidized bed gasifier, size-reduced solid feedstock is introduced into a reactor where it is suspended and mixed by an upward flow of gasifying agents like air, oxygen or steam. This fluidization enhances heat and mass transfer, leading to efficient and uniform gasification reactions. The U-GAS technology, developed by GTI Energy, is of this type, employing a single-stage fluidized bed gasifier designed for flexibility in feedstock, accommodating various ranks of coal, biomass and waste materials. The U-GAS technology is currently commercialized by SunGas Renewables for biomass and waste feedstocks. In the U-GAS system, the feedstock is dried and fed into the gasifier, where it reacts with steam and air or oxygen at temperatures ranging from 840°C to 1,100°C (1,550°F to 2,000°F). The operating pressure can vary between 3 to 30 bars (40 to 435 pounds per square inch absolute [psia]), depending on the desired application of the syngas. This design achieves high carbon conversion efficiency up to 99%, and a cold gas efficiency up to 85%. The resulting syngas is low in tar and oil content, reducing the need for extensive downstream cleaning. Additionally, the U-GAS process features dry feed and discharge systems, minimizing water usage and environmental impact. These attributes make the U-GAS technology a versatile and efficient solution for producing clean syngas from diverse feedstocks.

program area:
Gasification Systems

ending scale:
TRL 5, Pilot Scale 5-50 MWe

application:
Hydrogen Production

key technology:
Novel Technologies for Chemicals & Fuels

project focus:
U-GAS gasification of biomass & waste material feedstock blends

participant:
Gas Technology Institute

project number:
FE0032176

predecessor projects:
N/A

NETL project manager:
Drew O'Connell
andrew.oconnell@netl.doe.gov

principal investigator:
Martin Linck
mlinck@gti.energy

partners:
Idaho National Lab
Nebraska Public Power District
Electric Power Research Institute

start date:
12.01.2022

percent complete:
100%

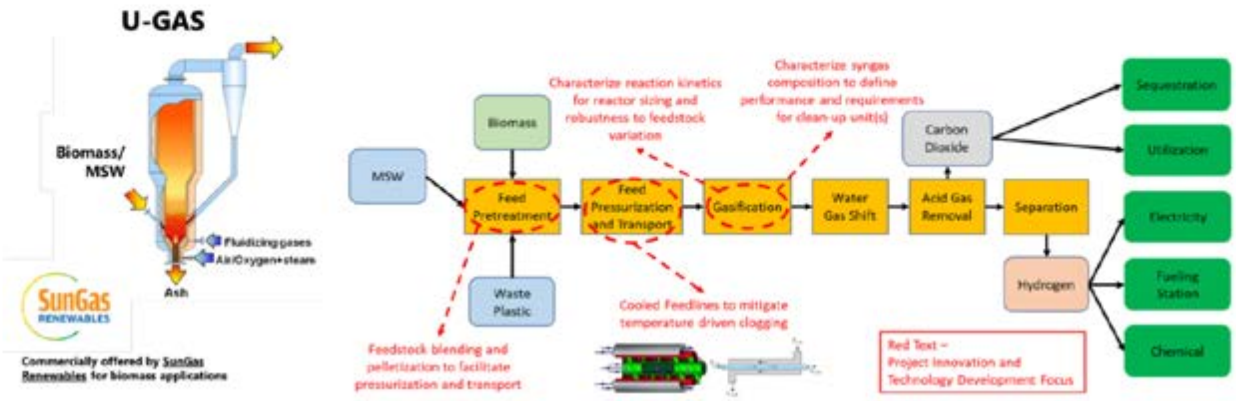


Figure 1: Process concept U-GAS gasification-based hydrogen production.

Project research and development (R&D) focused on using U-GAS gasification with a combination of low-cost biomass and MSW feedstocks for cost-effective, carbon-neutral production of hydrogen, as depicted in Figure 1. Feedstock preparation, feedline processing, subsequent reaction yields and reaction kinetics were studied/developed to advance process TRL to a value of 5.

To validate use of alternative feedstock sources and optimize feed mixtures, testing was done by Northwest University in South Africa on various mixtures of MSW, plastics and biomass with different ratios of fluid bed catalysts dolomite and brown alumina. The InnoVenton lab in South Africa also conducted char characterization and carbon dioxide (CO_2) reactivity studies; results indicated there was little functional difference between GTI's MSW and plastics feedstocks. Both MSW and plastics feedstocks were likely to produce very high yields of tars when devolatilized, but by contacting with large amounts of bed material (catalyst) during devolatilization tar conversion occurs and helps produce clean syngas. Gasification temperature of 800-850°C is hot enough to fully react feedstocks without melting ash to slag, thereby avoiding fouling issues in the U-GAS gasifier.

GTI conducted Mini-Bench Unit Gasifier (MBU-G) tests in Des Plaines, showing that 50/50 biomass and MSW produce lowest concentrations of CO_2 with higher yields for char, methane, ethane, ethene and hexanes. This ratio was chosen as the optimal pellet composition for pilot-scale feed testing due to carbon intensity and economics. Good ratios were achieved with the 50/50 biomass/MSW feed: an oxygen-to-carbon (O_2-to-C) ratio of 0.14:1 and a steam-to-carbon ratio of 0.4:1. Further, the deep bed of dolomite prevented tar formation, removing tars and preventing deposits in filters, lines, etc. Finally, a large hydrogen yield (12%) was observed over carbon monoxide (CO; 6.9%), (see Figure 2).

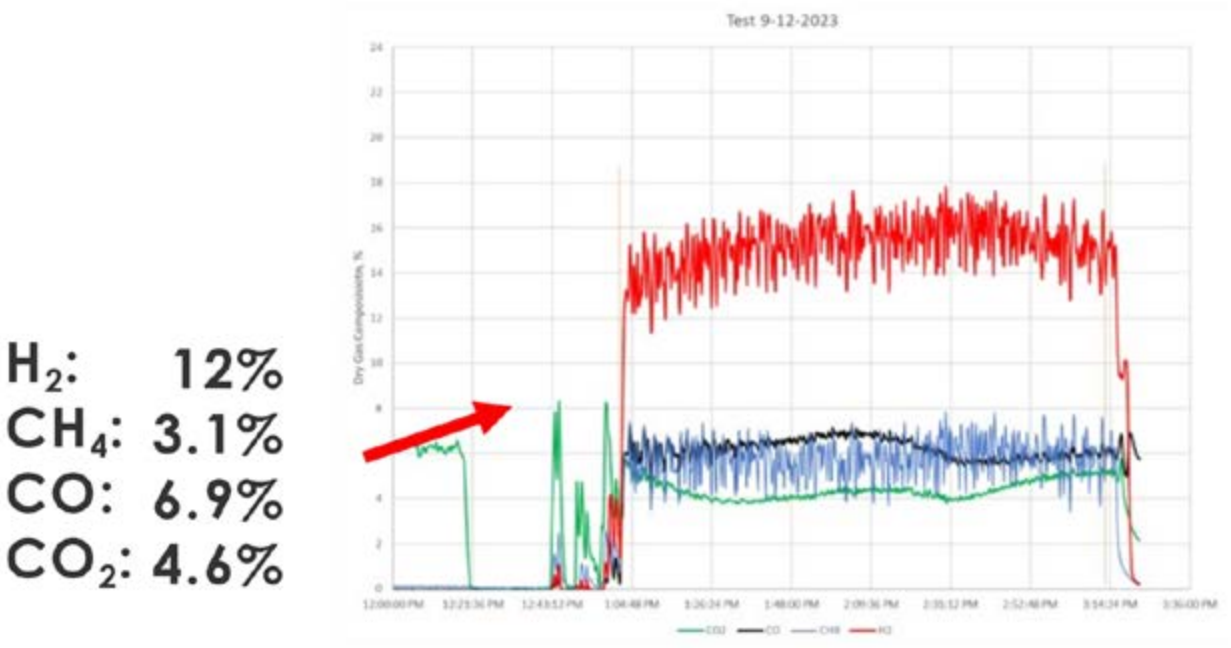


Figure 2: Syngas composition.

Ash analysis showed slag formation of 5% of the mass of ash. This was as expected with localized slag formation from low melting point material introduced by inorganics present in biomass. The bed material (dolomite) was partially transformed and decomposed to calcium oxide (CaO) and CO_2 and partially untransformed. The operating temperature of the MBU bordered the ash-slag transformation range (i.e., around 850°C).

Pneumatic and screw feed configurations were tested (see Figure 3). The conventional U-Gas pneumatic feeder resulted in no movement of feedstock pellets at operating temperatures and maximum feed velocity, showing that the pellets are too heavy for pneumatic feeding. However, testing of a screw feed system proved effective, without deleterious effects of heating on pellet morphology in the feeder over a wide range of feeding (1,200 lb/hr down to 300 lb/hr) even at elevated temperature up to 500°F.

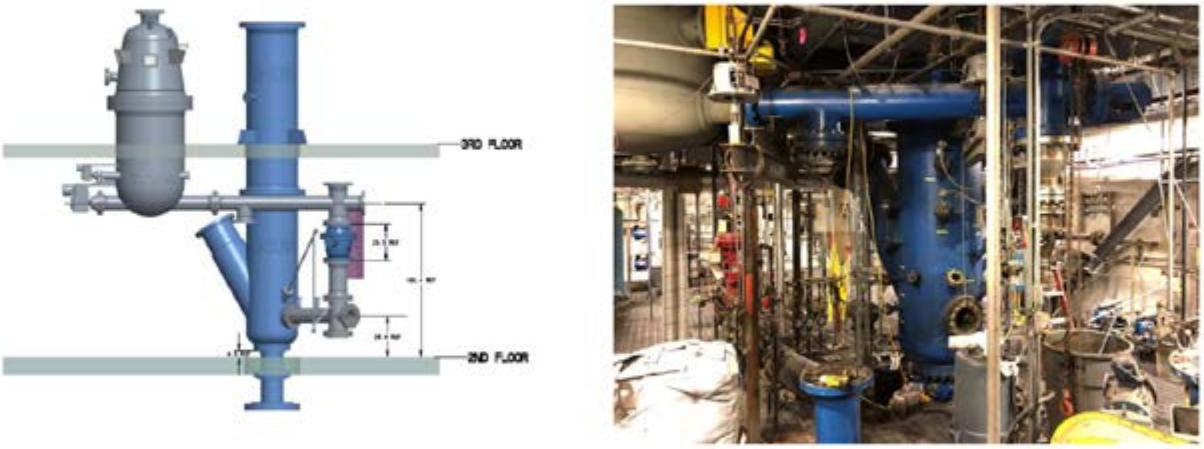


Figure 3: Pilot-scale U-GAS feed system.

Techno-Economic Analysis

The economics associated with a 1,000 ton per day (TPD) facility would depend heavily on the financing approach and incentives like 45V, but an H_2 selling price of approximately \$1/kg H_2 may be possible in some scenarios. Financial analysis indicates a feedstock cost of \$8.75/ton would allow current modular fluidized bed technology to meet the desired shot goal of \$1/kg hydrogen production. In an effort to approach this ambitious goal, MSW (-\$58/ton) may be used as a feedstock to offset the cost of biomass (\$75-150/ton) for carbon neutral production of cheap hydrogen.

The current estimated results and target R&D values for hydrogen production economics are shown in Table 1. It is anticipated that the target R&D values would be attainable, but that would require additional improvements to the technology dependent on further R&D work efforts in the relevant areas.

TABLE 1: HYDROGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Hydrogen	\$/kg H_2	\$3.49	\$2.02
Capital Expenditures	\$/kg H_2	\$1.27	\$0.78
Operating Expenditures	\$/kg H_2	\$2.22	\$1.13

The capital expenditure (CAPEX) target R&D value would be reached through the following technological improvements:

1) Enabling the U-GAS gasifier to operate at high pressures (30-40 bar).
2) Implementing an advanced piston-based feeder to the gasifier.

The operating expenditure (OPEX) target R&D value could be reached through the following design and operational improvements:

1) Enabling the gasifier to run on 100% MSW feedstock instead of a 50/50 biomass and MSW blend; with MSW made up of 50% biogenic components, it is expected the gasification-based H_2 production plant would still attain net-zero carbon intensity, assuming that CO_2 is captured and stored.
2) Increasing the hydrogen production plant capacity factor from 0.8 to 0.9; this could be accomplished with:
    a) Enhancing the plant maintainability through systems modularization.
    b) Improving plant operational reliability through extensive integrated pilot- or demo-scale testing.
3) Advancing an electrified reactor located downstream of the gasifier for tars and methane thermal decomposition; this electrification approach can increase the hydrogen throughput by up to 30%.
4) Sourcing 100% renewable power at \$40/MW-h or less

Conclusions/Findings

Feedstock Characterization — The North American waste streams identified by Idaho National Laboratory (INL) all contained large amounts of plastics waste. There was no clear real-world difference between “non-recyclable MSW” and “waste plastics” in this context.

Feedstock Optimization — Pellets with 50% biomass and 50% MSW offered the best balance of CO_2 reduction and economics.

Gasification — MSW-derived feedstocks contain higher ash content than biomass and lower fixed carbon and may produce very large amounts of heavy tars during devolatilization; gasification temperature of about 800-850°C is desirable to fully react fixed carbon while avoiding slagging. A deep bubbling bed of catalytic material like dolomite was effective in breaking up tars from MSW-derived feedstocks with no operational issues.

Feeder — Pneumatic feedstock injection hardware designed for pulverized coal is not suitable for use with pellets with the GTI gasifier. GTI's conventional injection screw had no problems with the 50/50 pellets, even when gasification hardware temperatures were simulated. GTI's passive approach to temperature control provides additional assurance that pellets will flow freely into gasifier bed during operation.

Definitions:

Cost of Hydrogen – Projected cost of capture per mass of H_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of H_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of H_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M, feedstock cost.

Other Parameter Descriptions:

Waste Streams Generated – CO_2 (largely renewable), gasifier bottoms residue (ash and dolomite bed material).

Process Design Concept – See Figure 1.

technology advantages

- **Feedstock Flexibility**: The system can process diverse feedstocks, including biomass, MSW and plastics, expanding its applicability and reducing dependence on single-source inputs.
- **Catalytic Optimization**: Catalyst loading effectively reduces tar formation, improving gasifier performance and syngas quality.
- **Environmental Impact**: The use of waste materials like MSW reduces landfill dependency and contributes to circular economy goals.

R&D challenges

- **Feedstock Variability**: Ensuring consistent gasifier performance with heterogeneous feedstocks remains a key challenge.
- **Tar Management**: Developing effective strategies for minimizing tar formation, especially with MSW and plastic-rich inputs.
- **Scale-Up**: Transitioning from bench-scale to larger-scale systems while maintaining performance and cost targets.
- **Ash Behavior**: Managing ash deposition and its impact on gasifier operation and maintenance.

status

Project was completed at the end of 2024.

available reports/technical papers/presentations

"Fluidized Bed Gasification for Conversion of Biomass and Waste Materials to Renewable Hydrogen," Martin Linck, GTI Energy, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems - PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Linck.pdf*.

"GTI Project 23302 Close-Out: FLUIDIZED BED GASIFICATION FOR CONVERSION OF BIOMASS AND WASTE MATERIALS TO RENEWABLE HYDROGEN," Martin Linck, Principal Investigator, GTI Energy Project 23302, FECM Project Close-Out Call: November 26, 2024.

U-GAS® Gasifier, NETL Gasifipedia page *https://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/ugas*.

"Overview on GTI Energy Gasification Technologies: Present and future," Zach El Zahab, Ph.D., Program Manager, Global Syngas Technology Council, 28-Oct-2022 *https://globalsyngas.org/wp-content/conference-presentations/2022/2022-D2-115-GTI.pdf*.

Performance Testing to Advance Modular, Moving-Bed Gasification for the Generation of Low-Cost, Clean Hydrogen From Biomass Mixed With Legacy Coal Waste, Waste Plastic and/or Other Waste

primary project goal

Electric Power Research Institute Inc. (EPRI) is evaluating blended feedstocks of biomass mixed with legacy coal wastes, plastic wastes and refuse-derived fuel (RDF) as feedstocks for moving-bed gasification for modular production of high-hydrogen-content raw syngas that can be shifted to produce clean hydrogen. In particular, the effects of the various fuels on syngas compositions, organic condensate production, ash characteristics and gasifier operations are targeted for study.

technical goals

- Develop pelletized feedstocks from biomass (woody biomass and corn stover) combined with legacy coal waste, plastic waste and RDF.
- Evaluate these feedstocks in an updraft moving-bed gasifier to produce high-hydrogen-content syngas suitable for clean hydrogen production.
- Gather data to inform the modular design of moving-bed gasification processes.
- Assess the impact of various fuel blends on feedstock development, syngas composition, organic condensate production, ash characteristics and gasifier operations.

technical content

Modular moving-bed gasification technology of blended feedstocks, including biomass, legacy coal waste and unrecyclable waste plastics, has promise as a basis for production of valuable, versatile hydrogen from these varied low-value feedstocks. By targeting flexibility in feedstock use and scalability in system design, current efforts aim to advance this technology, maintaining competitive cost performance while addressing operational and environmental challenges.

program area:
Gasification Systems

ending scale:
5-50 MWe equivalent

application:
Hydrogen Production

key technology:
Novel Technologies for Chemicals & Fuels

project focus:
Testing various feedstock effects on gasification operations

participant:
Electric Power Research Institute (EPRI)

project number:
FE0032180

predecessor projects:
FE0032044

NETL project manager:
Drew O'Connell
andrew.oconnell@netl.doe.gov

principal investigator:
Horst Hack
hhack@epri.com

partners:
Hamilton Mauer International (HMI)
NexantECA
Sotacarbo

start date:
09.01.2023

percent complete:
50%

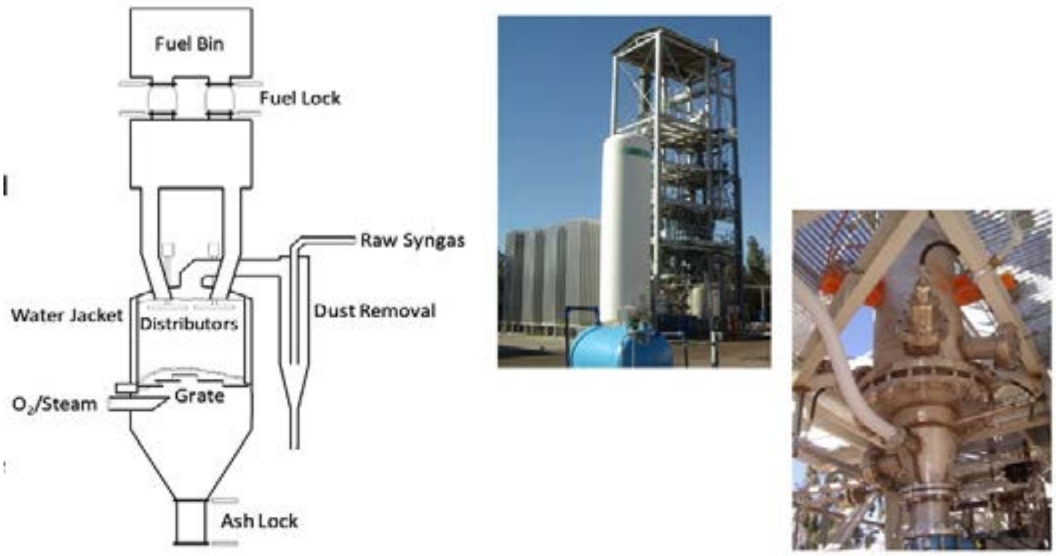


Figure 1: Diagram (left) and photographs (at Sotacarbo's test facility, right) of the moving-bed gasifier.

The gasification technology chosen as a basis for investigation on alternative feedstocks is the HMI gasifier, depicted in Figure 1. This is an updraft moving-bad gasifier based on the well-proven Wellman-Galusha gasification technology. The HMI gasifier pilot at Sotacarbo in Sardinia, Italy, has been proven in operation with conventional coal feedstocks (along with corn stover biomass and auto-shredder residue) in operational runs totaling more than 2,000 hours.

Gasification Performance on Alternative Feedstocks

Current investigations include preparing a range of pelletized feedstocks by blending biomass (woody biomass and corn stover), plastics and legacy coal waste. Physical and chemical analyses have revealed that pellet strength and durability depend heavily on the proportions of biomass and plastics, with higher biomass content improving structural integrity. Pellet blends containing up to 40% plastic demonstrated acceptable feeding behavior but required adjustment to reduce chlorine levels associated with RDF components.

Ash analysis showed substantial variability in composition, with biomass ash primarily consisting of calcium and potassium oxides, while plastics and coal waste contributed sulfur and silica. Blends with high coal waste content produced more fusible ash, necessitating adjustments to gasifier operating temperatures to avoid slagging.

Biomass-rich feedstocks exhibited high volatiles (60% to 70%), enhancing hydrogen yields but also increasing tar production. RDF blends exhibited elevated chlorine content (greater than 1%), prompting efforts to optimize blending ratios to minimize halogen-related corrosion risks.

Extensive testing was conducted using the Sotacarbo pilot gasifier, with experiments designed to assess hydrogen yields, syngas composition and operational parameters across feedstock blends. Optimal blends (50% biomass, 30% RDF and 20% coal waste) achieved hydrogen concentrations of up to 48% by volume in syngas. Plastic-heavy blends (greater than 40%) produced higher concentrations of methane (CH_4) and ethylene (C_2H_4), indicating potential downstream opportunities for hydrocarbon recovery or reforming. Feedstocks containing significant RDF or plastics produced more organic tars and condensates, ranging from 8% to 15% of total feedstock weight. Preliminary results suggest that the inclusion of catalysts, such as dolomite, in the gasifier bed can reduce tar yields by more than 30%, enhancing syngas quality.

Ash content in coal waste-rich feedstocks (greater than 40%) increased slagging tendencies at operating temperatures above 800°C. Implementing lower operating temperatures (700–750°C) reduced slagging risks while maintaining gasifier efficiency. The modular gasifier design demonstrated stable operation with feedstock blends containing up to 35% plastics, achieving steady-state conditions over eight-hour runs. Feeding consistency was maintained with pellets of uniform size (6 to 10 mm), ensuring predictable gasifier behavior.

Techno-Economic Analysis

Preliminary technoeconomic evaluations highlight the potential of blended feedstocks to achieve competitive hydrogen production costs: target hydrogen cost of \$1/kg appears feasible with feedstock costs below \$10/tonne, enabled by the inclusion of low-cost RDF and coal waste. Capital cost reductions are projected due to the modular design and reduced need for extensive syngas cleanup infrastructure, given improved gasifier performance.

The current estimated results and target research and development (R&D) values for hydrogen production economics are shown in Table 1.

TABLE 1: HYDROGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Hydrogen	\$/kg H_2	TBD	TBD
Capital Expenditures	\$/kg H_2	TBD	TBD
Operating Expenditures	\$/kg H_2	TBD	TBD

Definitions:

Cost of Hydrogen – Projected cost of capture per mass of hydrogen (H_2) produced under expected operating conditions.

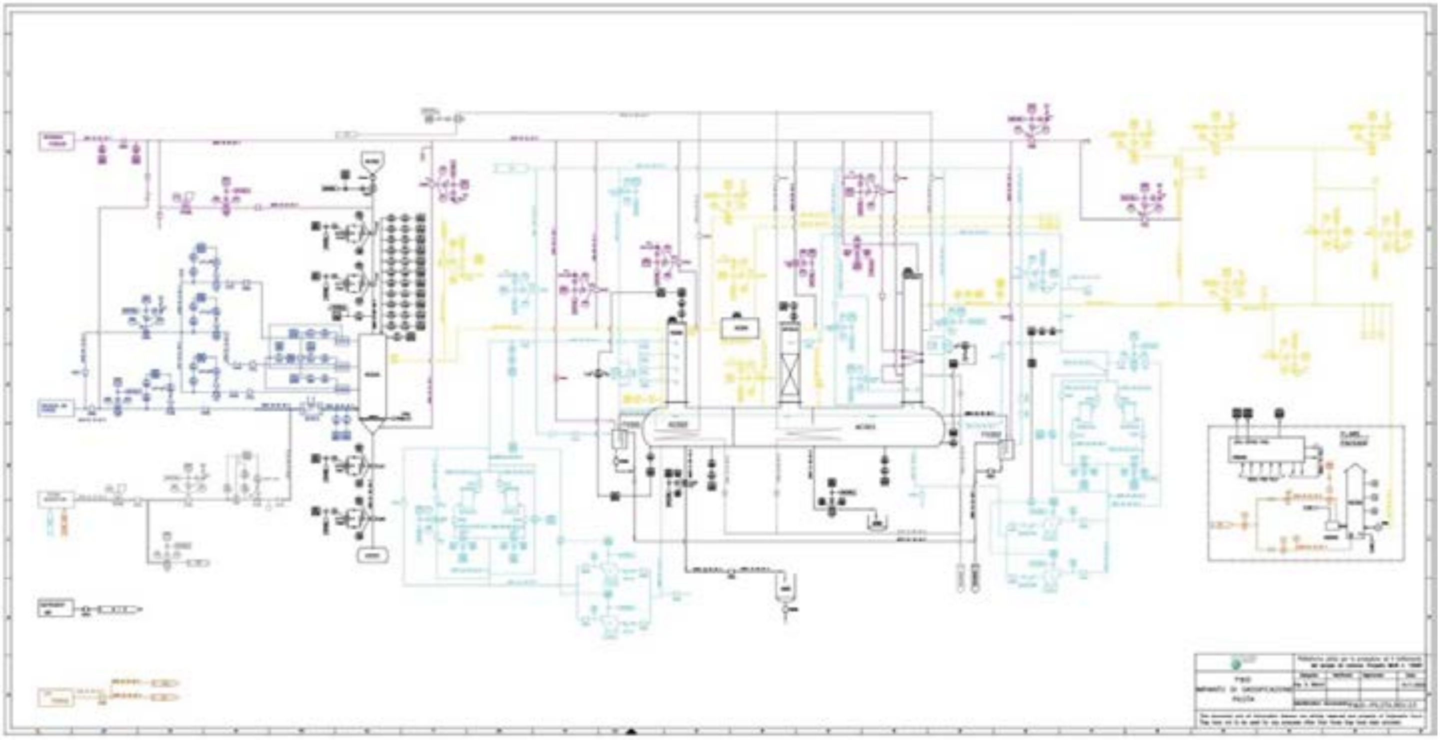
Capital Expenditures – Projected capital expenditures in dollars per kg of H_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of H_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M, feedstock cost.

Other Parameter Descriptions:

Waste Streams Generated – Not specified

Process Design Concept – See below.



Summary

Variations in feedstock properties, such as moisture, particle size and chlorine content, were mitigated by preconditioning and pelletization processes. Catalytic bed additives and adjustments to operating conditions have reduced tar formation, with ongoing tests aimed at further optimization. Finally, ash behavior modeling has informed strategies to maintain operational stability by adjusting blend ratios and modifying reactor temperatures.

technology advantages

- The ability to process diverse waste materials, including biomass, coal waste and plastics, enhances resource utilization and waste reduction.
- Developing modular/scalable gasification units (5–50 MWe equivalent) allows for adaptable deployment across various applications and locations.
- Producing high-purity, high-value hydrogen in modular/distributed applications offers varied market opportunities.

R&D challenges

- Ensuring consistent quality and composition of pelletized feedstocks from heterogeneous waste materials; fuel procurement issues.
- Managing gasification operational complexities associated with varying feedstock properties, such as moisture content and energy density.
- Effectively removing contaminants and impurities from syngas to meet the purity requirements for hydrogen production.
- Addressing potential corrosion issues within the gasifier and associated systems due to the presence of corrosive species particular to various waste-derived feedstocks.

status

Sotacarbo’s 12-inch pilot gasifier was determined to need various equipment upgrades to improve gasifier operations and testing results quality, specifically including control system upgrades and maintenance enabling real-time analysis, instrumentation replacement, tar/dust sampling system upgrades, loading and feeding system modification, and real-time bed height monitoring capability. These are underway.

available reports/technical papers/presentations

“Performance Testing to Advance Modular, Moving-Bed Gasification for the Generation of Low-Cost, Clean Hydrogen from Biomass Mixed with Legacy Coal Waste, Waste Plastic, and/or Other Waste,” Horst Hack, Electric Power Research Institute, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems - PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Hack.pdf*.

“Performance Testing to Advance Modular, Moving-Bed Gasification for the Generation of Low-Cost, Clean Hydrogen from Biomass Mixed with Legacy Coal Waste, Waste Plastic, and/or Other Waste,” Horst Hack, Electric Power Research Institute, Semi-Annual Project Review Meeting with DOE-NETL, November 13, 2024.

Hydrogen Production From High-Volume Organic Construction and Demolition Wastes

primary project goal

The University of North Dakota/Energy and Environmental Research Center (EERC) is studying gasification of difficult-to-recycle waste materials to make clean hydrogen (H_2). The focus is on utilization of construction and demolition (C&D) debris/wastes having a high proportion of treated lumber (containing various toxic contaminants such as arsenic) in a gasification-based process, converting this material efficiently and economically to clean hydrogen while simultaneously capturing the toxic species. Genuine C&D waste feedstock will be utilized in multiple trials using EERC's high-pressure fluidized bed pilot gasifier, in which improving shift catalyst performance, tar cracking and steady-state hydrogen generation will be evaluated/demonstrated.

technical goals

- Develop an integrated gasification and gas cleanup process to produce 99%-pure hydrogen from contaminated C&D waste feedstock.
- Determine the disposition of key contaminants, including arsenic, chromium and boron, and verify methods for their storage in ash.
- Test and optimize a commercially available oxygen-blown fluidized-bed gasification (FBG) technology for real-world C&D waste applications.
- Perform techno-economic and greenhouse gas (GHG) life cycle analyses for a commercial-scale plant in Kapolei, Hawaii.

technical content

The technical focus is on converting organic C&D waste into hydrogen through an innovative gasification and gas cleanup process. The highly contaminated nature of C&D waste presents unique challenges, including the need to manage heavy metals, chlorine and other pollutants inherent in treated wood and refuse-derived materials. By integrating advanced feedstock preparation, gasification and contaminant management techniques, a modular and scalable process for production of high-purity hydrogen can be advanced.

The first area of progress involved the comprehensive characterization of C&D waste as a feedstock. C&D waste, the largest solid waste stream in North America at more than 600 million tons annually, was analyzed to assess its composition and suitability for gasification. The team focused on feedstock components such as treated lumber containing chromated copper arsenate (CCA), borate-treatment, fire-retardant chemicals and other construction residues that cannot be readily recycled, and which usually end up in landfills. Initial findings indicated

program area:

Gasification Systems

ending scale:

Small pilot: 0.25 TPD (50 kW_{th})for H_2 production; Model & simulation: 50 and 500 tons waste in-feed per day (5 and 50 MW_e)

application:

Hydrogen Production

key technology:

Novel Technologies for Chemicals & Fuels

project focus:

Clean H_2 from construction and demolition (C&D) debris via oxygen-blown fluidized bed gasification

participant:

University of North Dakota's Energy & Environmental Research Center

project number:

FE0032183

predecessor projects:

USDA NIFA SBIR 2021-39410-35996

NETL project manager:

Mark C. Freeman
mark.freeman@netl.doe.gov

principal investigator:

Michael Swanson
University of North Dakota
mswanson@undeerc.org

partners:

Simonpietri Enterprises LLC

start date:

03.01.2023

percent complete:

80%

high levels of chlorine (from paints and plastics) and heavy metals, including arsenic, boron, chromium and copper. Pretreatment processes, including shredding, metal separation and pelletization, were optimized to produce a uniform feedstock that supports consistent feeding into a gasifier (see Figure 1). The resulting feedstock demonstrated improved flowability and reduced variability, key for steady-state operation in gasification trials.

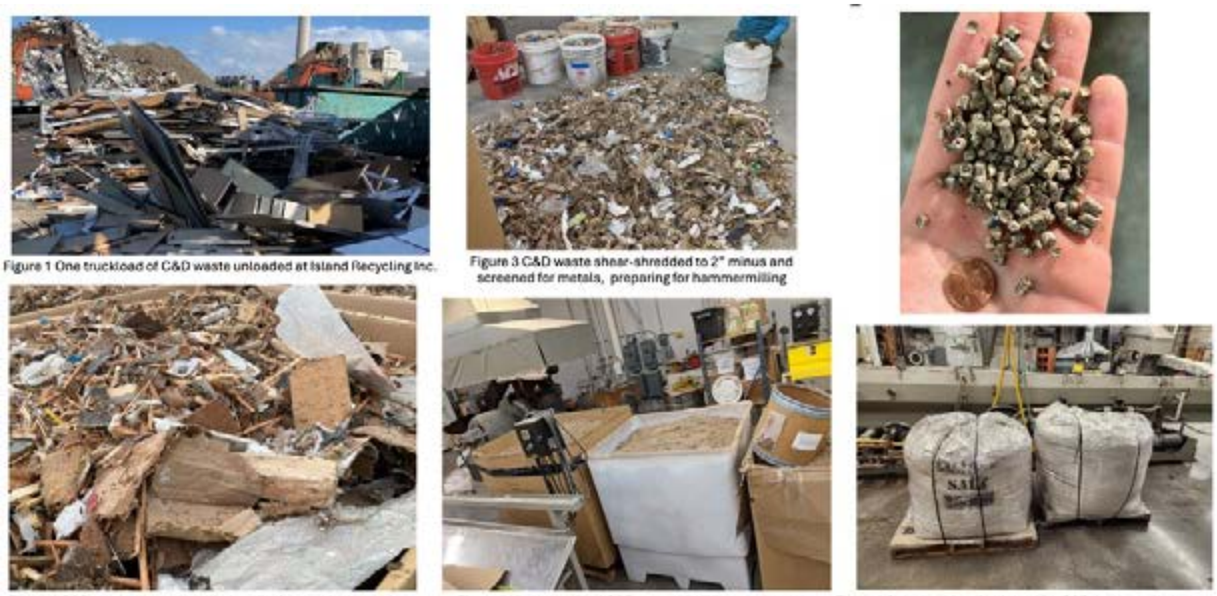


Figure 1 One truckload of C&D waste unloaded at Island Recycling Inc.

Figure 3 C&D waste shear-shredded to 2" minus and screened for metals, preparing for hammermilling

Figure 2 C&D waste shear-shredded to 4" minus and screened for ferrous and non-ferrous metals in a car shredder

Figure 5 Hammermilled C&D waste "fluff," preparing to be pelletized

Figure 6 Pelletized fuel feed used for C&D waste-to-hydrogen gasification trials

Figure 1: Waste feedstocks and pelletization.

An initial gasification trial focused on evaluating contaminant storage strategies to mitigate the impact of arsenic, boron and chromium on downstream hydrogen-shift catalysts. Using proprietary sorbents in the FBG, the project successfully stored more than 99.5% of arsenic in the ash phase while immobilizing it to reduce leachability.

A second trial targeted tar-cracking options to enhance syngas quality while also maintaining heavy metal storage performance. After considering three approaches — high-temperature tar-cracking catalyst, second stage tar cracking, and Linde hot burner technology (HOB) — the team identified HOB as the best option moving forward due to both lower risk of catalyst poisoning and the ability to use a co-located entrained flow gasifier (EFG) as a second stage tar cracker. This process concept is illustrated in Figure 2.

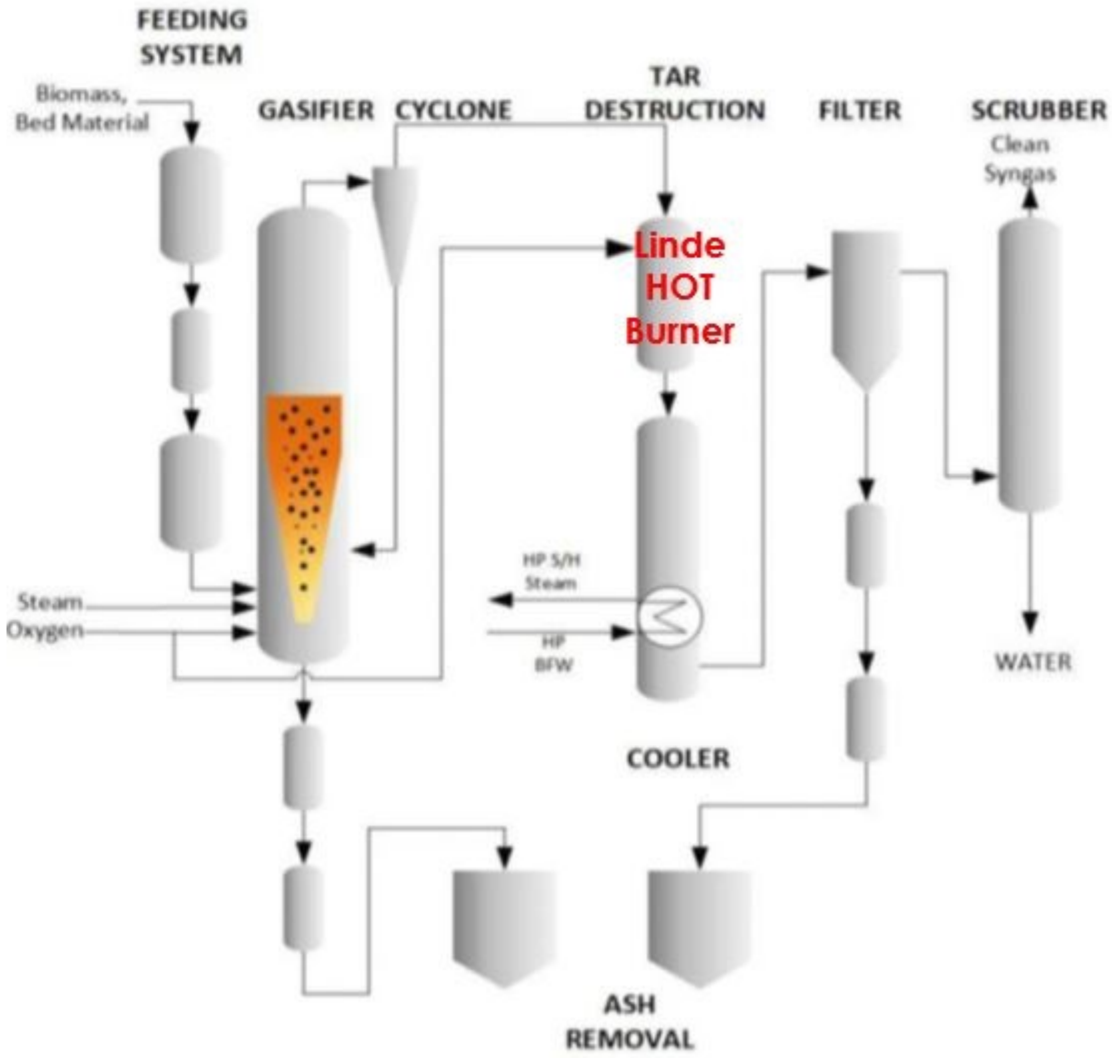


Figure 2: Process flow diagram of Sungas Renewables and Linde HOB integrated system.

The team conducted approximately 70 hours of continuous C&D fuel feed to the gasifier using a low-intensity mixing generic burner. Aromatic hydrocarbons concentrations were reduced by more than 80% but were still higher than in the typical syngas from oxygen-blown EFG of coal. Aliphatic hydrocarbon concentrations were more than 95% reduced and were similar to typical oxygen-blown EFG test outputs for coal. Utilization of the intensely mixed Linde HOB in the third and final test campaign is expected to complete the tar-cracking process even for the more thermally stable aromatic compounds. Recovered ash was mostly fly ash instead of slag; EFG reactor exit piping was not designed for that ratio and suffered ash overloading, which curtailed the testing. Significant conversion of carbon in the cyclone fines was observed with much less (greater than 50% less) carbon in the ash than without a second stage, due to additional carbon gasification at the high temperatures. Oxygen addition did result in some oxidation of syngas constituents, thereby reducing overall syngas energy value.

Contaminant capture in tar-cracking tests showed promising preliminary results. Arsenic capture was greater than 98.5% after a second stage tar cracker and filter, but only about 90% captured when sampled between the FBG outlet and EFG inlet. Boron was captured at 86% after the second stage and filter. Less than half of the chlorine was captured after the second stage and filter. All other trace metals were captured almost completely (greater than 99.9%) after the second stage tar cracker and filter. As a result of these rates of capture, no arsenic was detected in an arsine guard bed or further downstream in catalyst beds, though chlorine and small amounts of boron were detected in downstream catalyst beds. Chlorine management was not an initial focus for this research, but observation of chlorine capture through the process is informing future research and system design.

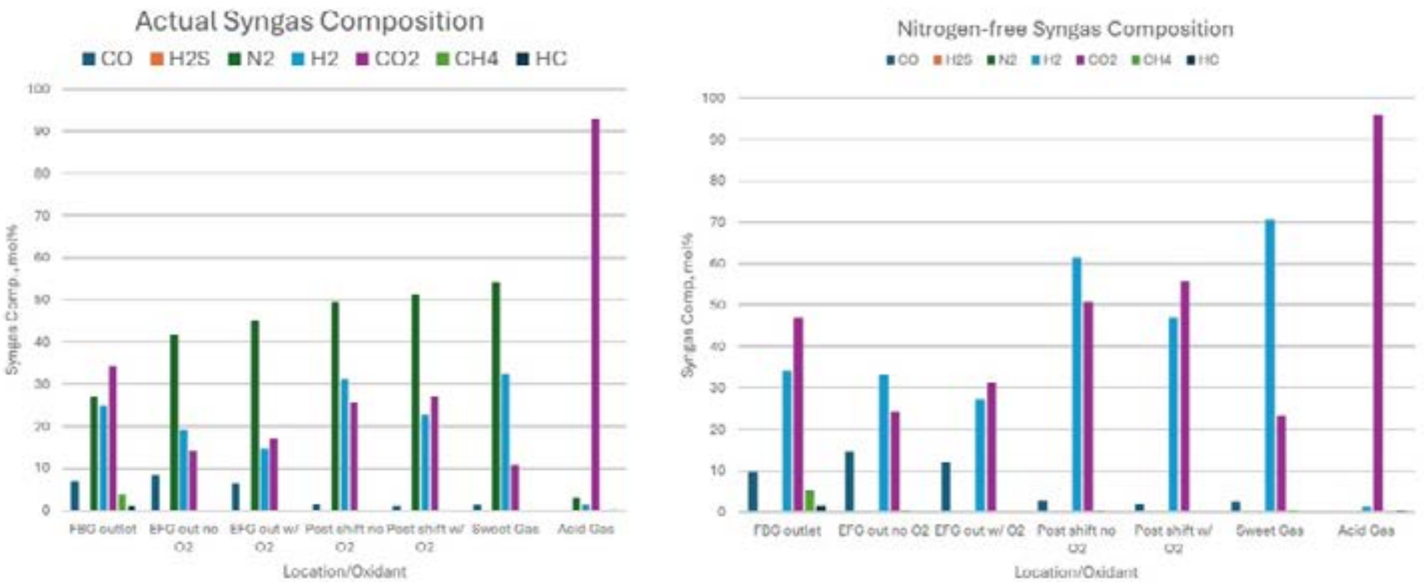


Figure 3: Syngas compositions.

Preliminary results from a GHG life cycle analysis for hydrogen production demonstrated near-zero carbon intensity at 2.08 gCO_2e/MJ, 97% reduction when compared to North American natural gas-derived H_2, 99% reduction compared to petroleum gas-derived H_2, and that the process approach would be investment-grade carbon credit-eligible.

Techno-Economic Analysis

A preliminary techno-economic analysis (TEA) for a commercial-scale plant in Kapolei, Hawaii, demonstrated promising economic viability. Leveraging the negative-value nature of C&D waste (due to tipping fees), the cost of hydrogen production was estimated to be highly competitive with conventional methods. Furthermore, life cycle GHG analysis indicated substantial environmental benefits, while also diverting up to 600 tons per day of construction waste from the landfill at each modular facility. The current estimated results and target research and development (R&D) values for hydrogen production economics are shown in Table 1.

TABLE 1: HYDROGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Hydrogen	$/kg H_2	2.67	$1
Capital Expenditures	$/kg H_2	1.16	TBD
Operating Expenditures	$/kg H_2	1.51	TBD

Definitions:

Cost of Hydrogen – Projected cost of capture per mass of H_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of H_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of H_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M, feedstock cost.

Other Parameter Descriptions:

Waste Streams Generated – Bed and fly ash stream generation of 5% to 15% of the solid waste in-feed, passing Toxic Characteristics Leaching Protocol for nonhazardous waste disposal; water waste condensate generated was shown to be able to be treated and disposed using conventional industrial wastewater treatment methods.

Process Design Concept – See Figure 2.

technology advantages

- Converts a significant high-tipping fee waste stream into valuable hydrogen, reducing landfill use and associated environmental impacts.
- Employs proprietary management techniques to store/immobilize harmful contaminants, ensuring the protection of downstream processes and catalysts.
- Technology is suitable for modular-scale plants, allowing for flexible deployment across various locations and capacities.

R&D challenges

- Managing the heterogeneous nature of C&D waste feedstock, which includes varying levels of contaminants and material compositions.
- Developing effective methods to store contaminants like arsenic, boron and chromium in the ash to prevent catalyst poisoning.
- Some sodium-based bed agglomeration was observed, which can be controlled with additive addition.
- Managing higher-than-desired levels of chorine and boron contamination after syngas cleanup.
- Identifying and optimizing tar-cracking methods suitable for biomass with C&D contaminants to ensure efficient syngas production.
- Ensuring seamless integration of gasification and gas cleanup processes to achieve the desired hydrogen purity and system efficiency.

status

Plans include conducting the third gasification trial focused on utilizing the Linde HOB to finalize testing on integrated processes, specifically focusing on contaminant storage and tar-management strategies. The project will also iterate TEAs for a commercial-scale system of 5-50 megawatt-electric (MWe), with a focus on establishing cost-effective hydrogen production and life cycle GHG impacts. Additional efforts will be directed at improving computational particle fluid dynamics (CPFD) models for the FBG to enhance system design. Finally, the team will transition to designing and implementing a pilot-scale demonstration facility, laying the groundwork for scaling to a full commercial modular plant.

available reports/technical papers/presentations

"Hydrogen Production from High Volume Organic Construction and Demolition Wastes," Michael Swanson, University of North Dakota Energy & Environmental Research Center, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems - PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Swanson.pdf*.

"Processing and Gasification of Construction and Demolition Debris" issued Patent No. 12,157,863 on Dec. 3, 2024, to Simonpietri Enterprises LLC employees Joelle Simonpietri and Zachary Wadas. Data from this research was used to defend this patent application, originally filed with the U.S. Patent and Trademark Office on Oct. 28, 2022.

"Aloha Sustainable Materials Recycling and Fertilizer Facility" Simonpietri Enterprises LLC, Final Environmental Assessment with a Finding of No Significant Impact - Published in the *State of Hawaii Environmental Register* Feb. 23, 2025, for a 5-Mwe-scale pilot facility to be constructed in Kapolei, Hawaii. Data from this research was used to inform the system design, environmental assessment, and community and agency consultation.

Machine Learning-Enhanced LIBS to Measure and Process Biofuels and Waste Coal for Gasifier-Improved Operation

primary project goal

Energy Research Company (ERCo) is collaborating with Lehigh University and Gas Technology Institute (GTI) to develop an instrument to measure the composition of feedstock to a gasifier in situ and in near real-time, resulting in immediate and time-sensitive fuel data that gasifier operators can use in a feedback or feed-forward control scheme to maximize performance and avoid instability of ash-forming constituents in feedstocks. The instrument combines laser-induced breakdown spectroscopy (LIBS) with machine learning (ML)/artificial intelligence (AI).

technical goals

- Develop ML-enhanced LIBS for real-time, in situ analysis of feedstock composition/properties, including ash, carbon, sulfur and fusion temperatures.
- Optimize gasifier operations using LIBS data to adjust slagging and fusion points dynamically.
- Test and evaluate biomass and coal waste blend ratios for improved gasification efficiency.
- Integrate advanced ML algorithms into LIBS software for real-time data processing and display.
- Use ML-LIBS outputs in GTI's gasifier simulator, better simulating a commercially operating gasifier and determining exact gasifier performance from ML-LIBS measurements.
- Develop and commercialize a fully automated, field-capable OnSpec™ LIBS instrument.

technical content

ERCo is leading an effort for developing and deploying an advanced ML-enhanced LIBS technology for accurate near real-time gasifier feedstock characterization. Gasification is a versatile and efficient process for converting biomass and coal waste into hydrogen and syngas, but variability in feedstock properties such as ash content, fusion temperatures and elemental composition presents significant operational challenges. This project seeks to address these challenges by integrating real-time, in situ LIBS analysis with ML algorithms to provide actionable data for gasifier control.

The core of the technology lies in the OnSpec LIBS instrument, which uses laser pulses to generate a plasma on the surface of feedstocks. The light emitted from

program area:

Gasification Systems

ending scale:

Commercial ready instrument in a laboratory setting

application:

Hydrogen Production

key technology:

Novel Technologies for Chemicals & Fuels

project focus:

Develop ML enhanced LIBS for feedstock measurement

participant:

Energy Research Company (ERCo)

project number:

SC0022696

predecessor projects:

N/A

NETL project manager:

Sarah Pfeiffer
sarah.pfeiffer@netl.doe.gov

principal investigator:

Robert De Saro
rdesaro@er-co.com

partners:

Lehigh University; Gas Technology Institute (GTI); SpG Consulting LLC

start date:

06.27.2022

percent complete:

75%

the plasma contains spectral signatures corresponding to the feedstock's elemental composition. These spectra are processed in real time by ML algorithms, which convert them into quantitative measurements of key feedstock properties such as carbon content, heating value, sulfur content, ash composition and slagging potential. This real-time analysis seeks to enable dynamic adjustments in gasifier operations, such as optimizing slagging behavior and fusion points, ensuring efficient and cost-effective gasification performance. The concept is illustrated in Figure 1.

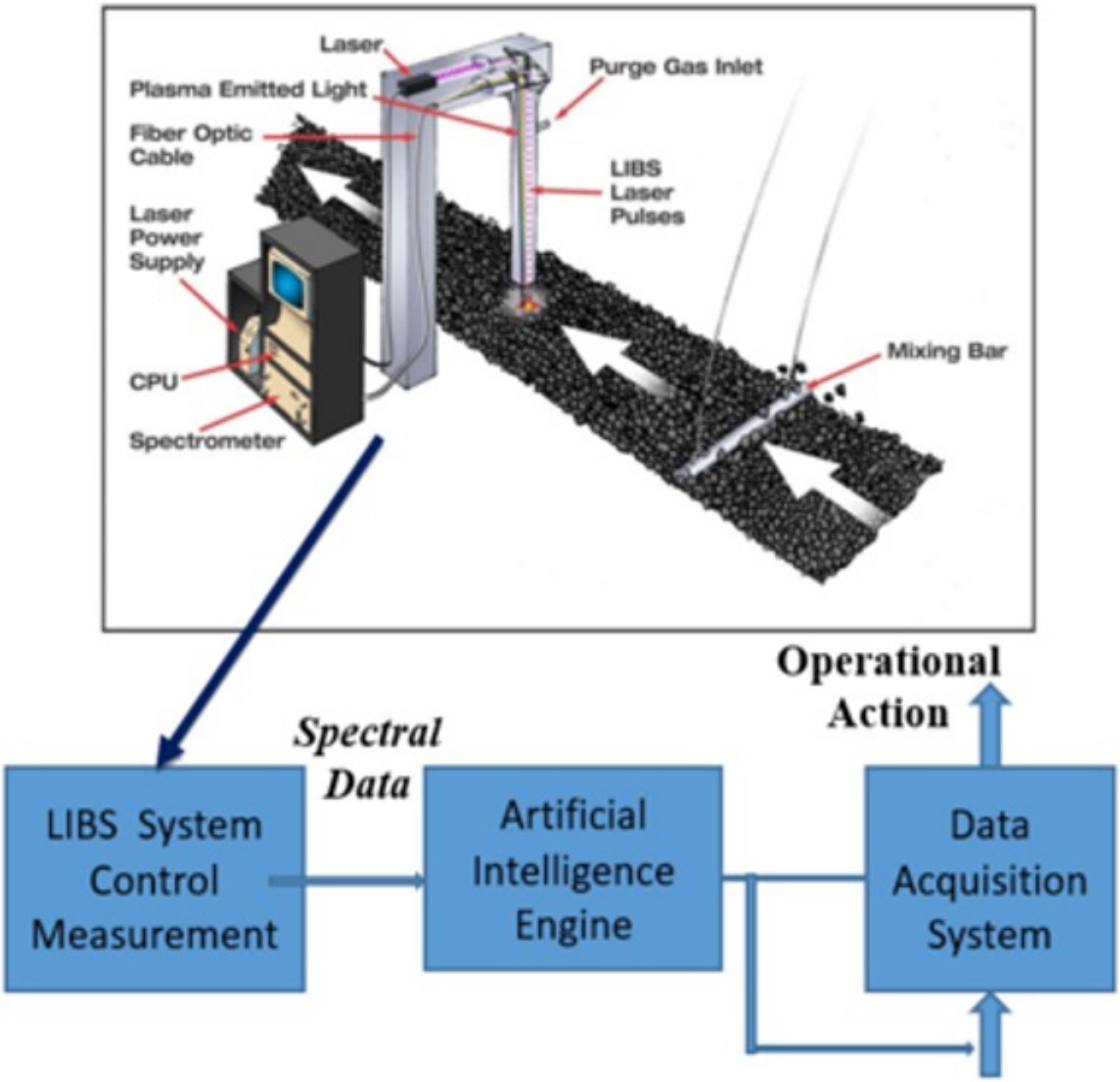


Figure 1: Concept of ML-enhanced LIBS technology.

Current development work includes expanding the LIBS technology's capabilities to handle a broader range of feedstocks, including various biomass and coal waste blends. The ML-enhanced LIBS system is being integrated with GTI's gasifier simulator to validate its impact on operational efficiency, slagging potential and syngas quality. By combining advanced spectroscopy, ML and gasifier modeling, ML-LIBS technology can be advanced to a commercially viable solution for improving the performance of modular gasification systems.

Results have demonstrated the feasibility and accuracy of the ML-enhanced LIBS technology for real-time feedstock characterization in gasification applications. The system has achieved high precision in measuring critical feedstock properties, including heating value, ash content, carbon, sulfur, various ash oxides and fusion temperatures, with R^2 values between 0.82 and 0.99. Testing on various feedstocks, including biomass, coal waste and blended materials, has shown excellent signal-to-noise ratios for all elements analyzed. An example of heating value prediction is shown in Figure 2.

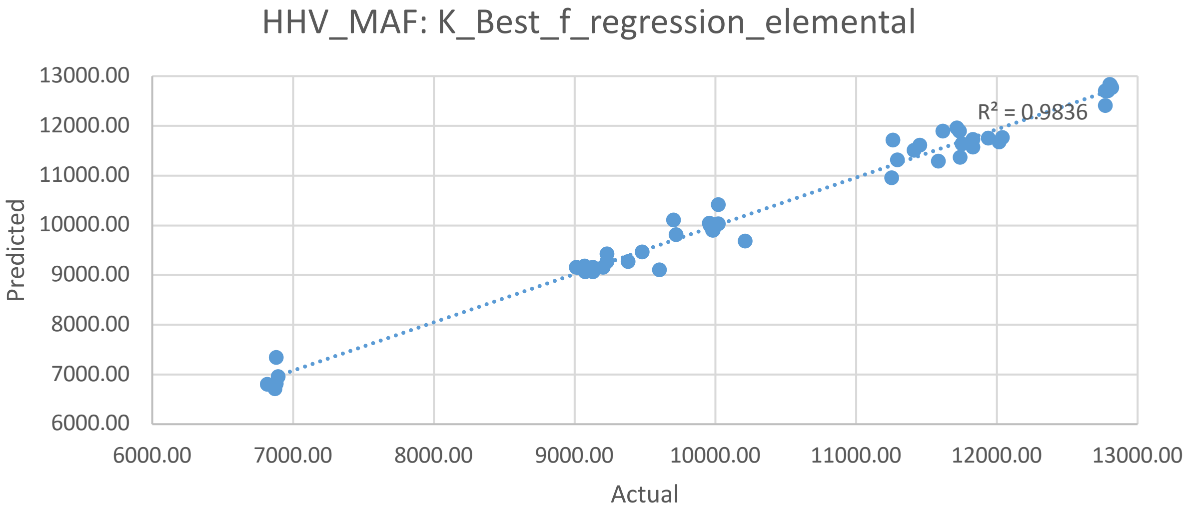
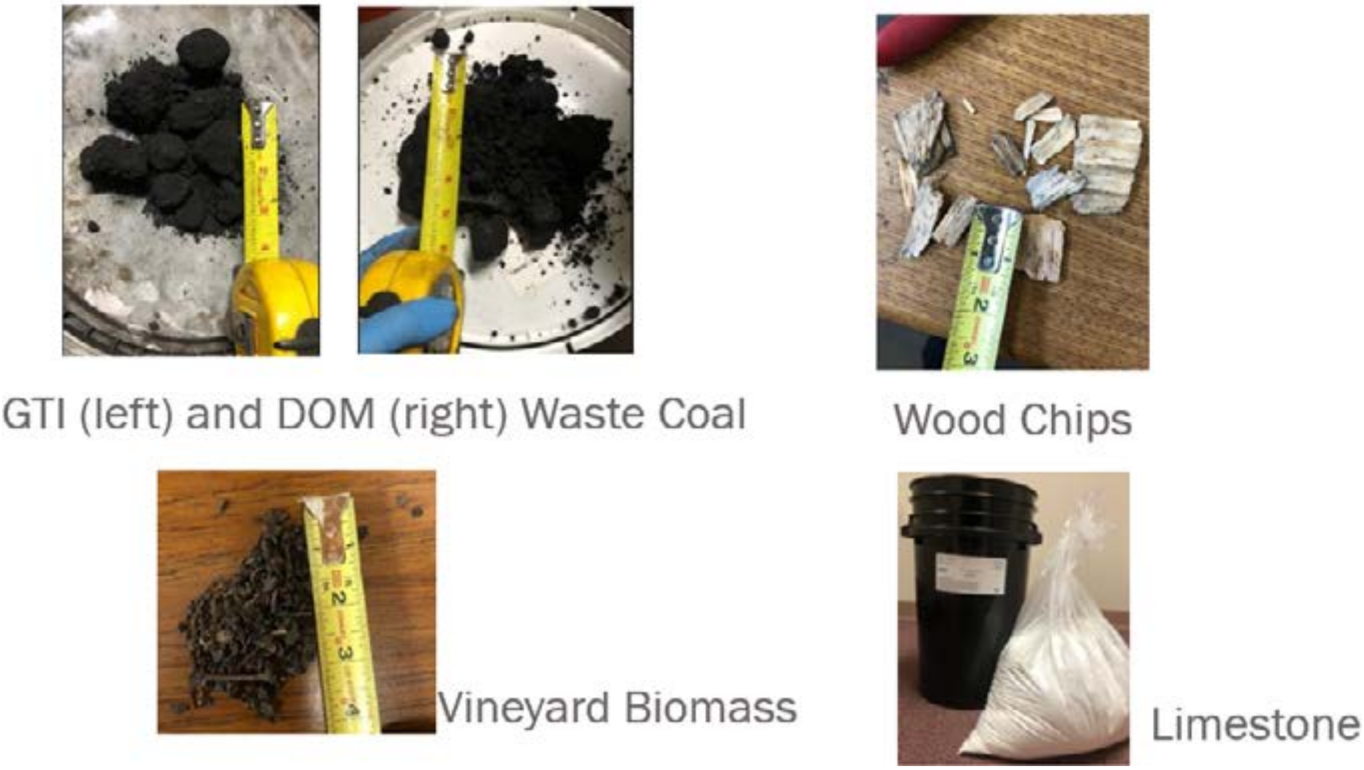


Figure 2: Heating value predictions compared to measured/actual values.

Current development work is focusing on realization of a fully automated OnSpec commercial instrument that provides data and conclusions from a single-button operation and real-time data display. A prototype is illustrated in Figure 3.

Figure 3: ERCo's commercial LIBS system.

This field-capable technology has been undergoing simulator results and commercialization feasibility testing. Gasifier feedstocks consisting or waste coal (two types), wood chips, vineyard biomass and limestone (see Figure 4) were sourced at 500 microns (0.5 mm) to 2 mm, and laboratory-measured using ML-enhanced LIBS and blending into many different feedstock mixture blends. Lab analysis results of composition of the blended feedstock samples were obtained, and feedstock blends were also scanned by LIBS.



GTI (left) and DOM (right) Waste Coal

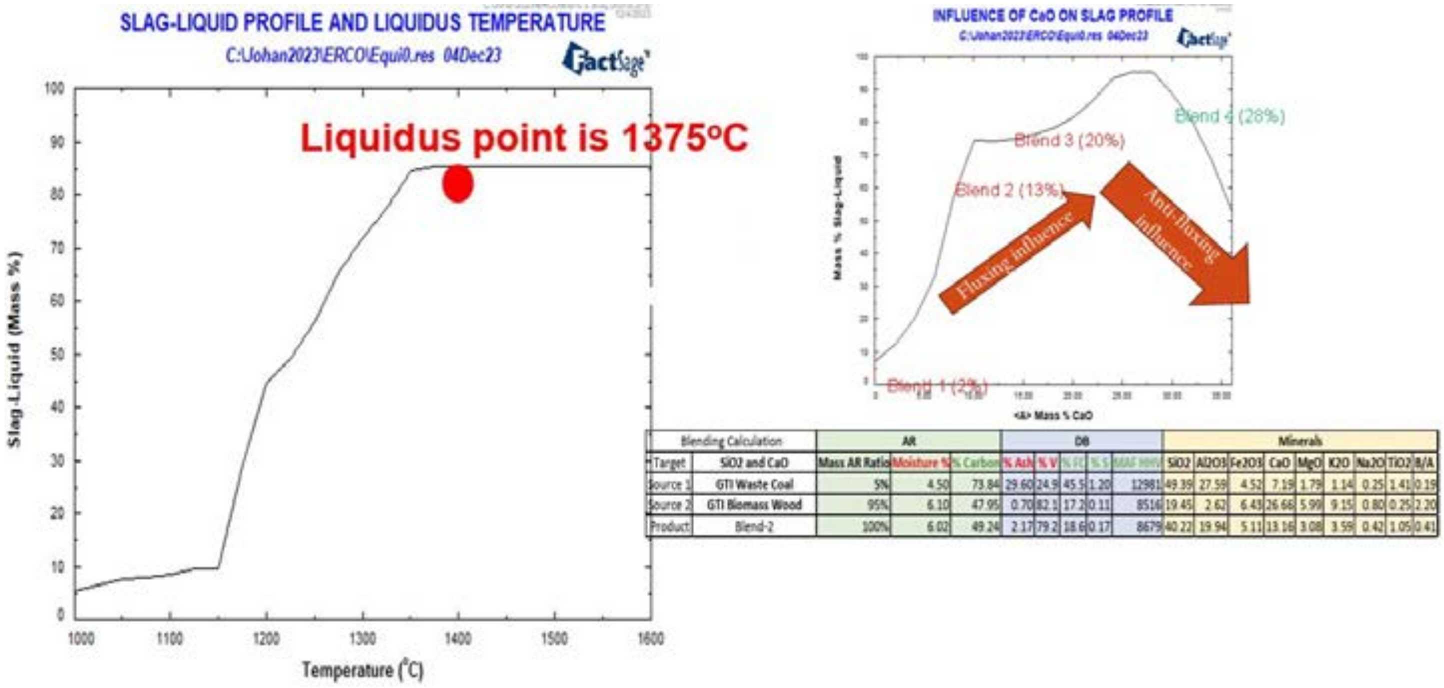
Wood Chips

Vineyard Biomass

Limestone

Figure 4: GTI gasifier testing raw feedstocks.

The main purpose of developing LIBS technology is for effective feed-forward control models in order to optimize gasification control in real-time. Crucially, LIBS data outputs must be translated into actual gasification parameters that can be utilized in controls, and this is being accomplished through the GTI Gasifier Simulator. The simulator has been used to model the slag profiles of certain materials (see Figure 5) and identify recommendations for either (1) temperature control of the gasifier or (2) manipulating the feed by adding fluxing compounds to speed up processing times if real-time process control is to be achieved. Gasification of the prepared feedstock blends has been modeled in the simulator, thereby predicting gasification performance as a function of varying feedstock blend composition.



Blending Calculation		AR			DB					Minerals								
Target	SiO2 and CaO	Mass AR Ratio	Moisture %	% Carbon	% Ash	% V	% FC	% S	MAF HHV	SiO2	Al2O3	Fe2O3	CaO	MgO	K2O	Na2O	TiO2	B/A
Source 1	GTI Waste Coal	5%	4.50	73.84	29.60	24.9	45.5	1.20	12981	49.39	27.59	4.52	7.19	1.79	1.14	0.25	1.41	0.19
Source 2	GTI Biomass Wood	95%	6.10	47.95	0.70	82.1	17.2	0.11	8516	19.45	2.62	6.43	26.66	5.99	9.15	0.80	0.25	2.20
Product	Blend-2	100%	6.02	49.24	2.17	79.2	18.6	0.17	8679	40.22	19.94	5.11	13.16	3.08	3.59	0.42	1.05	0.41

Figure 5: GTI simulator results on slag-liquid profile.

A gasification market review was conducted on four major gasification technologies: transport, moving bed, entrained flow and fluidized bed. As part of the market review, a brochure detailing the technology has been created, enabling more efficient market adoption. This brochure was distributed to a list of identified companies who would benefit from the LIBS characterization technology. Beyond the market review, a techno-economic analysis (TEA) is examining the impact of the LIBS system on several key aspects of gasifier operation. These include the flux consumption in the gasifier; gasifier temperature optimization and oxygen consumption; syngas quality, value and production rate; system availability and maintenance requirements; slag formation; and lab analysis costs.

technology advantages

- LIBS provides in situ, real-time measurements of critical properties such as feedstock carbon and sulfur content, heating value, ash content, and ash fusion temperatures.
- Achieves high precision and accuracy on measurements, ensuring reliable data for gasifier control.
- Enables dynamic control of gasification processes by providing actionable data to adjust slagging and fusion points.
- Useful for diverse feedstocks, including biomass, coal waste and blends, for versatile gasification applications.
- Minimizes cost per measurement with a fully automated system, reducing operational expenses.
- Commercial viability of the field-capable OnSpec LIBS instrument designed for easy deployment in industrial gasification systems.
- Sample preparation not needed.

R&D challenges

- Managing feedstock heterogeneity in biomass and coal waste properties to ensure consistent system performance.
- Integration with gasification systems so LIBS data properly translates to gasifier simulators and operational controls.
- Adapting the LIBS instrument for field deployment and reliable performance under real-world industrial conditions.
- Algorithm refinements for improved data processing and predictive accuracy across diverse feedstocks.
- Scaling the LIBS system for widespread commercial deployment while maintaining cost and performance targets.

status

The LIBS system is being enhanced for real-time field deployment, completing tests including diverse feedstock blends, and integrating the technology into gasifier simulators and operational systems, ultimately supporting the commercialization of a robust, cost-effective solution for optimizing gasification processes and advancing low-carbon hydrogen production.

available reports/technical papers/presentations

"Machine Learning Enhanced LIBS to Measure and Process Biofuels and Waste Coal for Gasifier Improved Operation," Robert De Saro, Energy Research Company, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_DeSaro.pdf*.

"Machine Learning Enhanced LIBS to Measure and Process Biofuels and Waste Coal for Gasifier Improved Operation," DOE STTR Phase II - DE-SC0022696, Annual Update Meeting, 26 August 2024.

this page intentionally left blank

GASIFICATION SYSTEMS
TECHNOLOGY SHEETS

National Laboratories FWP

Enabling Low-Carbon Feedstocks for Gasification

primary project goal

Oak Ridge National Laboratory (ORNL) is developing methods to characterize the physical and chemical transformations of feedstocks undergoing gasification to enable reliable low-cost hydrogen (H_2) and power generation from low-cost feedstocks such as municipal solid waste (MSW) and associated subcomponents, biomass, waste plastics, and waste coal.

technical goals

- Characterize physical and chemical properties of low-carbon feedstocks, including MSW, refuse-derived fuel (RDF) and waste plastics.
- Utilize unique neutron imaging and neutron scattering techniques to analyze transformations during pyrolysis and gasification.
- Construct and implement an in situ reactor for neutron-based studies of gasification reactions.
- Investigate catalytic effects on tar cracking and hydrogen production using micro-pyrolysis gas chromatography/mass spectrometry (GC/MS) and thermogravimetric analyzer (TGA).
- Develop and validate computational fluid dynamic (CFD) models for modular gasifiers (200 kW, 5 MW and 22 MW) in partnership with the National Energy Technology Laboratory (NETL).
- Enable improved gasifier design and operation for low-cost, low-carbon hydrogen and power production.

technical content

ORNL is characterizing the physical and chemical transformations that occur during the gasification of various low-carbon and low-cost feedstocks. An example of a low-carbon life cycle feedstock is biomass, which might be sustainably produced and utilized to minimize emissions/carbon footprint. As opposed to conventional gasification feedstocks such as coal or torrefied biomass, these feedstocks are less well characterized as to gasification behavior. Increasing understanding of this behavior can guide improved gasifier designs and optimize operational conditions, in turn helping to enable cost-effective and sustainable hydrogen and power generation via gasification. In so doing, more waste materials can be diverted from landfills and put to higher value uses and applications, as illustrated in Figure 1 for MSW. ORNL's innovative approach in this work utilizes state-of-the-art neutron-based techniques to investigate MSW, RDF, waste plastics, food waste and waste coal feedstocks.

program area:
Gasification Systems

ending scale:
Small Pilot, 1.4 TPD (275-335 kW_{th})

application:
Hydrogen Production

key technology:
Process Intensification for Syngas and Hydrogen

project focus:
Characterize gasification behavior of low-cost solid feedstocks

participant:
Oak Ridge National Laboratory

project number:
FWP-FEAA437

predecessor projects:
N/A

NETL project manager:
Diane Revay Madden
diane.madden@netl.doe.gov

principal investigator:
James E. Parks II
parksjeii@ornl.gov

partners:
Novastus; National Energy Technology Laboratory

start date:
01.01.2023

percent complete:
70%

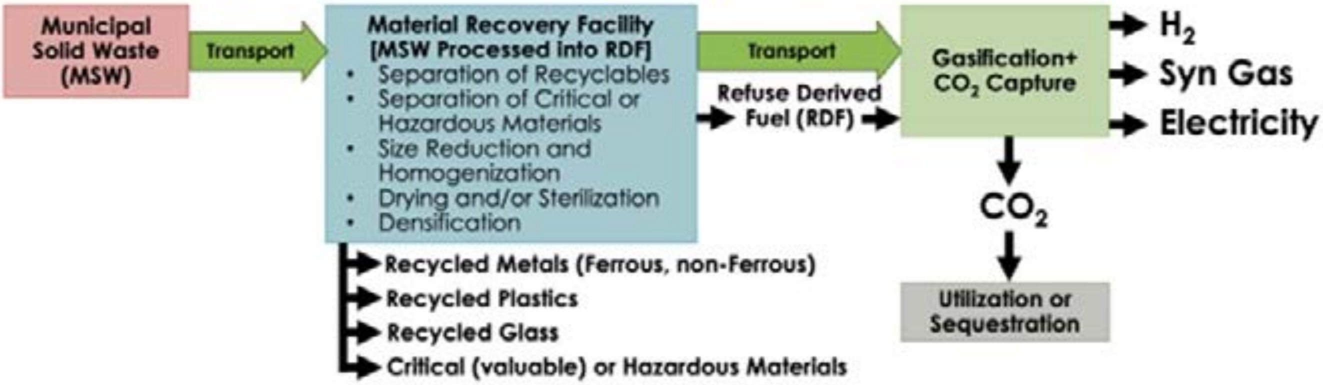


Figure 1: Preferred pathway with material valorization, CH_4 and CO_2 avoidance, and clean energy products.

ORNL's advanced neutron methods include neutron imaging and small-angle neutron scattering (SANS) to analyze feedstock morphology, porosity, density and chemical composition before and during gasification. These analyses are being complemented by catalytic studies to assess the effects of catalysts on gas product chemistry and solid mass loss. By combining these techniques, a comprehensive understanding of feedstock properties and transformations can be established, particularly for engineered refuse-derived fuels (ERDF) with reduced moisture content and homogenized composition.

One of the examples of ERDF studied is illustrated in Figure 2. On the right side, ERDF pellets from industry partner Novastus are shown, which are made from de-watered and compressed MSW components left behind after separation of metal, glass and large plastics for recycling. The left side shows an X-ray computational tomograph of a pellet, which contains plastics, cellulosic materials and other materials that may lead to ash formation upon gasification.

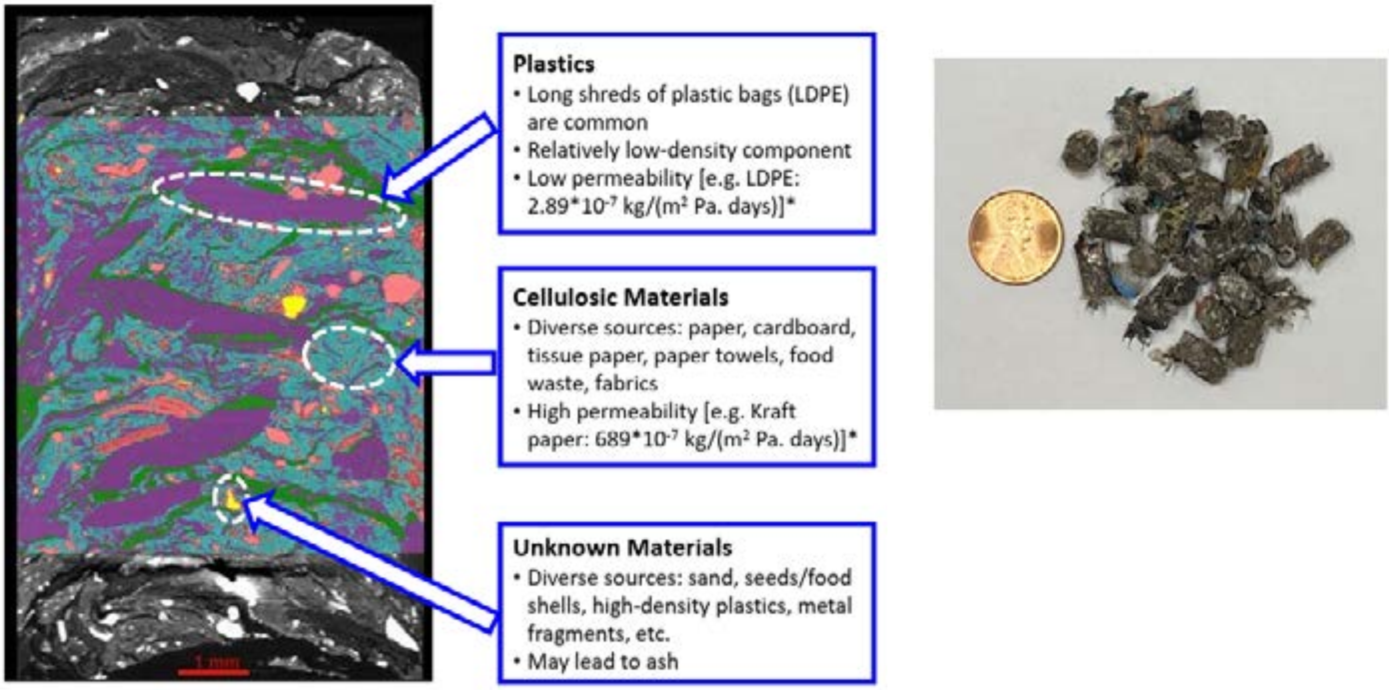


Figure 2: X-ray computational tomograph (left) of a Novastus ERDF pellet (right).

Neutron transmission analysis was deployed to study behavior of ERDF pellets pyrolyzed at varying temperatures. Results are shown in Figure 3. Hydrogen has the highest neutron adsorption cross section; therefore, as fuel samples lose volatile hydrogen-containing species during pyrolysis, the neutron transmission increases, resulting in lighter-appearing images. Together with neutron-scattering studies, this work has revealed critical transformations in porosity, density and hydrogen retention during pyrolysis, particularly at moderate temperatures (400–500°C), where small pore constriction was observed. This constriction affects gas transport and reaction rates, offering guidance for optimizing feedstock preparation and pyrolysis conditions. The critical data for these phenomena are shared with NETL, who inputs the information into CFD models of gasifiers to improve accuracy of models used for energy efficient gasifier design and process control optimization. Additionally, CFD modeling has been pursued to simulate gasifier reactor performance, using data derived from feedstock characterization to validate and refine the models. Models simulating the performance of modular gasifiers (200 kW, 5 MW and 22 MW) under different feedstock conditions have been developed

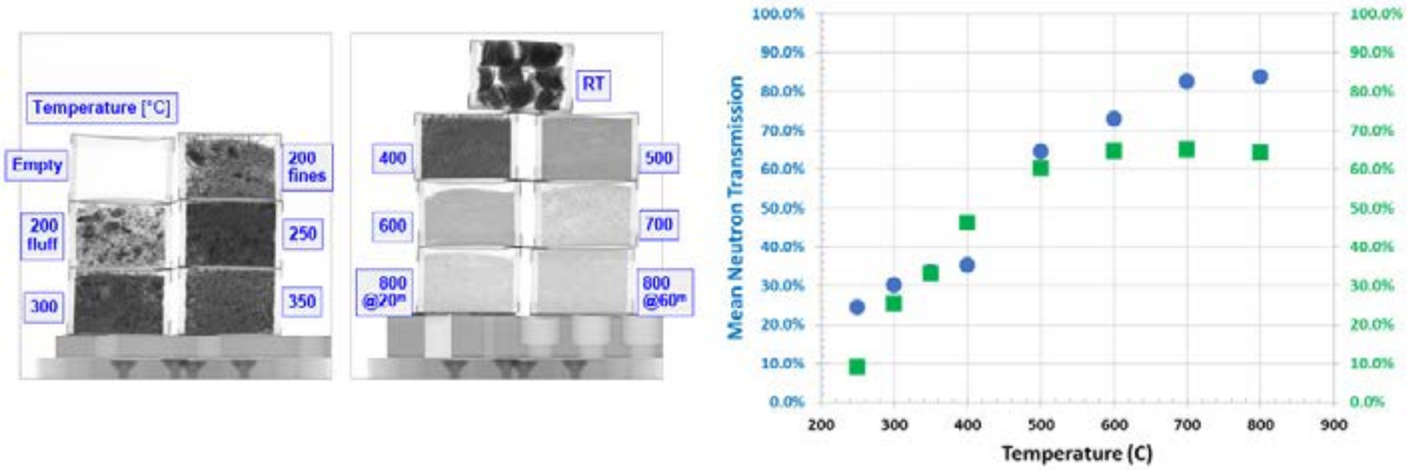


Figure 3: Neutron transmission images of ERDF pellets after pyrolysis at set temperatures (left) and corresponding data compared to mass loss as a function of temperature (right).

Another significant effort in this work has been investigation of catalytic effects on gasification. Micro-pyrolysis GC/MS has been utilized in bench-scale studies for this purpose. Additionally, the design and construction of an in situ reactor for neutron imaging enabled real-time observation of pyrolysis and gasification reactions. Catalytic studies using 1% Pt/Al_2O_3 catalyst on the pyrolysis of polyethylene showed substantial improvements in product composition: at 600°C, the catalyst reduced tar and hydrocarbon gas products by more than 80%, while increasing hydrogen yield to 24% of the gas product composition (Figure 4, top). These effects persisted during gasification (Figure 4, bottom), where catalytic conditions favored hydrogen production and reduced tar formation, supporting the potential for lower gasifier maintenance costs and higher efficiency. Without the catalyst, hydrogen production was negligible, highlighting the importance of catalytic enhancement for processing heterogeneous feedstocks such as RDF.

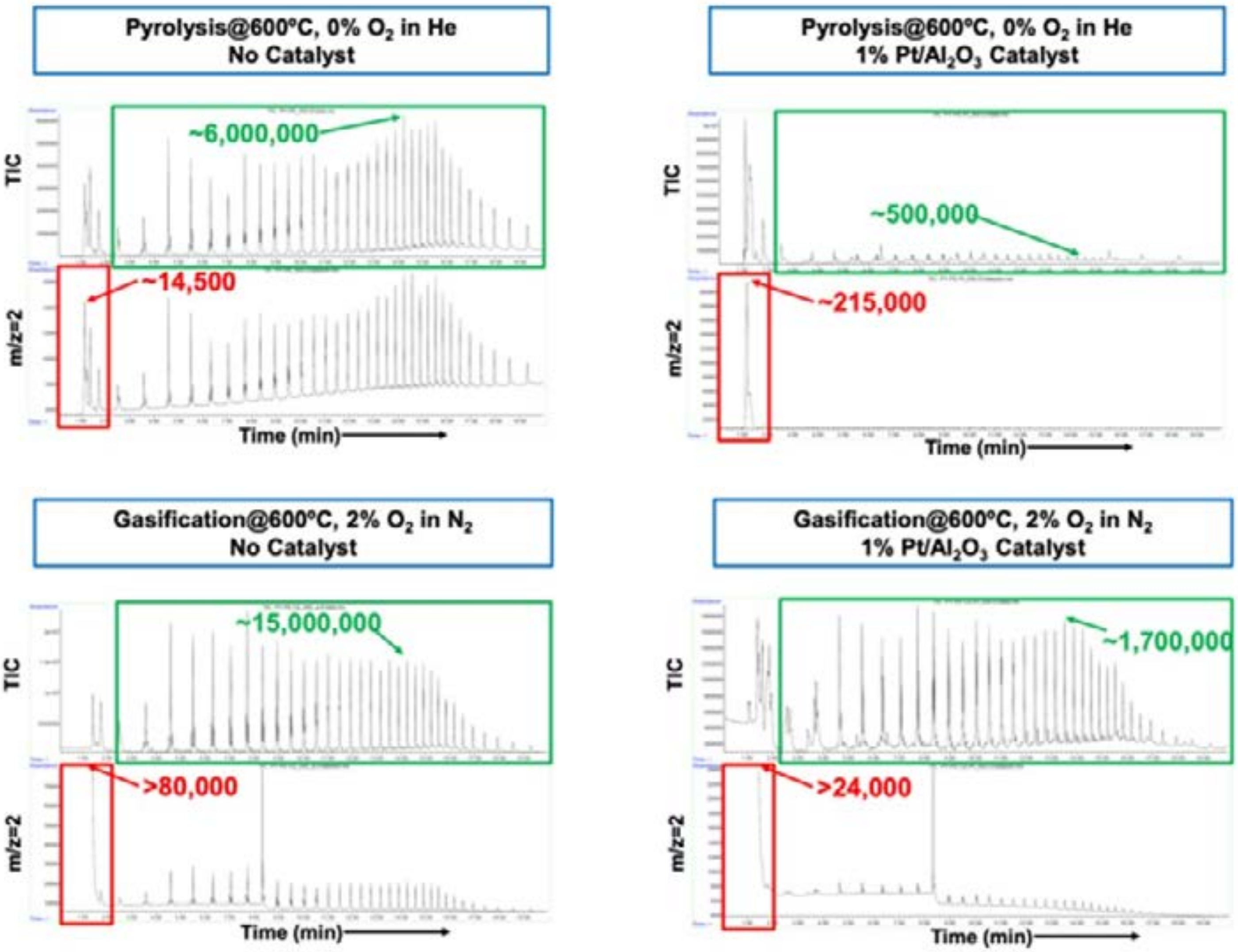


Figure 4: Catalytic effects on pyrolysis (0% O_2, top) and gasification (2% O_2, bottom) of polyethylene.

In summary, the integration of advanced experimental approaches in ORNL's work with NETL's advanced modeling of gasifier systems has provided a robust framework for improving gasification technologies, offering solutions to reduce costs; enhance efficiency; and support the use of sustainable, low-carbon feedstocks.

technology advantages

- Route to understanding pyrolysis/gasification behavior of homogenized RDF enhances ability to use this feedstock to advantage.
- Neutron imaging and scattering provides detailed insights into feedstock transformations during pyrolysis and gasification.
- Advancing catalytic gasification of ERFD to increase hydrogen yield while reducing tar and hydrocarbon by-products.
- Improving CFD models to tailor gasifier designs for various feedstock types and capacities (200 kW, 5 MW, 22 MW).

R&D challenges

- Managing the variability in feedstock composition to maintain consistent measurement accuracy and reliability.
- Analyzing complex physical and chemical phenomena associated with feedstock thermochemical conversion processes to provide actionable insights.
- Translating complex results to functional elements of CFD models to improve gasifier design and control.

status

Future directions include in situ neutron-imaging studies, refining CFD models with expanded experimental validation, and further optimizing catalytic strategies to enhance hydrogen production and tar reduction in gasification systems.

available reports/technical papers/presentations

“Enabling Low Carbon Feedstocks for Gasification,” James E. Parks II, Oak Ridge National Laboratory (ORNL), 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Parks.pdf*.

Pressure-Driven Oxygen Separation

primary project goal

Pacific Northwest National Laboratory (PNNL) is advancing air separation technology using mixed ion-conducting membranes in planar architecture and stack configuration. This technology employs doped cerium dioxide (CeO_2) as the ion conductor and lanthanum manganite ($LaMnO_3$) as the electronic conductor, supported on low-cost porous substrates made of $MgO\text{-}Al_2O_3$ composites. This setup allows oxygen separation by utilizing the difference in oxygen partial pressures across the membrane, without the need for electrical energy, offering significant operational efficiency. PNNL is focused on addressing several technological challenges to improve performance efficiency and cost-effectiveness of this technology, including use of low-cost materials; planar stack architecture for reliable and low-cost fabrication/processing and stack/seal performance; minimizing interactions between ionic and electronic-conducting phases during sintering to maximize oxygen permeability in the composite membranes; and controlling sintering to prevent warping and cracking of the planar composite membranes, thereby improving the mechanical stability and longevity of the system.

technical goals

- Develop a small-scale, modular air separation unit (ASU) capable of producing 10 tons per day of high-purity oxygen for use in 1–5 megawatt (MW) gasifiers, focusing on low cost and high efficiency.
- Develop ceramic membranes with bilayer structures for efficient oxygen separation operable at 700–800°C using no external electrical energy.
- Optimize composite membrane materials combining ionic and electronic conductivity to maximize oxygen permeability and ensure structural compatibility.
- Tailor membrane and support properties to enhance mechanical integrity and thermal expansion matching.
- Scale up fabrication of membranes to larger sizes while maintaining flatness and defect-free characteristics.
- Build testing rigs of various sizes and shapes to evaluate the performance of ceramic bilayers under realistic conditions.

technical content

The innovative technology being developed integrates planar ceramic membranes with bilayer structures consisting of a selective membrane layer on a porous membrane support. This design is aimed at achieving efficient oxygen separation at intermediate temperatures (700–800°C). Oxygen separation is accomplished by establishing a pressure gradient across the membrane, which drives oxygen

program area:
Gasification Systems

ending scale:
Pilot, 10 TPD O_2

application:
Hydrogen Production

key technology:
Air Separation Technology

project focus:
Mixed ion-conducting membranes for air separation

participant:
Pacific Northwest National Laboratory

project number:
FWP-73130

predecessor projects:
N/A

NETL project manager:
Katelyn Ballard
katelyn.ballard@netl.doe.gov

principal investigator:
Josef Matyas
josef.matyas@pnnl.gov

partners:
N/A

start date:
12.01.2018

percent complete:
90%

separation from air without the need of electrical energy. This feature significantly enhances efficiency and scalability and helps reduce costs. Figure 1 illustrates the planar design of an oxygen separation module incorporating planar membranes, while Figure 2 shows an imaged detail of the ceramic bilayer.

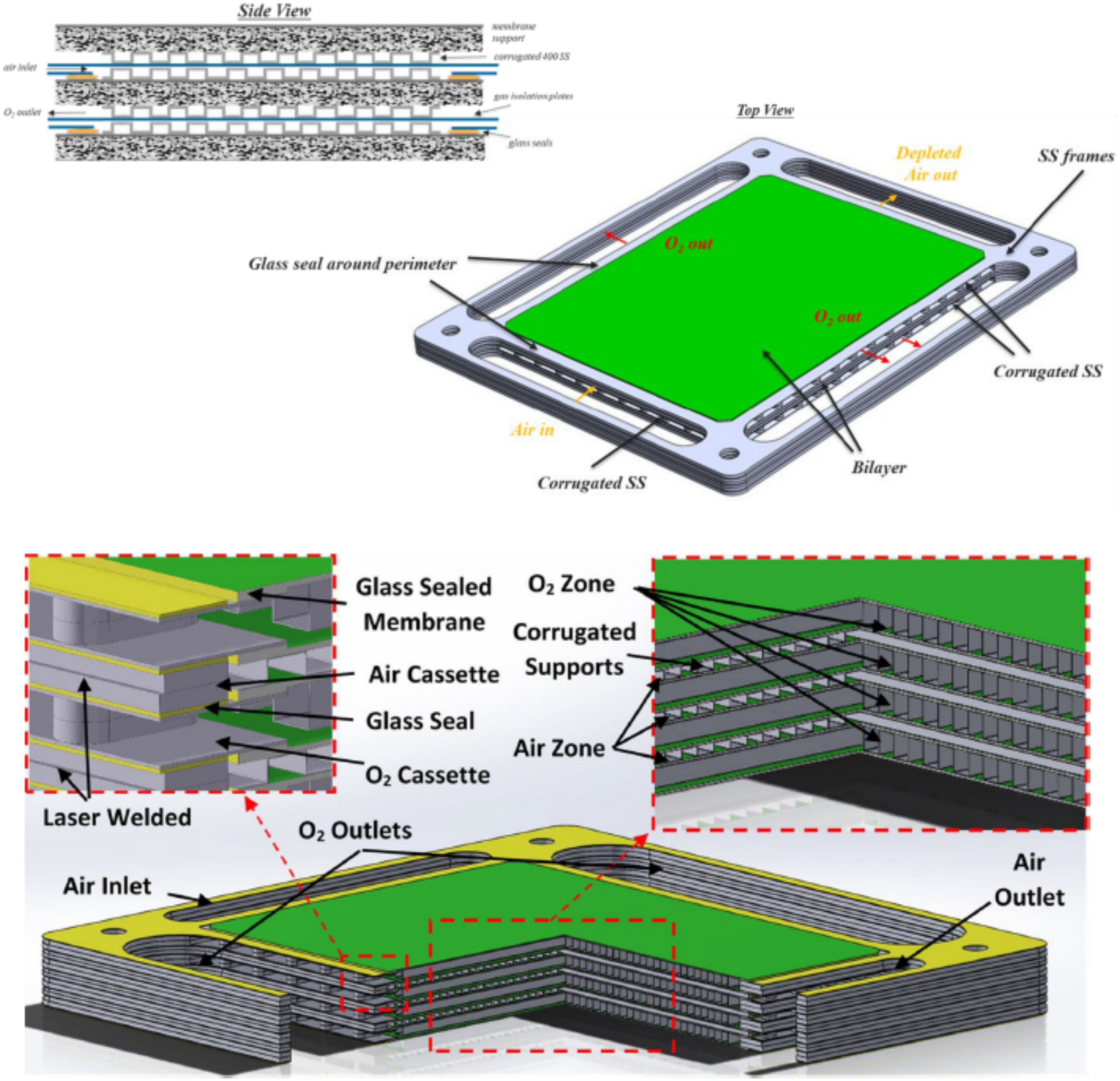


Figure 1: Schematic of ASU cell unit (top); a three-cell stack cross-section (bottom).

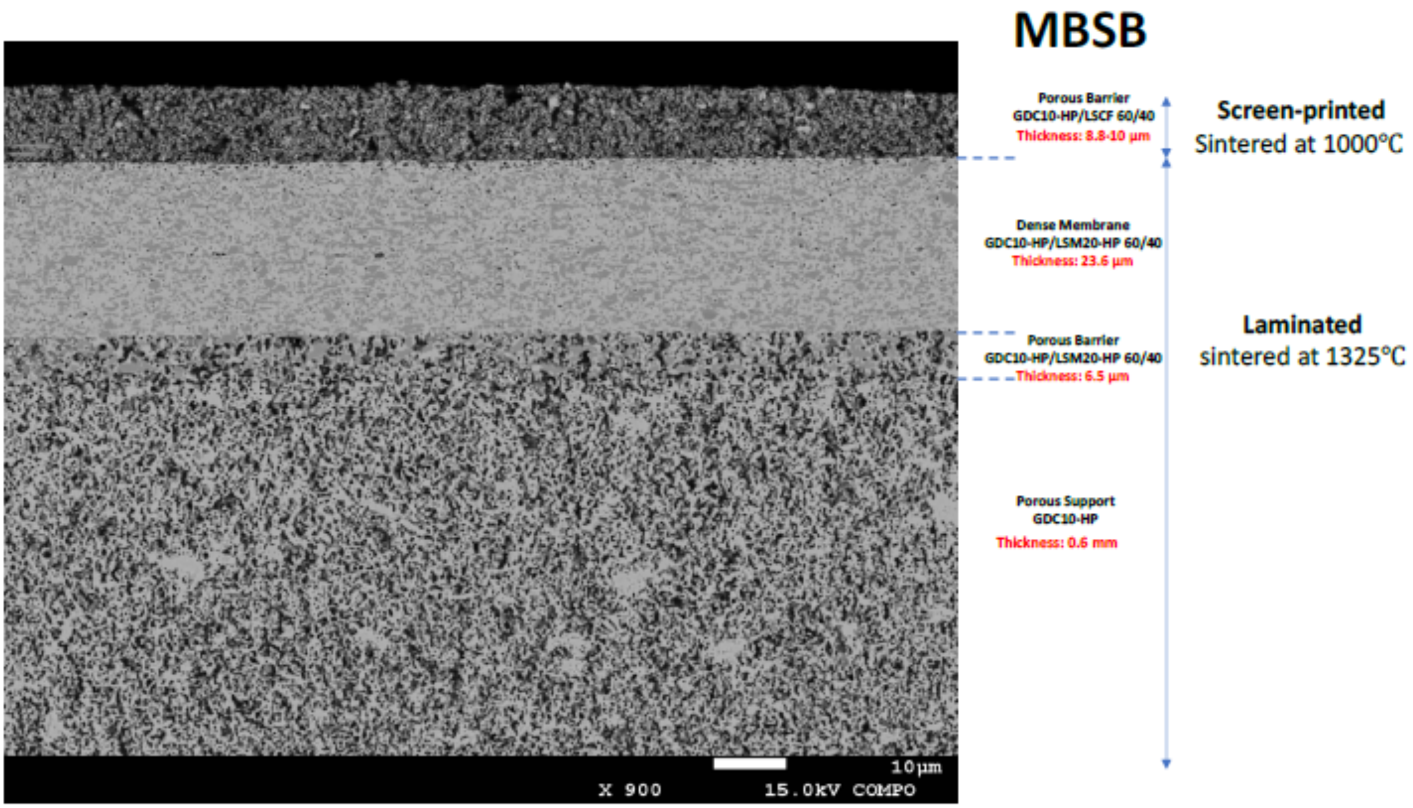


Figure 2: SEM image of the ceramic bilayer membrane cross-section.

The key innovation of this technology lies in composite ceramic membranes made from mixed-conducting two-phase materials that combine both ionic and electronic conductivity. These materials typically consist of an ionic conductor such as doped CeO_2, and electronic conductor such as doped $LaMnO_3$ or $LaFeO_3$ (see Figure 3). The materials are tailored to maximize oxygen permeability while maintaining mechanical strength and compatibility with other system components such as glass seals and metal components. This requires the use of materials with similar thermal expansion coefficients and minimizing their interactions during firing. The membranes are supported by porous structures designed to provide stability and effective gas diffusion. This advanced design aims to achieve high oxygen flux rates while ensuring system durability under realistic operational conditions.

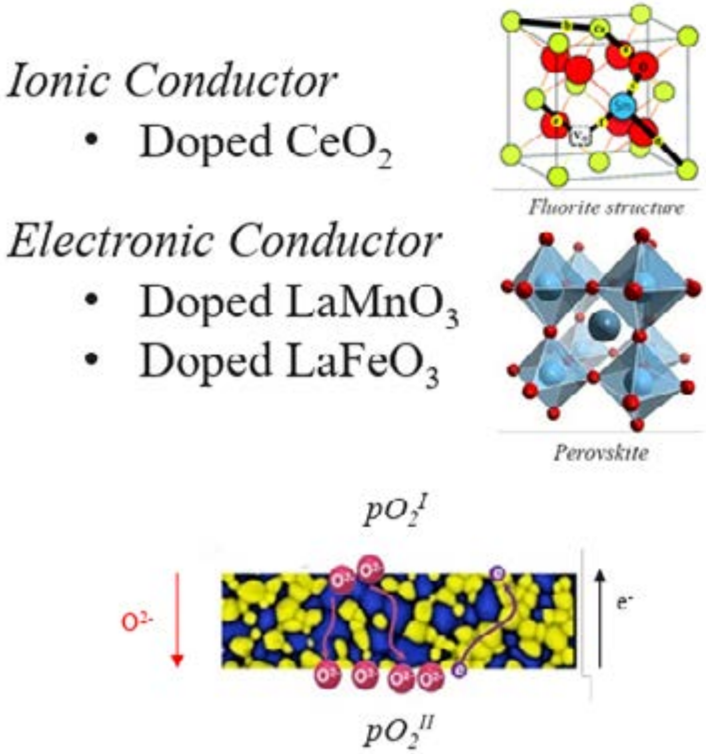


Figure 3: Two-phase composite ceramic bilayer technology.

A key developmental challenge is scaling up the ceramic bilayer fabrication process to produce larger, defect-free planar structures suitable for commercial-scale applications. While a three-cell stack having membrane/cell active area of about 50 cm^2 (Figure 1) has been tested, efforts are underway to develop larger area bilayers of 200–400 cm^2. Achieving defect-free ceramic bilayers at this scale requires cost-effective manufacturing methods such as tape casting, screen printing, catalyst impregnation and sintering.

Techno-Economic Analysis

Preliminary evaluations have already assessed multiple parameters influencing the cost and performance of an ASU utilizing PNNL's technology. Key parameters include oxygen permeability, stack size (i.e., 100 cm^2 versus 400 cm^2), number of circuits (each consisting of a vacuum pump, more than five cell stacks, a heater, a heat exchanger and a blower), as well as fabrication labor costs, electricity costs, ceramic yield and other associated expenses.

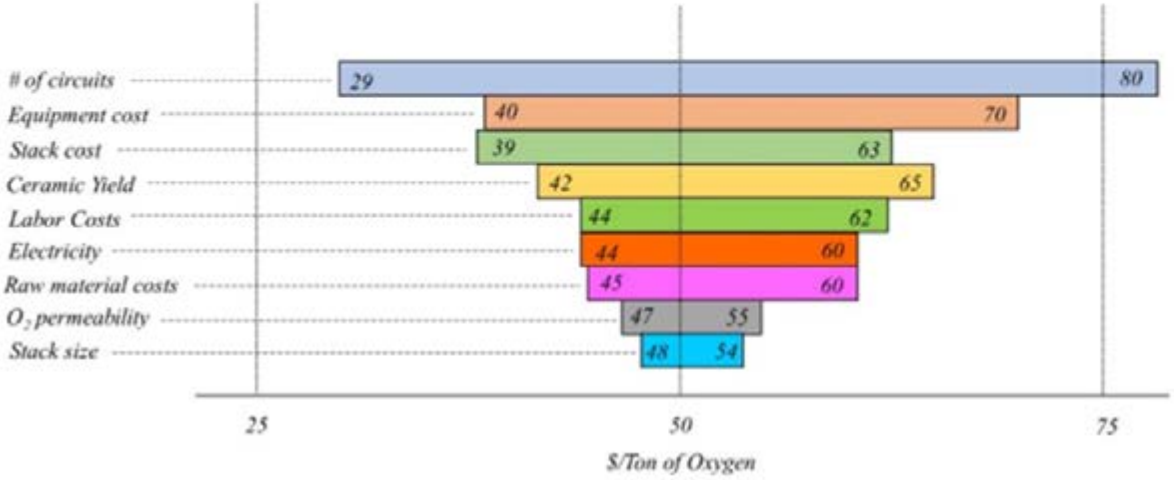


Figure 4: Tornado plot showing sensitivity of various ASU parameters to overall oxygen production cost.

The current estimated results and target research and development (R&D) values for oxygen production economics are shown in Table 1. Values displayed here are derived from preliminary evaluations; a detailed analysis of the oxygen production economics for ceramic bilayer technology is planned, after which these values should be updated.

TABLE 1: OXYGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Oxygen	$\$/\text{ton } O_2$	30-55	20-30
Capital Expenditures	$\$\text{M}$	2-3	1.5-2
Operating Expenditures	$\$/\text{ton } O_2$	25-45	20-25

Definitions:

Cost of Oxygen – Projected cost of capture per ton of oxygen (O_2) produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in millions of dollars

Operating Expenditures – Projected operating expenditures in dollars per ton of O_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M.

Other Parameter Descriptions:

Waste Streams Generated – Nitrogen-rich off-gas.

Process Design Concept – See below.

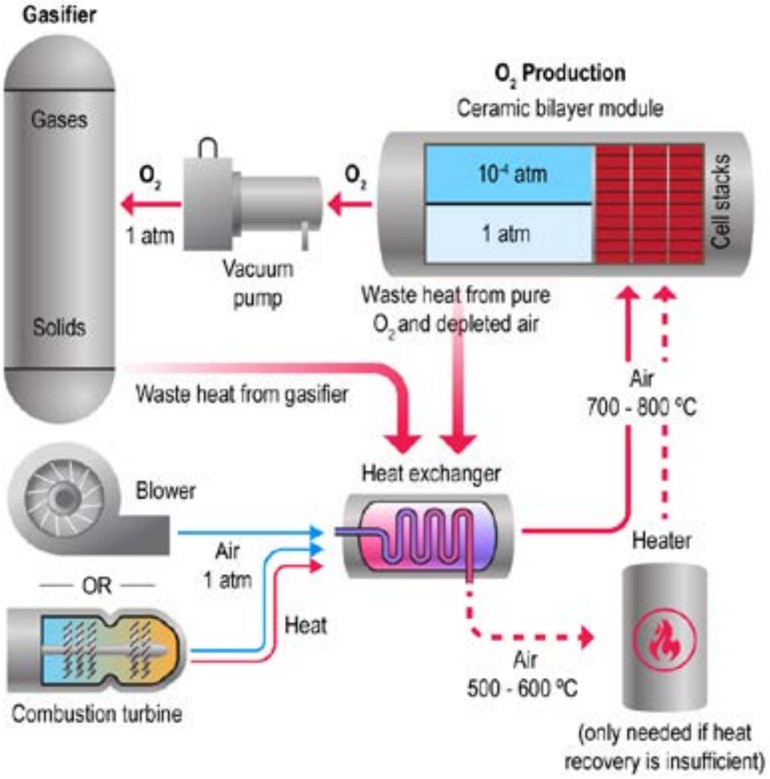


Figure 5: Process design concept.

technology advantages

- Planar ceramic membranes enable oxygen separation at high purity (99+%), making the produced oxygen suitable for various applications.
- Pressure-driven oxygen separation operates without external electrical energy, offering potential operational benefits and cost savings.
- The inherent modular design allows flexibility for small-scale applications, such as 1–5-MW gasifiers, while also simplifying scalability to larger systems.
- At smaller scales, planar ceramic membranes can rival alternative oxygen production methods in terms of cost efficiency.

R&D challenges

- Achieving consistent quality and defect-free membranes during fabrication, especially when scaling up to larger bilayer sizes (200–400 cm^2).
- Optimizing the particle size, distribution and composition of conducting materials in bilayers to maximize oxygen flux and minimize material degradation.
- Demonstrating performance and reliability of multicell stacks with active area membranes under real-life operating conditions.
- Addressing cost sensitivities related to material production, labor and stack assembly in commercial-scale applications.

status

Ceramic bilayers with thin and dense composite membranes (thicknesses of 10–20 µm) were successfully fabricated and tested for oxygen permeability, demonstrating substantial flux under realistic operational conditions. Mechanical and thermal integrity were optimized by ensuring material compatibility and matching thermal expansion properties across different layers of the ceramic bilayer glass seals and metal components.

available reports/technical papers/presentations

“Pressure Driven Oxygen Separation,” Josef Matyáš and David Reed, Pacific Northwest National Laboratory (PNNL), 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Matyas.pdf*.

“Pressure Driven Oxygen Separation via Mixed Conducting Dual Phase Technology,” Quarterly Report FY24 Q4.

Rotary Magnetocaloric Liquefier for Air Separation

primary project goal

Pacific Northwest National Laboratory (PNNL) is leveraging their previously developed magnetocaloric liquefaction technology to realize an efficient, compact cryogenic air separation unit (ASU). The goal is to replace two of the three modules of a conventional cryogenic ASU with two innovative technology components (refer to Figure 1):

1. Replace turbo-Brayton cycle air liquefiers with magnetocaloric liquefiers (MCLs). MCLs are solid-state in operation, avoiding much of the high mechanical work and energy penalty associated with conventional turbomachinery.
2. Replace conventional distillation columns with microchannel distillation columns (MCDs), which should reduce the distillation footprint by approximately 10 times.

PNNL had previously developed a reciprocating MCL concept. However, as this was found to have inherent technical barriers to scale up, a thermodynamically simpler two-stage rotary MCL has been devised that should reduce/eliminate current losses in magnets, utilize less refrigerant, operate at higher frequencies, simplify heat transfer process flows, and readily scale up in size.

technical goals

- Design and development of the MCL technology, with targeting to increase ASU energy efficiency by approximately 40% and decrease capital expenditures (CAPEX) by approximately 25%.
- Establish compatibility of the liquefier with small-scale, modular gasification units, facilitating decentralized hydrogen production.
- Enhance the magnetocaloric effect through material selection and system design to maximize oxygen (O_2) yield and purity.
- Validate the system's performance at engineering scale (200 kg/day) to ensure it meets the demands of different modular gasification applications.

technical content

This technology leverages magnetocaloric materials that can be cooled through application of powerful magnetic fields, achieving refrigeration to cryogenic temperatures and liquefaction of air. This is in stark contrast to conventional ASUs, which accomplish the refrigeration through repeated compression, cooling and expansion of the gases. As such, the MCL eliminates the need for complex and expensive compression and turbomachinery in an ASU. The magnetocaloric materials are solid, rare-earth alloys, which exhibit a pronounced magnetocaloric effect under magnetic field change. Figure 2 illustrates the temperature changes

program area:
Gasification Systems

ending scale:
Pilot (200 kg O_2 per day)

application:
Hydrogen Production

key technology:
Air Separation Technology

project focus:
Solid state air liquefaction

participant:
Pacific Northwest National Laboratory (PNNL)

project number:
FWP-82796

predecessor projects:
FWP-73143

NETL project manager:
Katelyn Ballard
katelyn.ballard@netl.doe.gov

principal investigator:
Corey Archipley
corey.archipley@pnnl.gov

partners:
N/A

start date:
10.01.2023

percent complete:
75%

that can be induced in one of these magnetocaloric alloys ($GdNi_{0.90}Co_{0.10}$) when the refrigerant is moved into or out of a magnetic field.

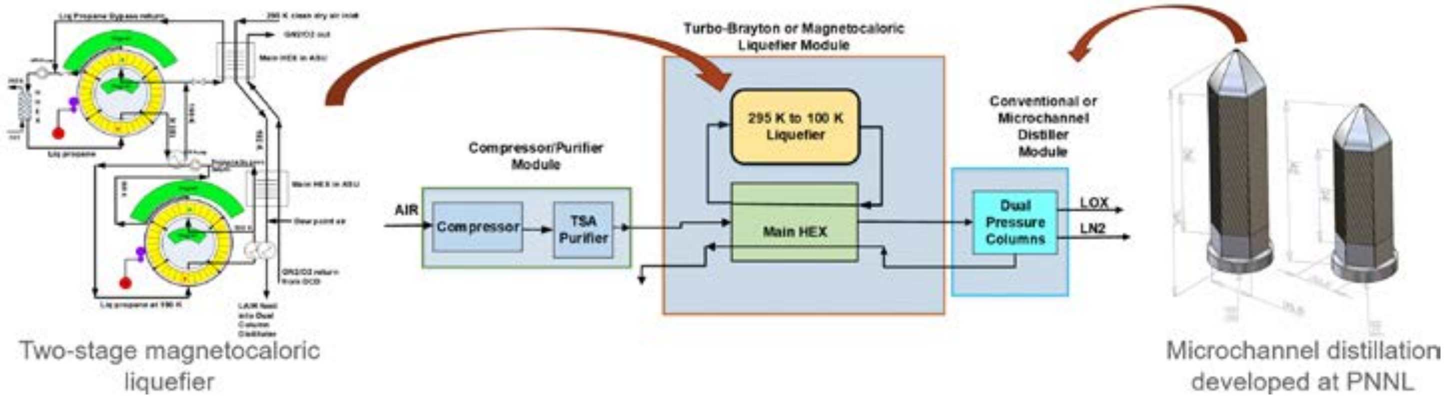


Figure 1: ASU improvements from PNNL-developed technologies.

The magnetocaloric effect results in the magnetocaloric refrigerants heating up when exposed to a magnetic field or cooling down when demagnetized. A refrigeration cycle is established by removing heat from the refrigerants while in the magnetic field, resulting in cooler refrigerants once removed from the magnetic field.

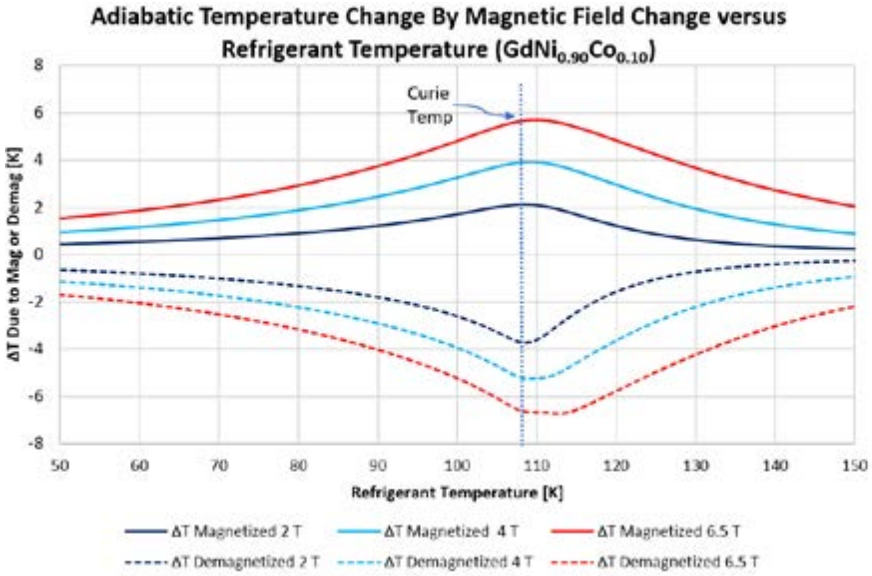
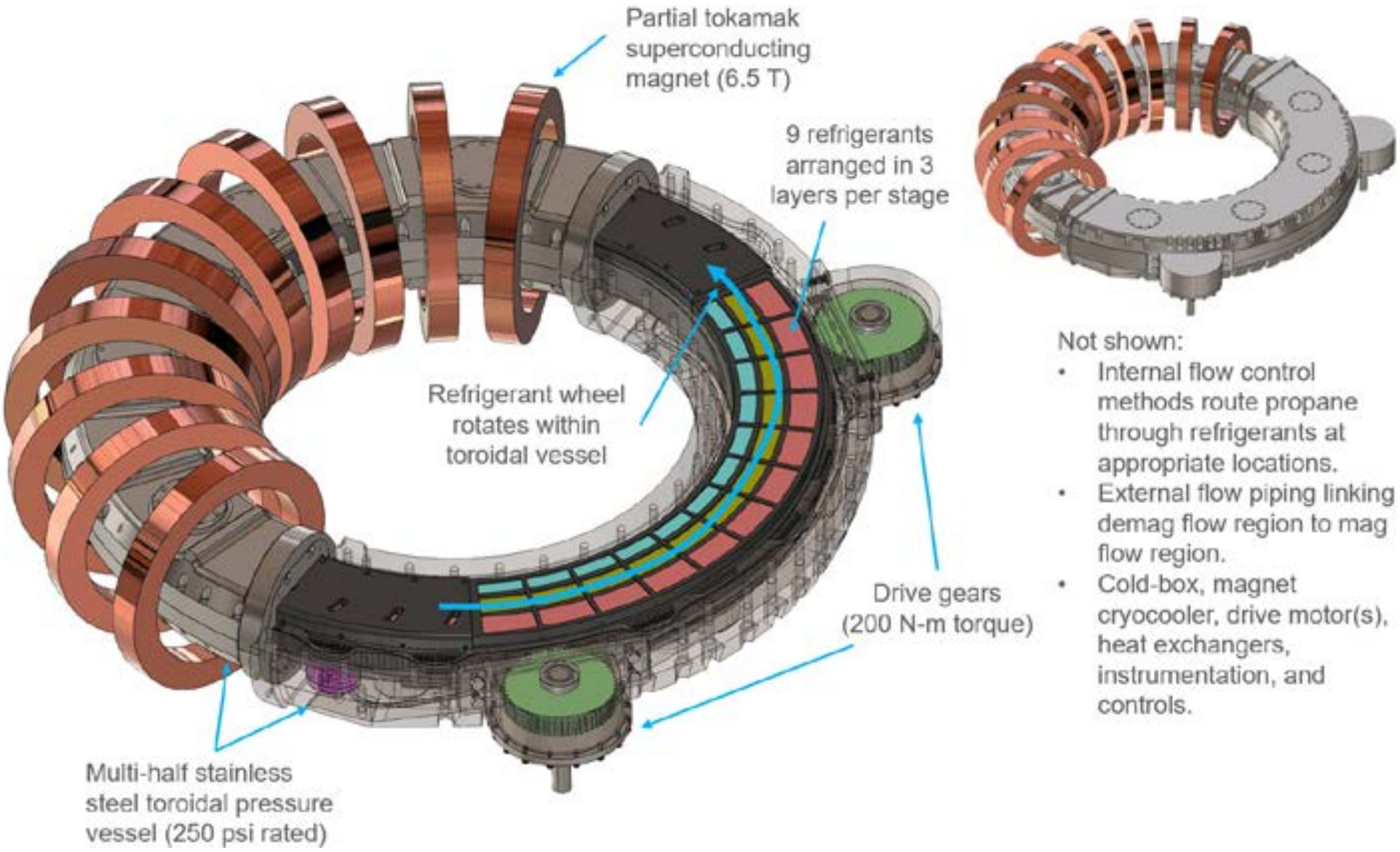


Figure 2: The magnetocaloric effect results in changes in temperature when exposed to a magnetic field.

MCL Operation

Current development efforts are focused on a two-stage rotary MCL, as illustrated in Figure 3. The mechanical design includes a proprietary toroidal pressure vessel that enables the rotation of a regenerator wheel, which contains nine solid-state magnetocaloric refrigerants in and out of a 6.5 T high-field region and 0.5 T low-field region. The nonmagnetic vessel contains 250 pounds per square inch (psi) liquid propane (or propane, ethane, methane mixture) from 300 K to 100 K. Drive gears rotate the refrigerant wheel, providing the work input to the refrigeration cycle. The magnetic field is generated by an NbTi superconducting partial tokamak magnet.



Not shown:
- Internal flow control methods route propane through refrigerants at appropriate locations.
- External flow piping linking demag flow region to mag flow region.
- Cold-box, magnet cryocooler, drive motor(s), heat exchangers, instrumentation, and controls.

Figure 3: Two-stage rotary MCL.

Liquid propane (or a propane, methane, ethane mixture) heat transfer fluid is routed through the rotating refrigerants on the demagnetized side to be cooled down before entering the next stage of the liquefier or lifting the load from the air process stream. Most of the fluid then enters the magnetized side of the rotating refrigerants where the fluid is warmed up to exit and deposit the load of liquefaction in a room-temperature heat sink. A small percentage of the propane leaving the demagnetized side of the second stage is bypassed around the magnetized region to precool the incoming air process stream to its dew point. Bypass flow takes advantage of the reduction of heat capacity of the refrigerants due to magnetization. (See Figure 4 for illustration of heat transfer scheme deployed in the rotary MCL.)

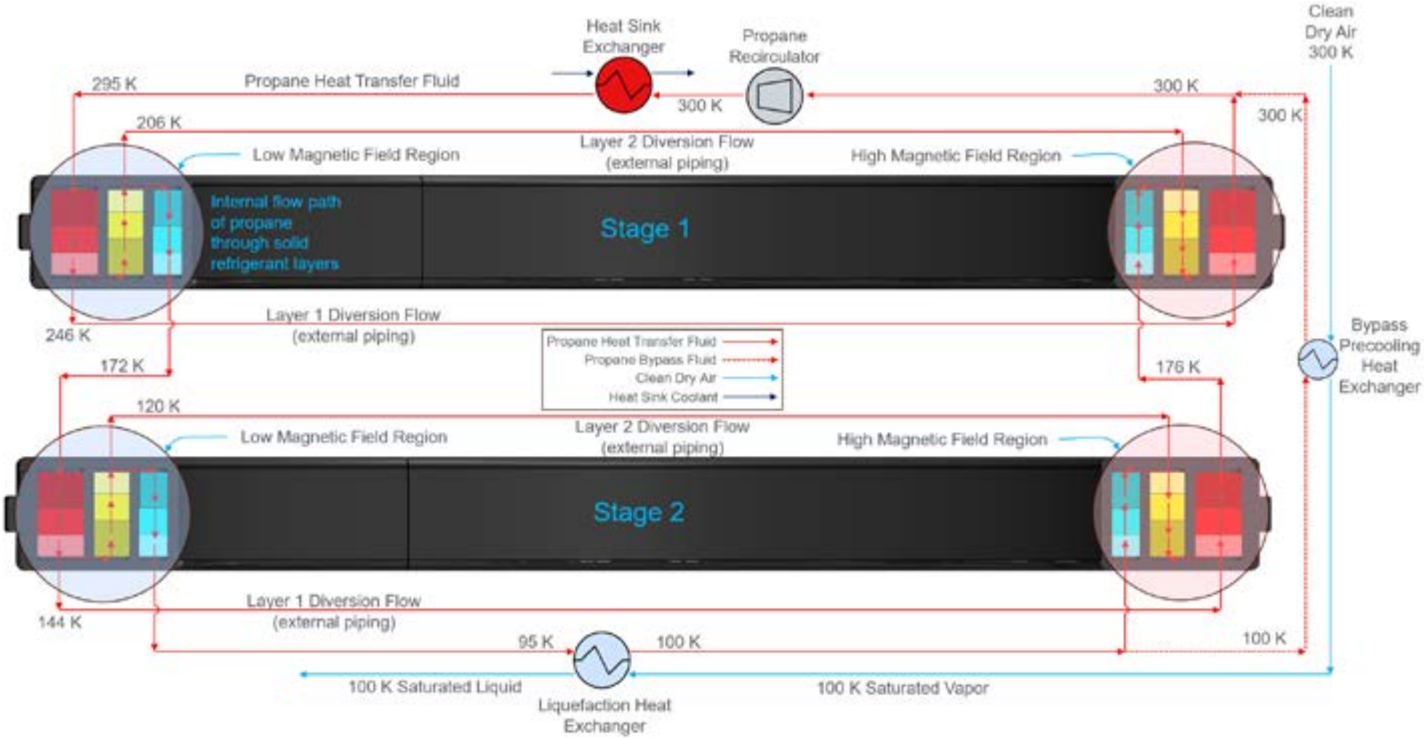


Figure 4: Propane heat transfer fluid flow path through the two-stage liquefier.

Each stage utilizes nine unique magnetocaloric refrigerants to achieve a temperature span from 295 K to 172 K in stage 1 and 172 K to 100 K in stage two. The nine refrigerants in each stage are combined in groups of three, with the average change in temperature due to magnetization from 0 T to 6.5 T of 9 K. The demagnetization of the refrigerants from 6.5 T to 0.5 T results in an average reduction in temperature of 7 K after the heat of magnetization is removed. The propane heat transfer fluid couples the changes in the refrigerant temperatures due to magnetization or demagnetization from one refrigerant to the next to lift the load of liquefaction from 100 K to 295 K.

The refrigeration cycle will operate at 1 Hz. One-third of the one-second cycle will be the time the refrigerants spend in the magnetized region experiencing heat transfer to the propane heat transfer fluid. One-sixth of the cycle is the time for demagnetization of the refrigerants without heat transfer occurring. Another one-third of the cycle is the time the refrigerants experience heat transfer with the propane while demagnetized. And a final one-sixth of the cycle, the refrigerants are magnetized without heat transfer occurring. This is depicted in Figure 5.

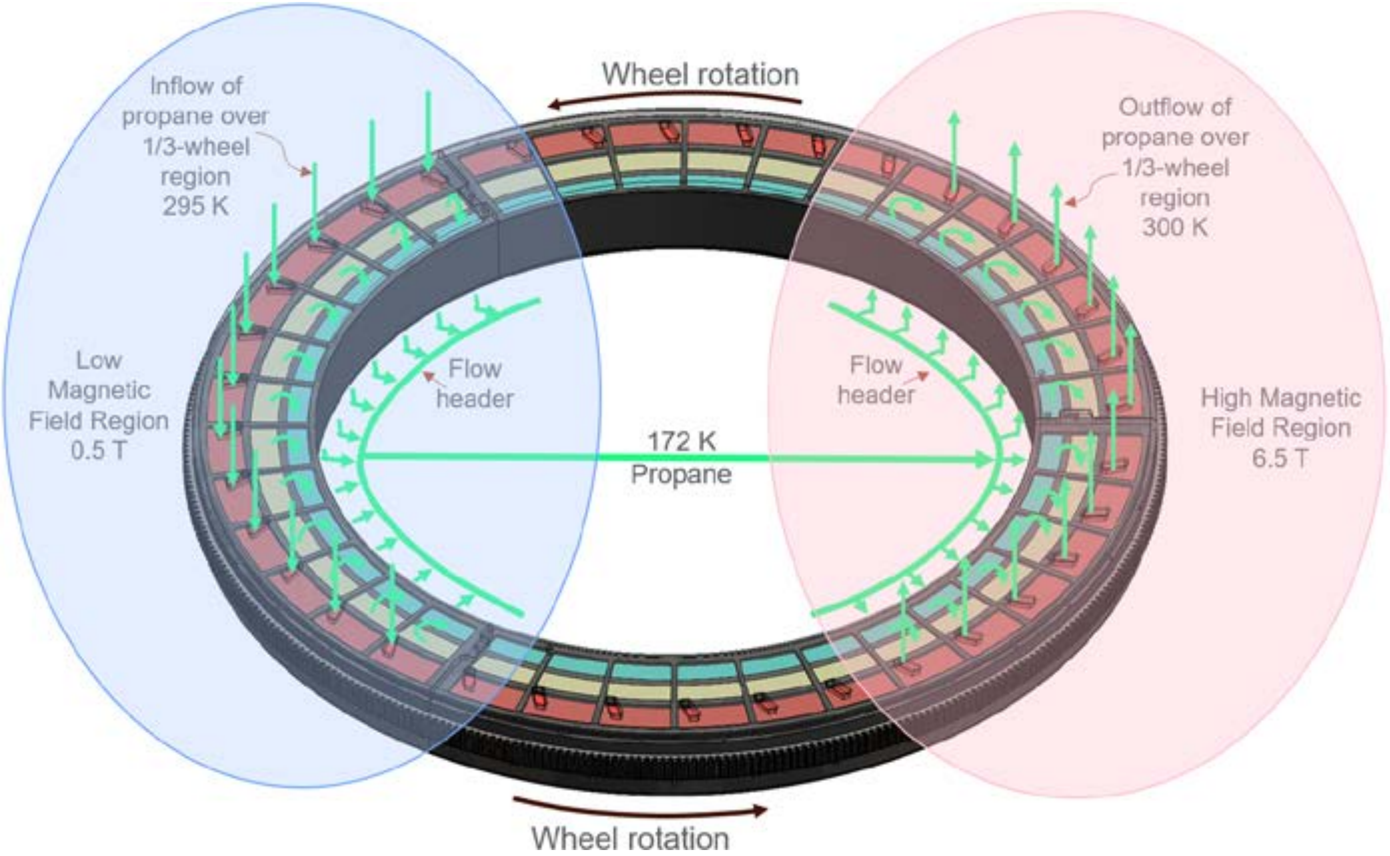


Figure 5: Propane heat transfer fluid flow occurs in one-third of the rotating wheel while demagnetized and one-third of the wheel while magnetized.

Flow control headers and rotary seals positioned in the demagnetized and magnetized regions direct the flow in and out of the rotating refrigerants at precise locations within the enclosed pressure vessel. Entrance and exit ports route the flow from internal flow control means to external components like flow control valves and heat exchangers via tubing. In effect, within the toroidal pressure vessel there will be ducting that routes the flow from the external flow loop to the refrigerant regenerators in a certain flow path. External piping will connect the toroidal pressure vessel to an external circulating pump and heat exchangers, as well as connect the different diversion flow stream from the demagnetized region to the magnetized region. The pump maintains a specific propane flow rate that overcomes head-losses. The flow rate matches the thermal mass changes in the refrigeration cycle due to the magnetocaloric effect, mass of the refrigerants and cycle frequency.

The internal rotary seal system that integrates with the toroidal pressure vessel and drive system is a vital component to the success of the effective control of the propane flow. Key progress includes the successful design and testing of rotary seals, achieving leakage rates below the target of 2% and torque requirements within acceptable limits for cryogenic conditions. Once functionality of a single-stage rotary MCL system has been demonstrated, showing cooling capacity between 295 K and 172 K, further optimization is planned for the second stage to reach temperatures as low as 100 K, with 1 kilowatt (kW) of lift at 100 K.

The advantage of magnetocaloric refrigeration is that it eliminates a compressor from the refrigeration cycle, thus removing a the commonly inefficient component of traditional compress-expansion gas cycles. The critical component of efficiency improvements in MCL is the interaction between the heat transfer fluid and the solid-state refrigerants regenerators. Reduction in irreversible entropy generation in the fluid to regenerator interaction through regenerator geometry optimization holds the key for high-efficiency MCL technology. Competing considerations include heat transfer fluid density, fluid flow regimes, regenerator heat transfer surface area, total regenerator volume, reduction in magnetic AC losses within the refrigerants, regenerator strength to withstand magnetic forces, and thermal conduction across regenerator temperature gradients.

Research currently focuses on regenerator geometry optimization through computational and simulated analysis. Experimentation on advanced regenerator design is also being conducted. To date, MCL research at PNNL has utilized monolithic, packed-bed regenerators composed of approximately 200 um magnetocaloric alloy particles combined with pressurized helium as the heat transfer fluid. The data in Table 1 show that simply moving to a liquid heat transfer fluid such as propane has a huge impact on reducing losses in the heat transfer process due to pressure drop minimization. Further research is focused on reducing losses further through advanced geometry designs such as a microchannel construction, which leverages advanced fabrication capabilities such as additive manufacturing.

TABLE 1. COMPARING LOSSES IN REGENERATOR AND HEAT TRANSFER FLUID TYPES

	Packed Bed (200 µm, ε=0.38) w/ 400 psia Helium					Packed Bed (200 µm, ε=0.38) w/ 200 psia Propane					Microchannel (ε=0.38) w/ 200 psia Propane				
	Long Conduction	Eddie Diffusivity	Pressure Drop	Heat Transfer	Heat Leak	Long Conduction	Eddie Diffusivity	Pressure Drop	Heat Transfer	Heat Leak	Long Conduction	Eddie Diffusivity	Pressure Drop	Heat Transfer	Heat Leak
Layer 1	15.2%	12.4%	61.7%	6.1%	4.6%	53.6%	15.5%	0.2%	14.9%	15.8%	21.1%	13.3%	0.0%	38.3%	27.2%
Layer 2	4.0%	10.4%	76.7%	4.5%	4.4%	32.8%	19.4%	0.6%	20.4%	26.8%	19.6%	11.6%	0.1%	36.5%	32.2%
Layer 3	3.3%	12.3%	72.3%	6.5%	5.6%	26.7%	19.0%	0.8%	25.3%	28.2%	15.0%	10.7%	0.2%	42.6%	31.6%
Layer 4	14.1%	21.7%	26.8%	11.9%	25.5%	33.0%	22.8%	0.3%	14.1%	29.9%	20.9%	14.4%	0.1%	26.7%	38.0%
Layer 5	7.7%	24.7%	22.4%	19.5%	25.7%	16.8%	33.9%	0.7%	22.5%	26.1%	9.9%	19.9%	0.1%	39.5%	30.6%
Average	**8.9%**	**16.3%**	**52.0%**	**9.7%**	**13.2%**	**32.6%**	**22.1%**	**0.5%**	**19.4%**	**25.4%**	**17.3%**	**14.0%**	**0.1%**	**36.7%**	**31.9%**
Total Parasitics [W]	**253.5**					**80.4**					**62.7**				

Bed Type	**Surface Area to Volume Ratio [m²/m³]**
Packed Bed	18600
Microchannel	4222

Analytical, simulation and experimental approaches are being used to optimize regenerator performance. Figures 6 and 7 show COMSOL computational fluid dynamics (CFD) with heat transfer simulations of microchannel and packed-bed geometries.

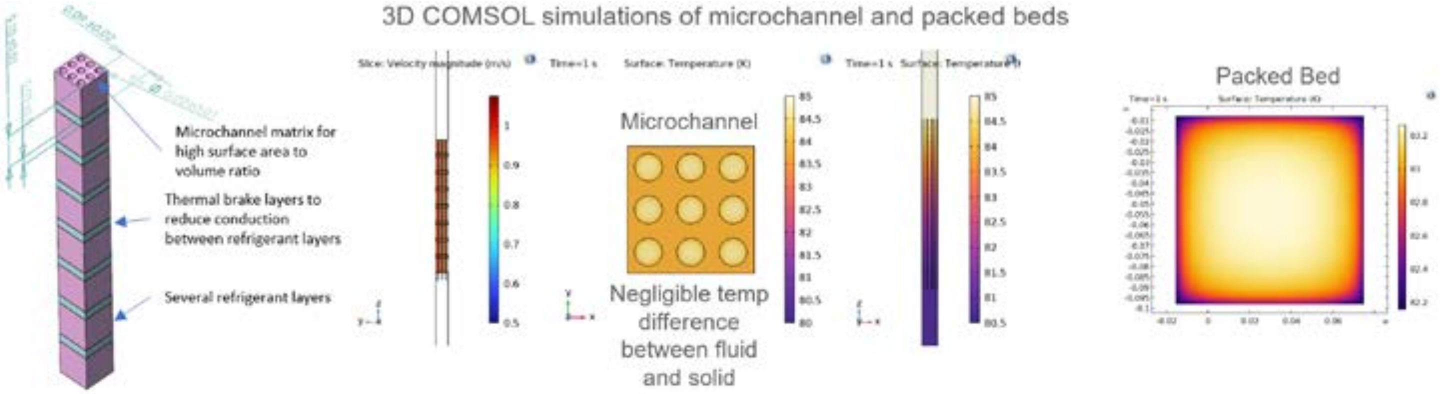


Figure 6: Results from COMSOL simulations for high-performance regenerators to achieve high-efficiency MCL.

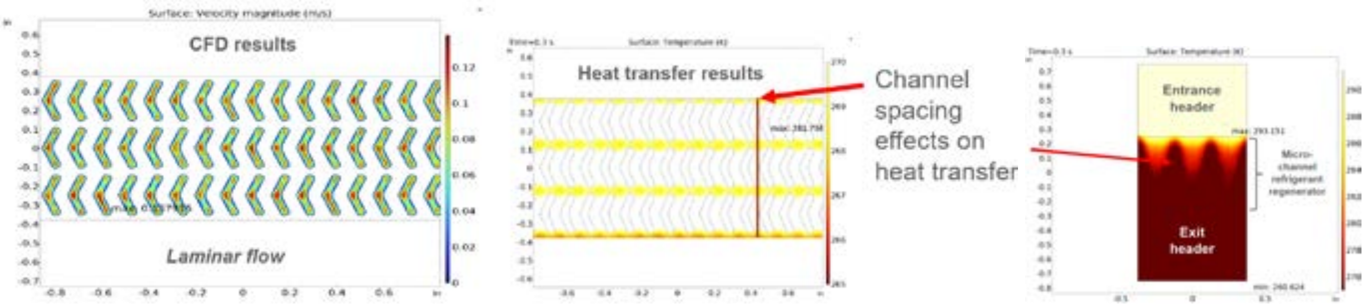


Figure 7: Computational modeling results.

Liquid Air Distillation

The PNNL rotary MCL technology results in liquefaction of air. Oxygen production still requires fractional distillation to separate product oxygen from nitrogen. PNNL microchannel distillation technology can reduce the size and energy demand of air separation units, making it suitable for distributed and modular applications. The microchannel column is an additively manufactured porous honeycomb (AMPH) column. The column is comprised of an internal solid framework surrounded by a solid outer shell. The framework is built of porous walls that are approximately 150 µm thick. The framework has a hexagonal honeycomb-like structure, and in the vertical direction it follows an undulating pattern to minimize the possibility of liquid droplets falling through the device without interacting with the wicking structures. This undulation generates the wave-like surface of the outer shell. The microchannel distillation (MCD) column is depicted in Figure 8.

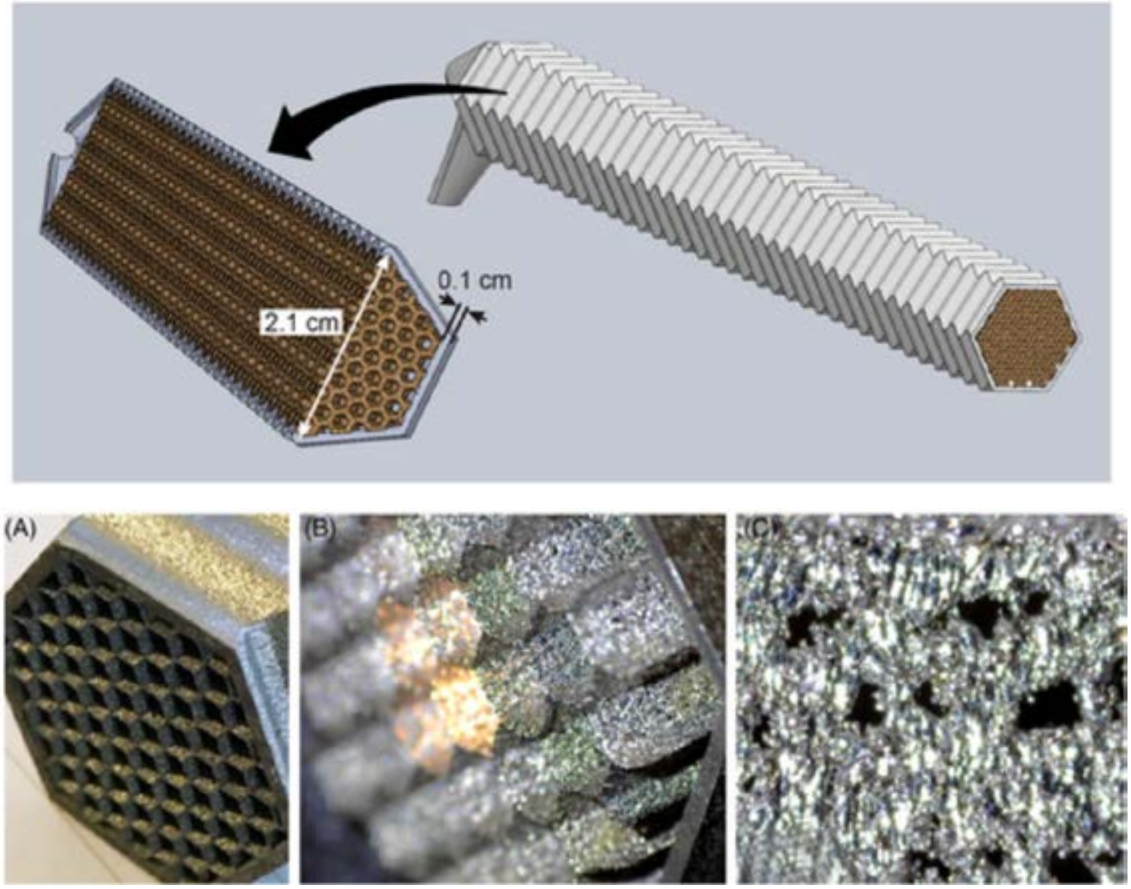


Figure 8: Computer-aided design (CAD) model and close-up images of the AMPH air distillation column.

Research of this design demonstrates that, relative to traditional random packing, the column efficiency of oxygen from air in an MCD column can be greatly enhanced by using a custom AMPH internal structure. This enhanced efficiency results from the porous liquid wicking structures present in the AMPH column.

Techno-Economic Analysis

Preliminary techno-economic analyses (TEAs) indicate substantial reductions in operational and capital costs compared to conventional air separation systems, with energy efficiency improvements exceeding 40%. The integration of high-performance refrigerant regenerators was validated, demonstrating low entropy generation and effective thermal management for the magnetocaloric cycle.

The current estimated results and target research and development (R&D) values for oxygen production economics are shown in Table 2.

TABLE 2: OXYGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Oxygen	$\$/kg\ O_2$	1.28	1.03
Capital Expenditures	$\$/kg\ O_2$	0.56	0.42
Variable Operating Expenditures	$\$/kg\ O_2$	0.11	0.06
Fixed Operating Expenditures	$\$/kg\ O_2$	0.61	0.55

Definitions:

Cost of Oxygen – Projected cost of capture per mass of O_2 produced under expected operating conditions.

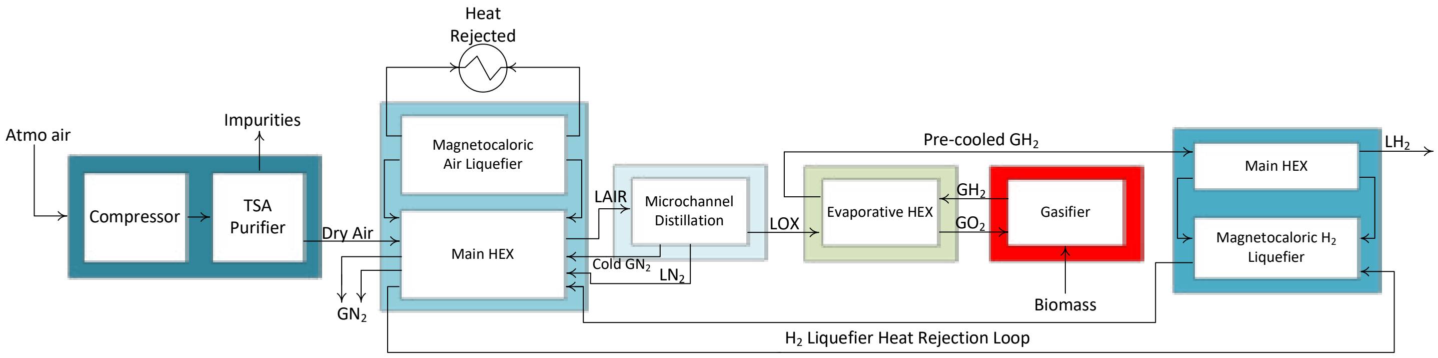
Capital Expenditures – Projected capital expenditures in dollars per kg of O_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of O_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M.

Other Parameter Descriptions:

Waste Streams Generated – Impurities from atmospheric air, primarily CO_2, water (H_2O).

Process Design Concept –



technology advantages

- The rotary MCL theoretically achieves up to 40% greater energy efficiency compared to traditional turbo-Brayton air liquefiers.
- Compact Design: Integration of microchannel distillation reduces the system footprint by a factor of 10 compared to conventional distillation.
- Scalability/modular design supports distributed applications for liquid oxygen and nitrogen production.
- Minimal environmental impact from durable, solid refrigerant materials.

R&D challenges

- Ensuring cryogenic seals meet low leakage and torque requirements.
- Refrigerant/regenerator optimization for minimal entropy generation and effective thermal properties.
- Fabricating robust, nonmagnetic pressure vessels that operate at cryogenic temperatures and high pressures.
- Overcoming challenges in integrating rotary components with magnetic systems for efficient operation.

status

Completion of multistage rotary MCL design and conducting full-scale performance tests to validate its efficiency and cooling capacity are slated. System capability to produce liquid oxygen and nitrogen under real-world conditions is planned, focusing on scalability for engineering applications. Additionally, efforts will address optimizing refrigerant regenerators, enhancing seal and pressure vessel designs, and refining system integration with microchannel distillation.

available reports/technical papers/presentations

"Rotary Magnetocaloric Liquefier for Air Separation," Corey Archipley, Pacific Northwest National Laboratory (PNNL), 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Archipley.pdf*.

"Additively manufactured cryogenic microchannel distillation device for air separation" *Danny R. Bottenus*, *Paul H. Humble*, *Russell Burnett*, *Warren Harper*, *Tim Veldman*, *Michael R. Powell*, *John A. Barclay*, *James Ely*, First published: 13 July 2022, *https://doi.org/10.1002/amp2.10139*.

"Methane liquefaction with an active magnetic regenerative refrigerator"
Corey Archipley, *John Barclay,*[a] Kerry Meinhardt, Greg Whyatt, Edwin Thomsen, Jamie Holladay, Jun Cui, Iver Anderson, Sam Wolf *https://doi.org/10.1016/j.cryogenics.2022.103588*.

High-Selectivity and High-Throughput Carbon Molecular Sieve Hollow Fiber Membrane-Based Modular Air Separation Unit for Producing High-Purity O_2

primary project goal

Los Alamos National Laboratory (LANL) is developing carbon molecular sieve (CMS) hollow fiber membranes for incorporation in a modular air separation unit (ASU) for high-purity oxygen (O_2) production. A multistage membrane process is being optimized to achieve the O_2 purity target while minimizing energy consumption. Core to the proposed work is development of polybenzimidazole (PBI)-derived CMS (PBI-CMS) hollow fiber membranes having exceptional O_2/nitrogen (N_2) selectivity and high O_2 permeance. The PBI-CMS hollow fiber membranes are obtained via controlled pyrolysis of PBI hollow fibers having microstructures tailored for gas separations using PBI hollow fiber manufacturing methods recently discovered/patented by the LANL team.

technical goals

- Synthesize PBI-derived CMS hollow fiber membranes achieving O_2/N_2 selectivity greater than 15, suitable for modular 1–5-megawatt-electrical (MWe) gasification systems.
- Refine a multistep membrane fabrication process, including pyrolysis conditions, to enhance membrane performance and scalability.
- Scale up membrane and module fabrication methods to fabricate multifiber industry-representative modules, ensuring consistent quality and performance in multifiber modules.
- Demonstrate a cost-effective/competitive solution for oxygen production in 1–5-MWe gasification systems, for which conventional cryogenic distillation systems would be inefficient or impracticable.

technical content

Development work at LANL is focused on designing high-permeance and high-selectivity oxygen separation membranes derived from PBI. LANL's process for forming the CMS membranes leverages a multistep fabrication process including crosslinking and pyrolysis to optimize the morphology and separation performance. By tailoring pyrolysis temperatures and pressures, the researchers aim to produce defect-free membranes with ultrathin selective layers. A depiction of the CMS membrane formation process is shown in Figure 1.

program area:
Gasification Systems

ending scale:
Lab-scale prototype

application:
Hydrogen Production

key technology:
Air Separation Technology

project focus:
ASU based on PBI-derived CMS hollow fiber membranes

participant:
Los Alamos National Laboratory (LANL)

project number:
FWP-FE-1049-18-FY19

predecessor projects:
N/A

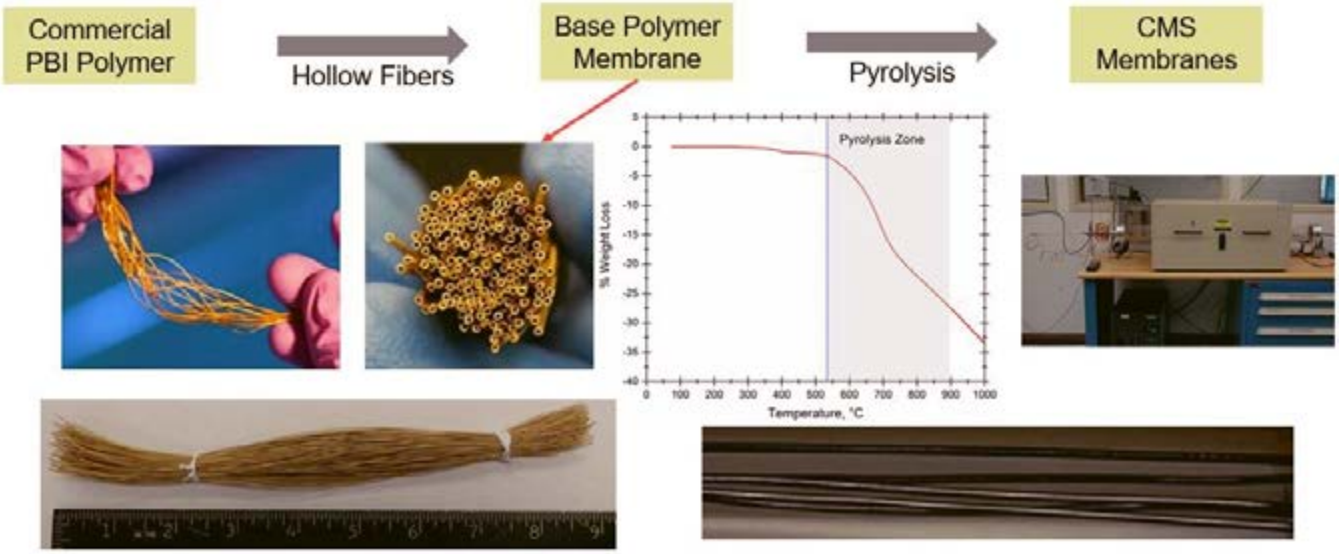
NETL project manager:
Katelyn Ballard
katelyn.ballard@netl.doe.gov

principal investigator:
Rajinder P. Singh
rsingh@lanl.gov

partners:
N/A

start date:
12.01.2018

percent complete:
90%

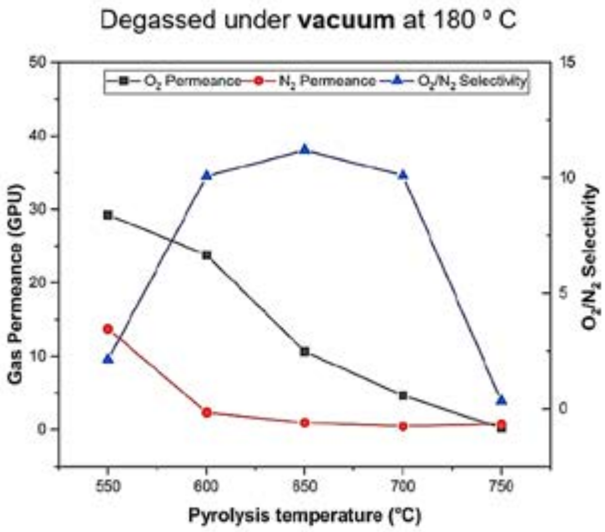


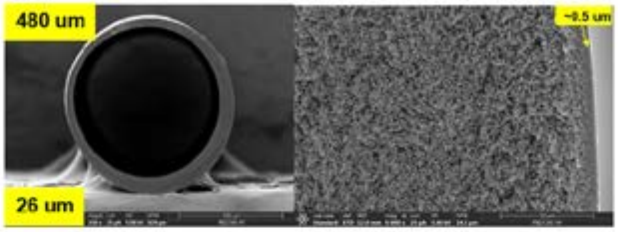
Ref. Berchtold & Singh, et al. 2018 US Patent 10071345

Figure 1: CMS membrane formation process.

The CMS membranes are in hollow fiber configuration, intended for incorporation in compact hollow fiber membrane modules for gas separations. These modules have a highly reduced footprint compared to other possible membrane module types, such as plate-and-frame and spiral-wound modules.

Optimization of O_2/N_2 separation performance has been accomplished through control of pyrolysis temperature, as illustrated in Figure 2. Selectivity showed 450% improvement with pyrolysis at 550°C to 650°C, but dropped 90% when temperatures exceeded 700°C. Optimum pyrolysis temperature for O_2/N_2 separation was found to be around 600°C to 650°C.





- Selectivity improved significantly (~4.5x) with increase in pyrolysis temperature from 550 to 650 ° C while a sudden drop (~90%) in selectivity was observed at 750 °C when compared to 700 °C.
- Optimum pyrolysis temperature was found to be 600-650 ° C to achieve high O_2/N_2 separation.

Figure 2: Temperature-dependent performance metrics for process optimization.

Testing of the membranes has shown consistent performance under various operational conditions, validating their pressure-independent separation capabilities. Multifiber modules were fabricated to assess scalability, with initial results indicating promising performance metrics comparable to laboratory-scale single-fiber tests. The membranes demonstrated robustness and reliability in separating oxygen from air, highlighting their suitability for integration into modular gasification systems.

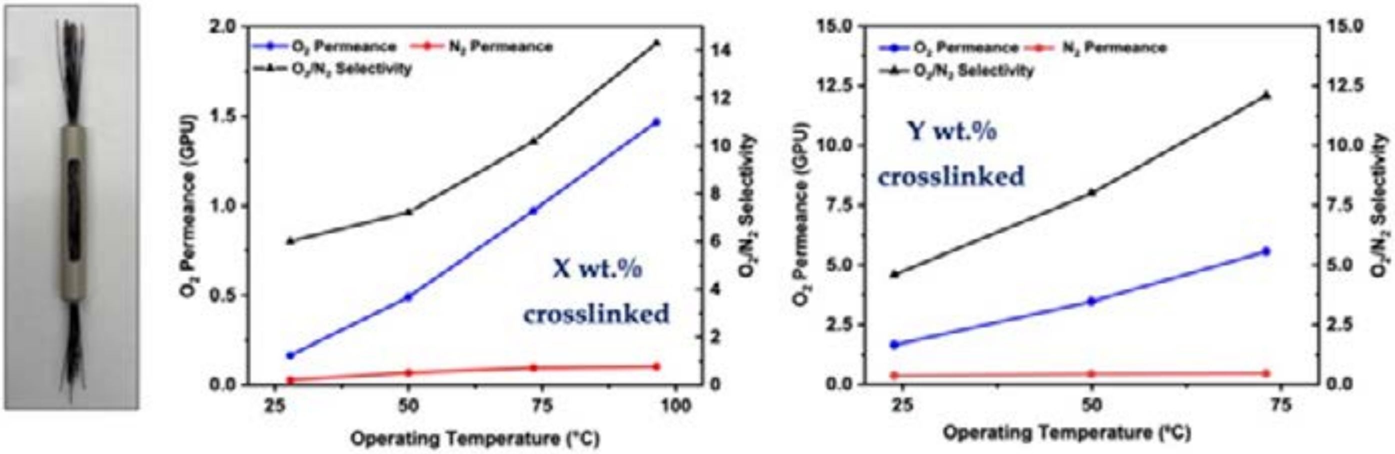


Figure 3: O_2/N_2 selectivity of industry representative multifiber module.

Techno-Economic Analysis

Process modeling and preliminary techno-economic analysis (TEA) have been performed to assess the feasibility of the CMS hollow fiber membranes in an actual ASU configuration involving multiple membrane module stages. Figure 4 compares oxygen production cost for a two-stage membrane-based process with two different membrane costs, against conventional cryogenic and pressure-swing adsorption ASU technologies. Membrane cost strongly drives the economics, and for a lower membrane cost of \$50/m^2, the CMS hollow fiber membrane ASU could offer competitive oxygen cost up to 90% purity.

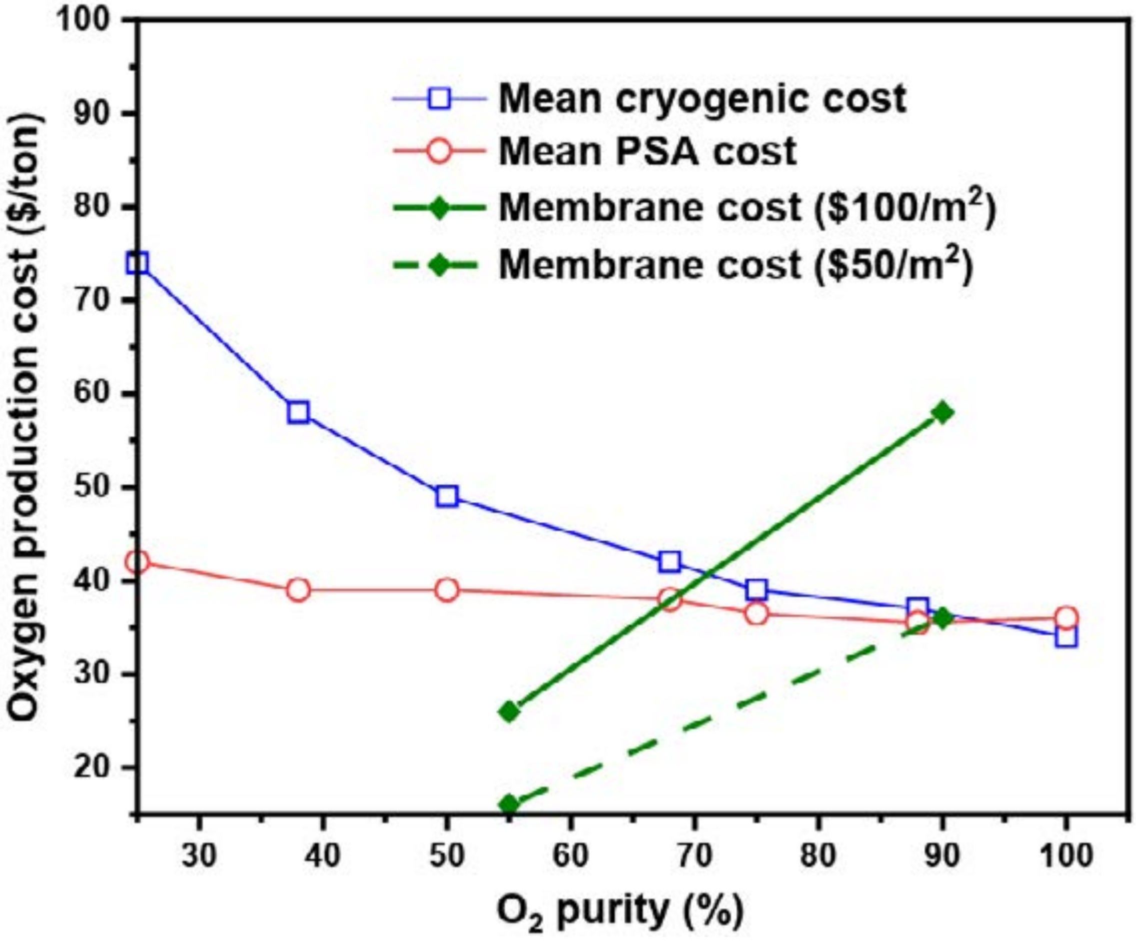


Figure 4: Oxygen production cost comparison.

The current estimated results and target research and development (R&D) values for oxygen production economics are shown in Table 1.

TABLE 1: OXYGEN PRODUCTION ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Oxygen	$/ton O_2	TBD	<100
Capital Expenditures	$/ton O_2	TBD	TBD
Operating Expenditures	$/ton O_2	TBD	TBD

**TBD based on the lab-scale multifiber module evaluation.*

Definitions:

Cost of Oxygen – Projected cost of capture per mass of O_2 produced under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per kg of O_2 produced.

Operating Expenditures – Projected operating expenditures in dollars per kg of O_2 produced. Could be split into variable operations and maintenance (O&M), fixed O&M.

Other Parameter Descriptions:

Waste Streams Generated – None.

Process Design Concept – See below.

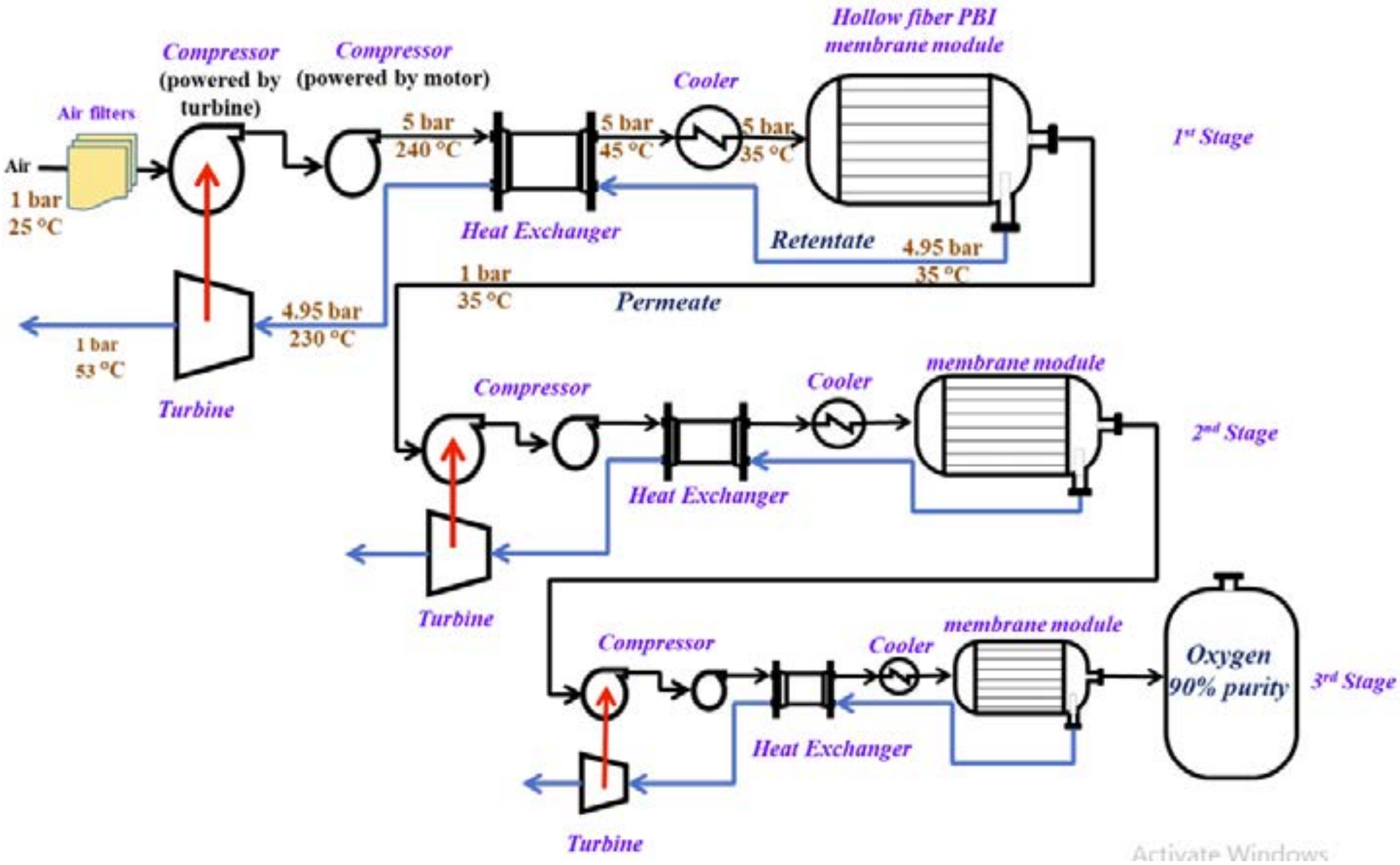


Figure 5: Three-stage process option for greater than 90% O_2 production using LANL membrane modules.

technology advantages

- Membrane-based air separation processes are inherently more energy-efficient than cryogenic distillation, especially at smaller scales.
- The compact and scalable design of the membrane modules allows for easy integration into modular gasification systems, facilitating flexible deployment.
- Optimized CMS membranes achieve high-enough O_2/N_2 selectivity and oxygen permeance to provide oxygen suitable for gasification processes.
- CMS hollow fiber membranes use compact module configuration, resulting in a small footprint suitable for applications with space constraints.

R&D challenges

- Ensuring uniformity and reproducibility in membrane fabrication at an industrial scale to maintain consistent air separation performance for commercial modules.
- Attaining mechanical strength and toughness of the hollow fiber membranes to withstand operational stresses and prevent failure during use.
- Attaining long-term stability of membrane system under continuous operation to ensure reliability and durability.

status

Mitigation of CMS hollow fiber structural collapse during the pyrolysis process has been satisfactorily accomplished with high mechanical strength of the hollow fiber membranes obtained. With thinner selective layer (less than 1 µm) effectively obtained on the membranes, the goal of high-O_2/N_2 selectivity (approximately 15) has also been achieved. Membrane module development continues with satisfactory high-temperature epoxy identified and utilized.

available reports/technical papers/presentations

"High Selectivity and Throughput Carbon Molecular Sieve Hollow Fiber Membrane-Based Modular Air Separation Unit for Producing High Purity O_2," Harshul Thakkar and Rajinder P. Singh, Los Alamos National Laboratory (LANL), 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Thakkar.pdf*.

"Polybenzimidazole-derived carbon molecular sieve hollow fiber membranes with tailored oxygen selective transport" Jong Geun Seong, Jeremy C Lewis, John A Matteson, Erica Craddock, Ulises Martinez, Harshul Thakkar, Angelica D Benavidez, Kathryn A Berchtold, Rajinder P Singh, Carbon 192,2022, 71-83.

Gasification of Blended Feedstocks for Hydrogen Production

primary project goal

The National Renewable Energy Laboratory (NREL) is investigating the production of hydrogen (H_2) through a combination of systems analysis, gasification reactor modeling and real-time feedstock characterization. Systems analysis comprises techno-economic analysis (TEA), life cycle analysis (LCA) and resource analysis on gasification of blended carbonaceous resources (i.e., sustainable biomass, mixed plastics waste, coal waste) to produce H_2. Gasification mesoscale modeling produces high-fidelity, particle-scale simulations of gasification, augmented with machine learning methods to produce fast-solving sub-grid models that account for feedstock-specific behavior in Multiphase Flow with Interphase eXchanges (MFiX) reactor simulations. Real-time feedstock characterization work involves measurement of the chemical and physical attributes of mixed gasifier feedstocks in real-time to enable feed-forward control, ensure stable operation of the gasifier, and optimize H_2 production. Gasification experiments in the NREL Single Particle Reactor (SPR) and the NREL Research Gasifier (NRG) are critical for model validation.

technical goals

- Create and baseline gasifier models (indirect, direct non-slagging and direct slagging) using harmonized operating assumptions for both single-component and blended feedstocks.
- Construct and parameterize particle-scale models to simulate intra-particle heat and mass transfer for various feedstocks.
- Identify and develop real-time, low-cost sensors for characterizing mixed biomass, municipal solid waste (MSW), and fossil fuel feedstock streams.
- Map resources and infrastructure to identify optimal locations for low-carbon hydrogen production facilities.
- Incorporate CCS into gasification models to assess its impact on techno-economic performance.

technical content

The National Renewable Energy Laboratory (NREL) is developing advanced gasification technologies for producing low-carbon hydrogen from blended feedstocks including biomass, MSW and fossil fuel-derived materials.

program area:
Gasification Systems

ending scale:
N/A (modeling emphasis)

application:
Hydrogen Production

key technology:
Novel Technologies for Chemicals & Fuels

project focus:
Investigating H_2 production through systems analysis, modeling, and feedstock characterization

participant:
National Renewable Energy Laboratory

project number:
FWP-OMS27850

predecessor projects:
N/A

NETL project manager:
Katelyn Ballard
katelyn.ballard@netl.doe.gov

principal investigator:
Michael Talmadge
michael.talmadge@nrel.gov

partners:
N/A

start date:
04.01.2023

percent complete:
90%

Real-Time Feedstock Characterization

Mixed biomass and MSW feedstocks have heterogeneous chemical attributes that can make real-time, feed-forward control of gasifiers extremely challenging. NREL has hypothesized that a minimal set of attribute data (component fractions, moisture content, bulk inorganic content and material size/morphology) measured by low-cost sensors would ensure satisfactory collection of feed stream properties needed for proper gasification process control (see Figure 1).

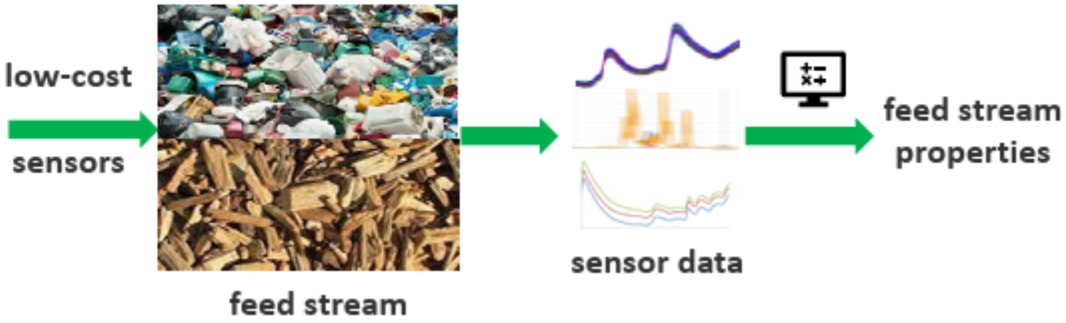


Figure 1: Concept of real-time feedstock characterization via sensor technology.

Sensing and sorting technologies are anticipated to become better and cheaper in the future, and the application to biomass/MSW/fossil fuel waste is unlikely to be a major technology hurdle. Real-time sensing using commercial offerings, and the U.S. Department of Energy (DOE) investments already made in the area (e.g., Energy Research Company's laser-induced breakdown spectroscopy [LIBS] technology), can be leveraged, and considerable investments continue to be made by the private sector in machine learning and artificial intelligence associated with online sensing. NREL and National Energy Technology Laboratory (NETL) researchers will collaborate on generating well-curated datasets using multiple sensing modalities of well-characterized mixtures of biomass/MSW/fossil fuel waste; these will be readily accessible via NETL's Energy Data Exchange (EDX; *https://edx.netl.doe.gov/*).

Meso- and Particle-Scale Modeling

Advanced computational modeling is being leveraged at both mesoscale and reactor scale, allowing for detailed simulations that account for the impact of feedstock variability on gasifier performance over a range of operating conditions. For example, Figure 2 illustrates particle finite element simulations, parameterized based on particle size, shape, composition and physical properties (e.g., density, thermal conductivity, porosity). Internal heat and mass transport are coupled to conversion reaction kinetics. Spherical models are shown here, but arbitrary shapes may also be simulated. Results show that effective heating and conversion rates vary substantially as a function of feedstock particle characteristics and provide predictions of residence times required to achieve complete conversion of each feedstock variant.

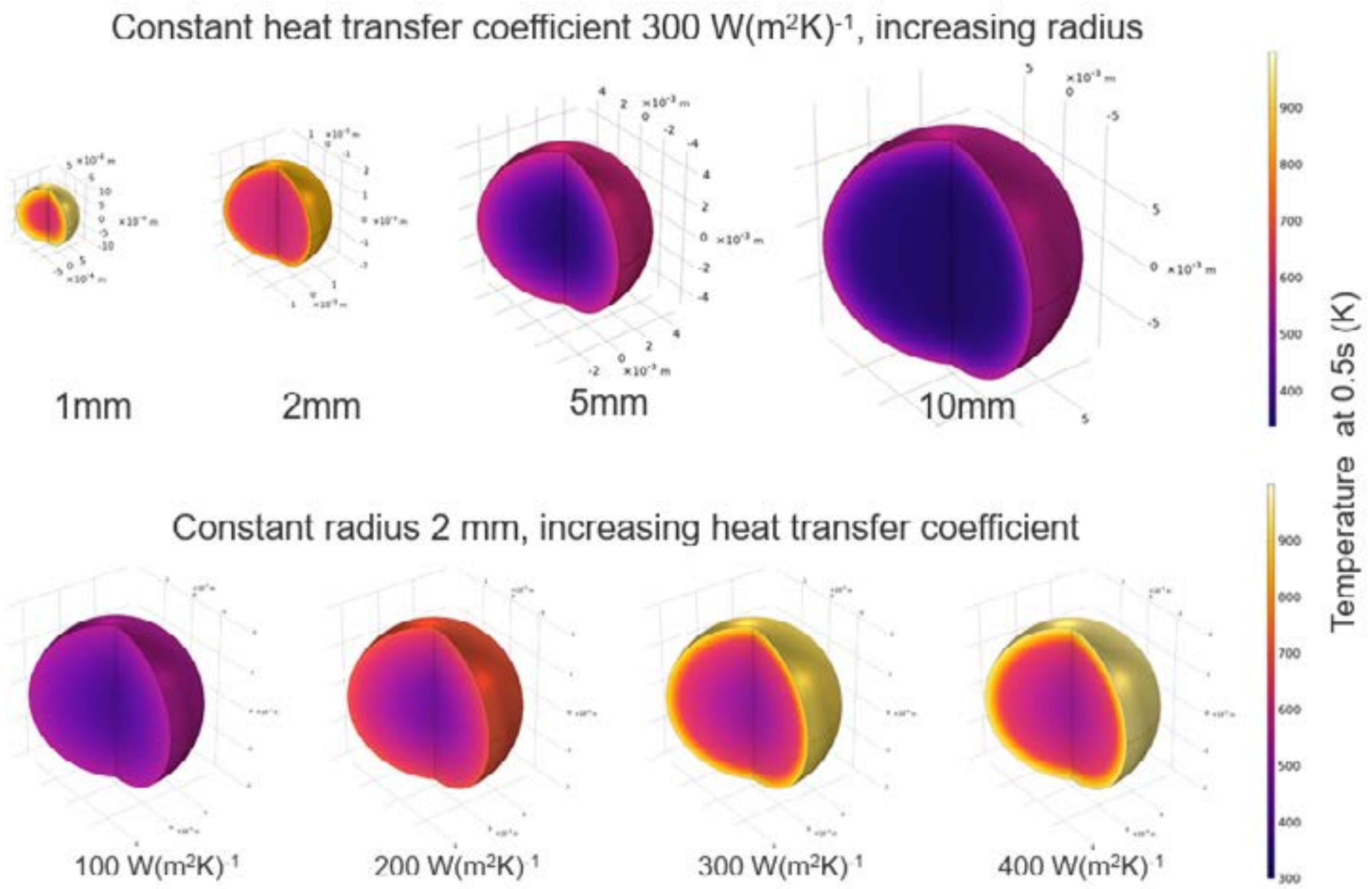


Figure 2: Snapshots of parametric sweep simulations.

NREL applied this modeling to particles of wood and high-density polyethylene, and from these simulations, conversion times, product distributions, and heat and mass flux were computed (see Figure 3). Results are used to inform MFiX modeling for capture of feedstock effects at the reactor scale.

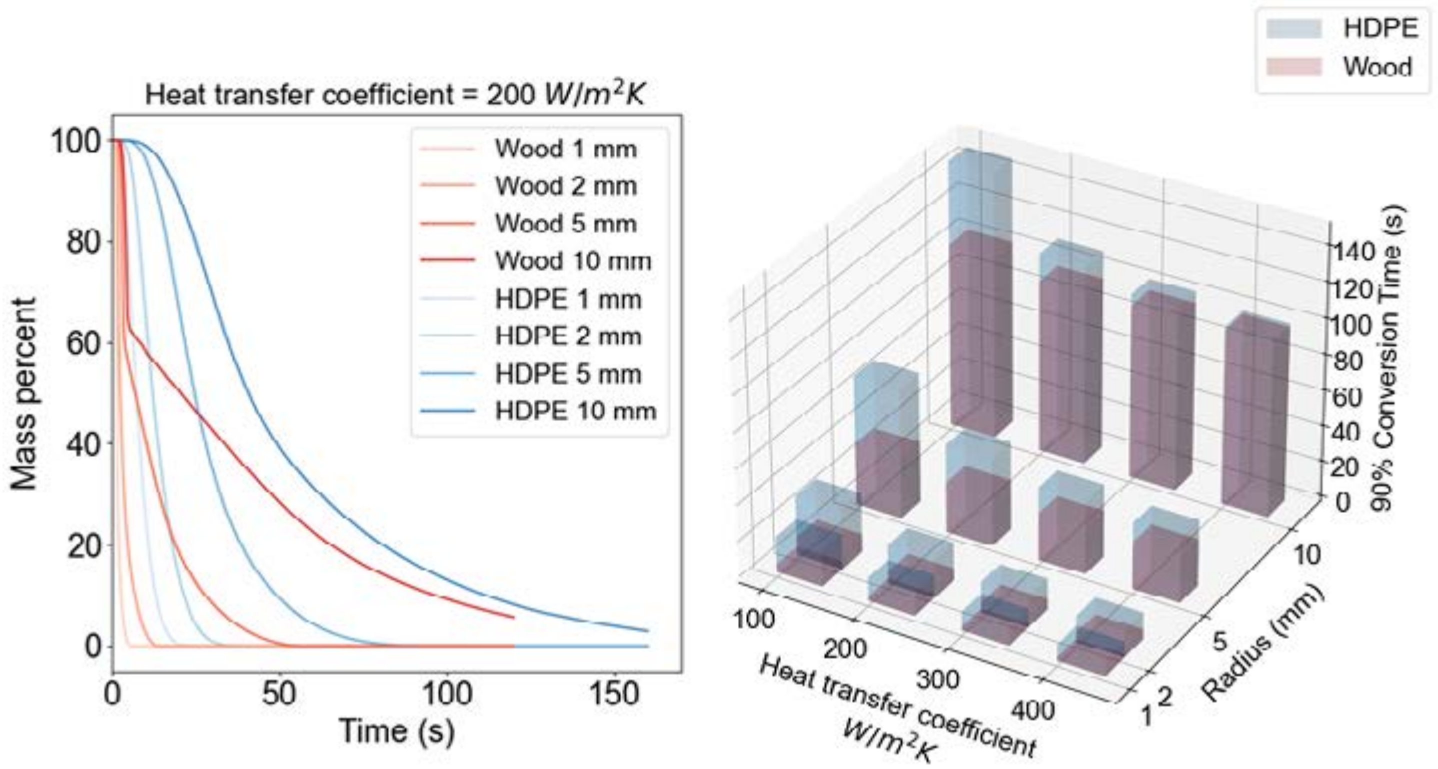


Figure 3: Predicted conversion of biomass and waste-derived particles with varying particle properties.

Kinetic models for specific plastics species developed by NETL are being implemented in simulations. These particle models are being validated by experiments using NREL's SPR (see Figure 4), leveraging models previously developed for the SPR, and enabling robust validation for particles of varying size, shape and composition.

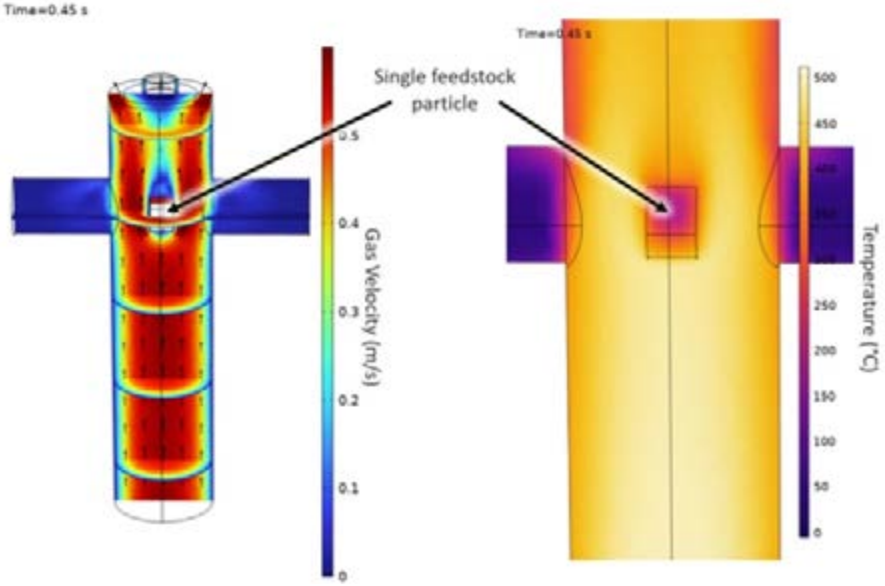


Figure 4: Simulations of NREL's Single Particle Reactor.

Experimental Data Collection for Model Parameterization and Validation

As mentioned in the meso- and particle-scale modeling section, experimental datasets are collected for model development and hypothesis testing. Two reactor systems are used for these efforts: (1) NREL's SPR and (2) NREL's NRG. Collecting data from different reactor scales and configurations is essential for validating the applicability of the model to a range of reactor types. The SPR was designed for particle-scale model development as it suspends a single particle or a mesh basket of ground particles, up to 2 grams, from a balance to measure the weight loss of the particle under reaction conditions. A thermocouple is placed just beside the particle to measure the free-stream temperature change as the particle reacts. In the case of low-density polyethylene (LDPE) samples, the SPR measures an endotherm, presumably as the particle melts before it reacts, as shown in Figure 5, from two steam gasification experiments. Additionally, a small gauge thermocouple (0.001-inch diameter) can be placed in the center of the particle to measure its internal temperature as well as the free-stream temperature just outside the particle. Figure 6 shows the difference in the heating of the free-stream and the center of the particle during pyrolysis experiments with pine particles. Lastly, gas bags are collected during mass loss and analyzed with gas chromatography (GC) to characterize the gases produced. The NRG provides gasification data, including mass balances and gas characterization via GC and nondispersive infrared (NDIR) before and after a fixed-bed catalytic reformer from continuous steam gasification at feeding rates from 0.3 to 2 kg/hr. Two feedstocks from the SPR experiments will be selected for NRG-scale gasification experiments for model validation.

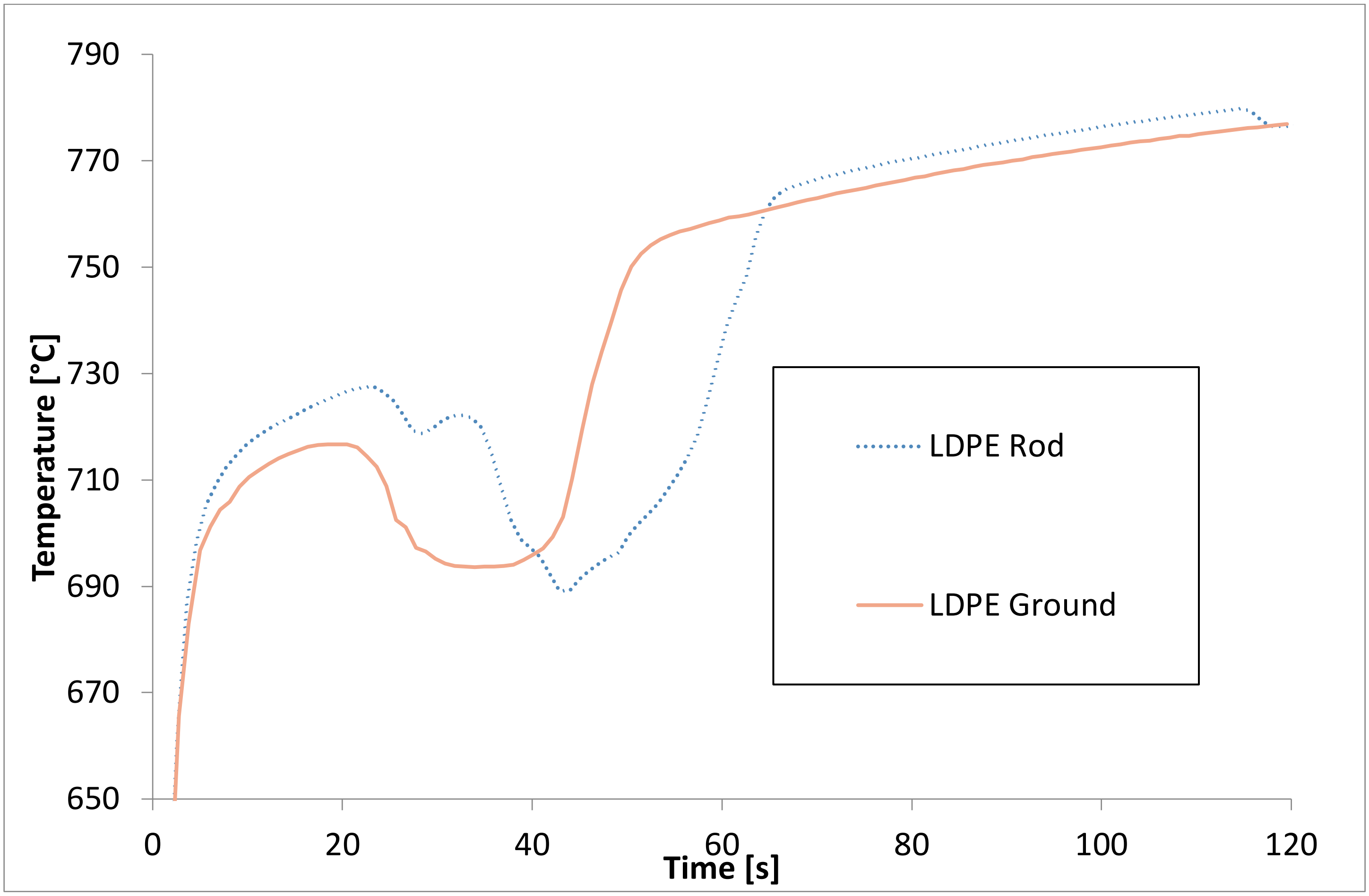


Figure 5: Free-stream temperature next to LDPE pellet (dotted trace) and LDPE ground sample (solid trace) in hanging basket during steam gasification.

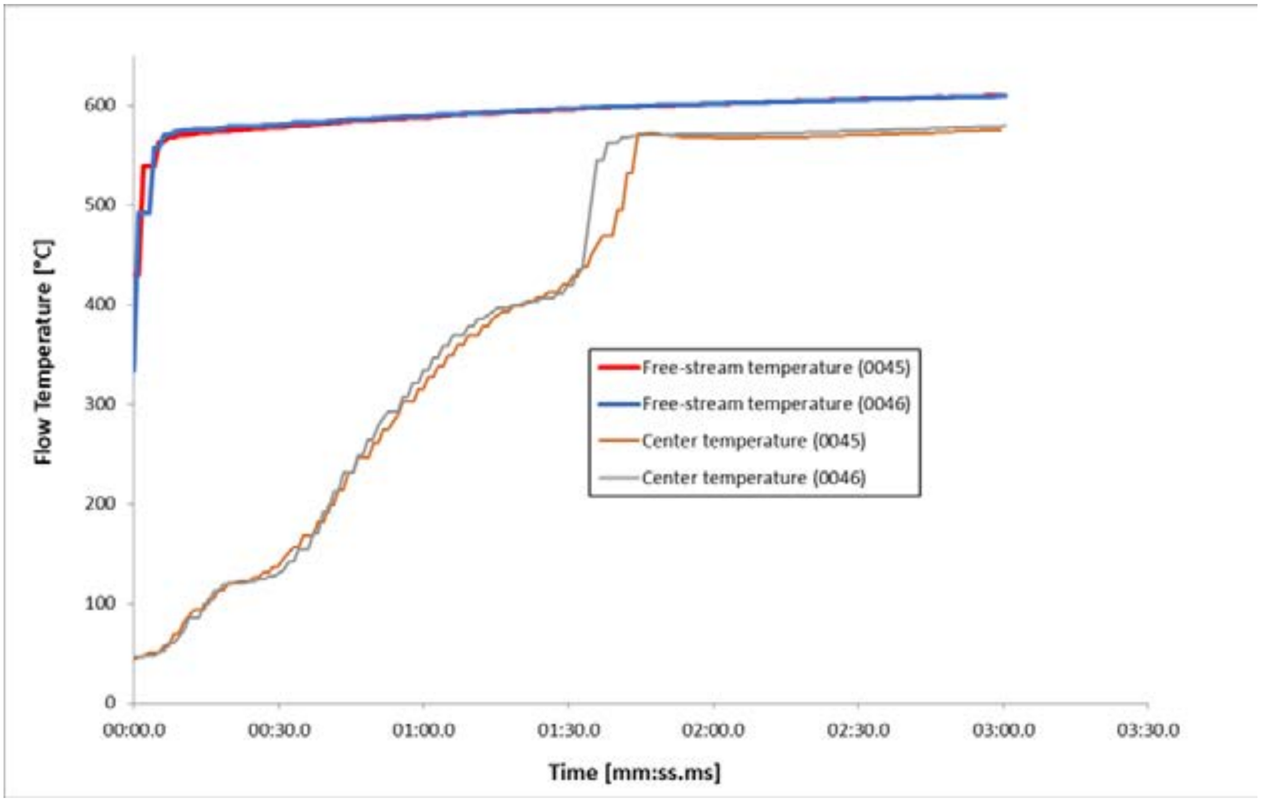


Figure 6: Changes of temperature with time during pine particle pyrolysis experiments of the free stream (top two traces) and the center of the pine particle (bottom two traces).

Resource and Facility Siting Analysis

Resource and facility siting analyses are being used to identify possible locations for hydrogen production facilities. As a first step, NREL has evaluated high-resolution geospatial data on feedstock availability, existing infrastructure, carbon capture and storage (CCS) locations, and H_2 end-market demand, leading to the identification of several possible “hotspots” where these key logistical elements overlap (see Figure 7).

To further refine the siting assessment, NREL is now integrating resource availability data within gasifier TEA and LCA models in an effort to quantify a relative weighting for key variables, such as transportation mode and distance for gasifier feedstocks, carbon dioxide (CO_2) storage, and H_2 product delivery. These relative weightings help narrow down and prioritize locations that minimize logistical costs and life cycle impacts associated with producing H_2. The results lay the groundwork for future detailed techno-economic evaluations and strategic planning, ensuring the scalability and viability of hydrogen production pathways.

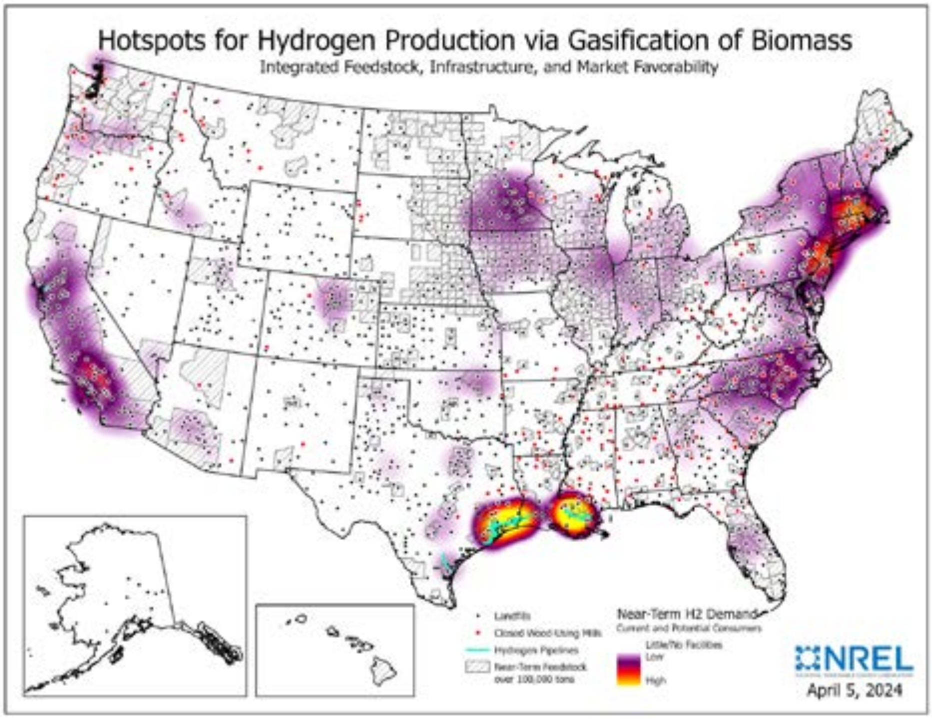


Figure 7: High-level siting analysis results combining resource availability, existing infrastructure and near-term H_2 demand.

Gasification Process Modeling

Gasification models for indirect steam-blown, direct non-slagging, direct slagging and plasma direct slagging configurations were developed and updated with a consistent set of harmonized operating assumptions. These models incorporated blended feedstocks, such as biomass and MSW, allowing for detailed analysis of process performance. Preliminary results indicate that the models accurately predict key parameters such as gas composition, carbon conversion efficiency and energy outputs, enabling comparative evaluation of different gasifier designs. Further, when baselined against literature and other gasification references, projected H_2 costs are in good agreement with other estimates, validating the modeling approach (see Table 1).

Table 1: Comparing NREL projected H_2 costs with literature.

Ref	Gasifier Style	H_2 MSP ($/kg)
Salkuyeh 2018	Entrained Flow	3.51
Salkuyeh 2018	Fluidized Bed	3.48
Wu 2023	Dual FB	2.92
NETL 2023	EF (Coal + Biomass)	3.64
IEA Estimated	N/A	2.75 – 3.35
NREL	**Indirect**	**2.52 – 3.48**
NREL	**Direct Slagging**	**2.92 – 4.00**
NREL	**Plasma**	**4.34 – 5.58**
NREL	**Direct Dry Ash**	**3.00 – 4.24**

With biomass and MSW existing primarily as decentralized resources, with availability varying from region to region, two key questions that the economic modeling sought to address were (1) the impact of scale and (2) the impact of feedstock transportation distance on final H_2 selling price. Shown in Figure 8, NREL evaluated the impact of feed rate for all four gasifier models for both 100% MSW and 100% biomass feedstocks. TEA results show that for all eight cases studied, H_2

selling prices were significantly affected when total feed rates were below 500 to 1,000 dry tonnes per day. At these relatively low rates, H_2 prices ranged from approximately $3/kg in the best case up to greater than $18/kg. As the total feed rate was increased to approximately 1,500+ tonnes per day, the impact of scale was diminished, suggesting that at a minimum, gasifier facilities should ideally be siting in locations capable of providing a minimum of approximately 1,500 tonnes per day of feed. Also of note, the preliminary TEA data shows that of the four gasifier types, indirect gasification consistently showed the lowest overall cost due primarily to its comparatively high yield of H_2. Indirect gasification was followed by direct ash, direct slagging and finally plasma gasification.

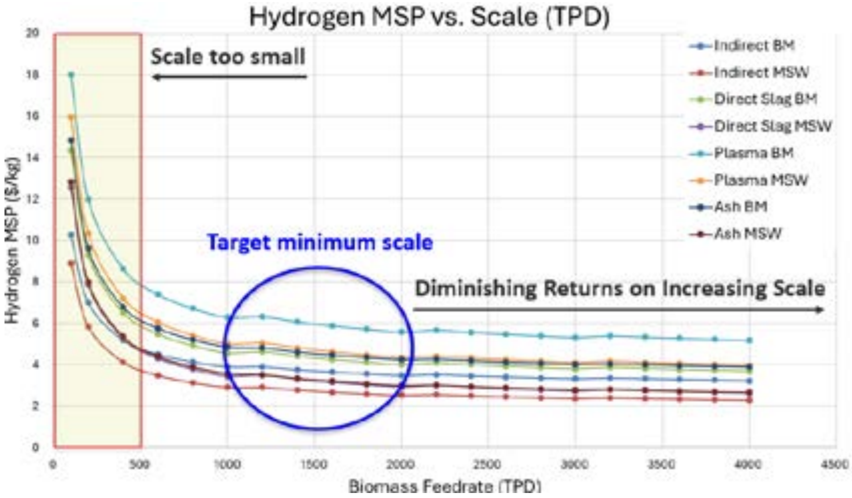


Figure 8: Impact of scale and feedstock flowrate on H_2 selling price.

With scale factoring so significantly into cost, the tradeoff between expanding the area of operation (e.g., feedstock transportation distance), which is a net increase to cost, versus increasing process scale, which is a net decrease to cost (see Figure 8), was investigated. As shown in Figure 9, at small scales (e.g., less than 1,000 tonnes per day), expanding the radii of operating by an additional 50 to 400+ miles to access an additional 100-tonnes-per-day feedstock capacity was shown to result in a net decrease to H_2 selling price. However, as the impact of scale becomes less pronounced, the breakeven distance for sourcing additional feedstock is reduced where an operator may only be willing to go an additional approximately 10 (trucking) to 30 (rail) miles to source feedstock before it becomes uneconomical to do so. Quantifying these logistical tradeoffs, not only for feedstock transportation, but also CO_2 storage and H_2 delivery, is critical for informing the final siting analyses.

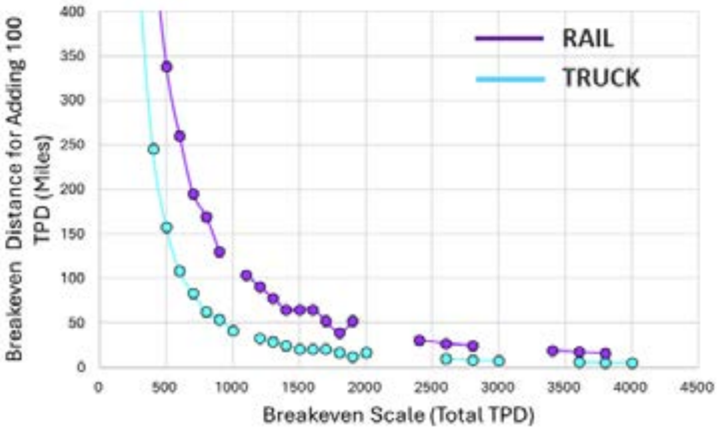


Figure 9: Impact of feedstock transportation distance and mode on H_2 selling price.

technology advantages

- Supporting utilization of blended feedstocks, including biomass, MSW and fossil-fuel derived materials, for adaptable and cost-effective hydrogen production.
- Advanced modeling combining mesoscale and reactor-scale simulations for precise predictions of gasifier performance and feedstock behavior.
- Low-cost sensors enable accurate, real-time measurement of feedstock properties, optimizing gasifier control.
- Geospatial analyses identify optimal production locations, minimizing transportation costs and carbon emissions.

R&D challenges

- Validating computational models with experimental data for various feedstock blends and gasifier configurations.
- Minimizing costs of feedstock pre-processing while maximizing operational reliability of gasifiers.
- Managing feedstock variability and providing feed-forward control for adjusting operations with changes in feedstock quality.
- Achieving operational scale to minimize costs with variable feedstock availability and quality.
- Metallurgical requirements driven by operating conditions and feedstock contaminants.

status

Validating gasification models with experimental data, refining feedstock characterization tools, and conducting integrated techno-economic and carbon-intensity analyses to optimize low-carbon hydrogen production at commercial scales in process.

available reports/technical papers/presentations

"Gasification of Blended Feedstocks Coupled with Carbon Capture and Sequestration to Achieve Net-Zero or Net-Negative Emissions H_2," Michael Talmadge, National Renewable Energy Laboratory (NREL), 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Talmadge.pdf*.

this page intentionally left blank

GASIFICATION SYSTEMS TECHNOLOGY SHEETS

NETL RIC

Modeling and Simulation for Optimization of Gasification Systems

primary project goal

The National Energy Technology Laboratory's (NETL) simulation-based engineering tools (Multiphase Flow with Interphase eXchanges [MFiX], Optimization Toolset) are being used in design and optimization of novel pyrolysis and gasification reactor designs, including a novel oxygen (O_2)-blown, pilot-scale pyrolyzer and gasifier for use in hydrogen (H_2) production. Simulations guide design and scale-up of gasification reactors for mixed feedstocks, including biomass, plastics and municipal solid waste (MSW). Simulations verify that pilot-scale systems meet design parameters and help guide reactor optimization. Gasifier models are evaluated over a range of operating conditions and feed rates to provide information on flows, temperatures, and solid and gas compositions in the reactor. Geometric design and operating parameters can be optimized in this approach.

technical goals

- Develop microwave heating integration for fluidized bed gasifiers.
- Model microwave energy interactions using computational electromagnetics (CEM) and computational fluid dynamics (CFD) simulations.
- Design methods to prevent agglomeration caused by melted plastics.
- Optimize gasifier configurations for energy efficiency and scalability.
- Conduct experimental testing of microwave-integrated gasifier systems.

technical content

NETL is advancing gasification technologies through research and development (R&D) in several areas aimed at enabling the utilization of diverse feedstocks for hydrogen and value-added products.

Work discussed here focuses on development of innovative gasifier designs that leverage microwave heating technology to enhance reaction efficiency and operational flexibility. Traditional gasifiers rely on fuel heating value to drive endothermic reactions required for feedstock conversion, which can result in energy inefficiencies and uneven temperature distributions. To address these challenges, microwave energy can be transmitted into fluidized bed reactors, enabling selective heating of specific particles and improving overall reaction kinetics.

Microwave heating offers unique advantages, such as the ability to target microwave-absorbing particles, allowing for localized temperature control within the gasifier. This capability not only reduces energy losses but also enhances the gasification of challenging feedstocks such as waste plastics and biomass.

program area:
Gasification Systems

ending scale:
N/A

application:
Hydrogen Production

key technology:
Process Intensification for Syngas and Hydrogen

project focus:
Using computational tools to help develop novel gasification designs and technologies

participant:
National Energy Technology Laboratory (NETL)

project number:
Gasification MYRP - Goal 4

predecessor projects:
FWP-1022405-03

NETL project manager:
Jennie Stoffa
jennie.stoffa@netl.doe.gov

principal investigator:
Christina Wildfire
christina.wildfire@netl.doe.gov
CFD Task Lead - Mehrdad Shahnam
mehrdad.shahnam@netl.doe.gov

partners:
N/A

start date:
04.01.2023

percent complete:
60%

Advanced CEM and CFD simulations are employed to model microwave interactions within the reactor, providing insights into temperature differentials and particle behavior under varying operating conditions. These models inform the design and optimization of the gasifier.

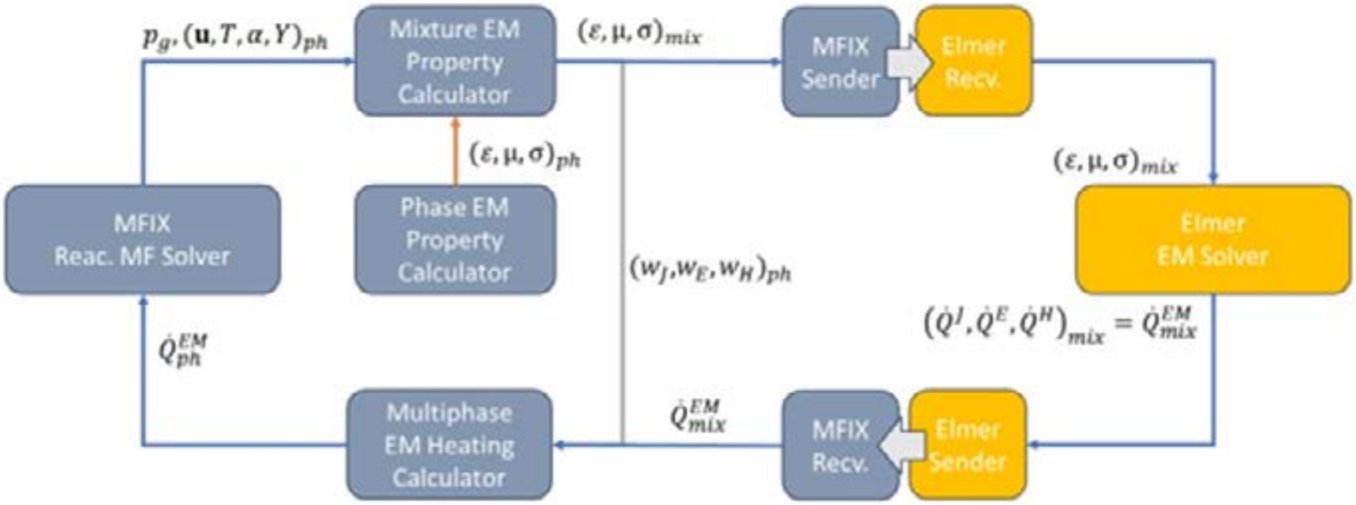


Figure 1: A fully coupled approach using MFiX and Elmer is in progress.

Progress has been made in integrating microwave heating technology into fluidized bed gasifiers to improve energy efficiency and address feedstock conversion challenges (see Figure 2). Computational simulations using combined CEM and CFD were employed to model microwave interactions with different particle types in the gasifier. These models revealed significant temperature differentials between microwave-absorbing and microwave-transparent particles, validating the potential for selective heating. This selective heating capability enhances reaction kinetics by providing localized heat to targeted regions within the gasifier.

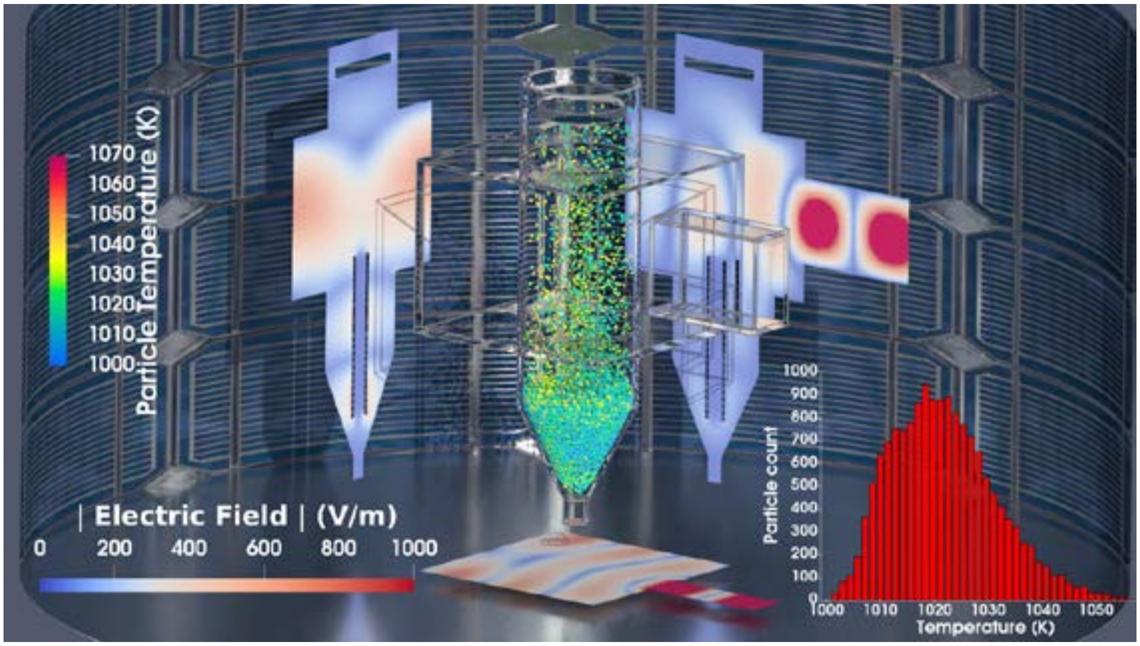


Figure 2: Microwave-assisted heating of solid particles in a fluidized bed reactor.

Additionally, work scope addresses operational challenges associated with complex feedstocks such as the agglomeration caused by melted plastic particles during pyrolysis, a common issue that arises when processing mixed feedstocks containing plastics. This phenomenon, often caused by liquid bridges forming between particles, can lead to defluidization and reduced reactor performance (refer to Figure 3). To mitigate these issues, a liquid bridge model was developed to predict and manage particle interactions in the reactor. Preliminary findings indicated that the model could effectively simulate the conditions leading to agglomeration and provide insights for mitigating defluidization risks. This advancement is expected to enable more stable operation of fluidized bed reactors when processing complex feedstocks like waste plastics and biomass.

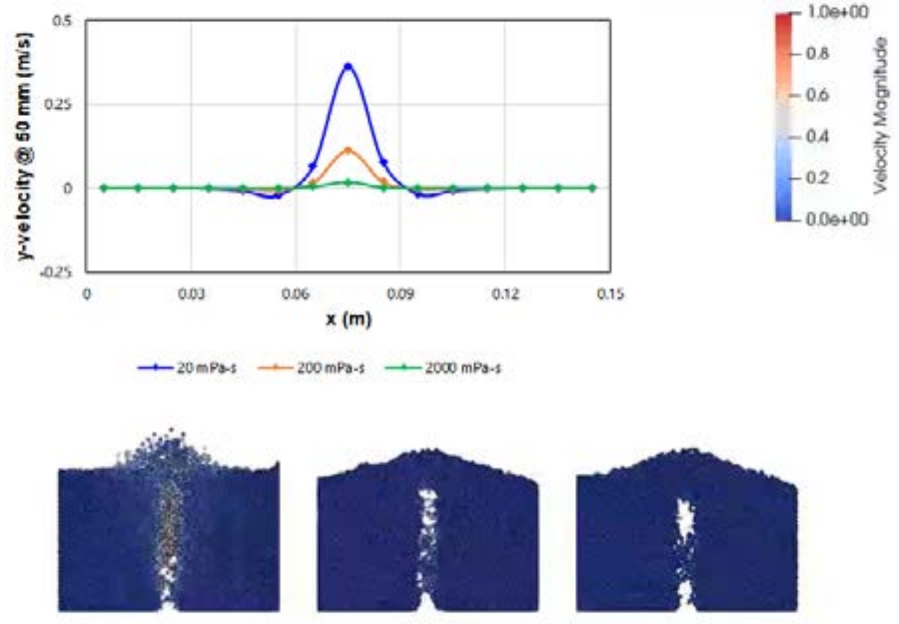


Figure 3: Defluidization of a spouted bed at melted plastic viscosity of 20 mPa-s (L), 200 mPa-s (C) and 2,000 mPa-s (R), along with center line velocities.

Experimental testing of microwave heating in fluidized beds demonstrated the feasibility of using microwaves to enhance gasification performance. Results indicated that microwave-assisted systems could improve energy distribution and reduce overall energy consumption compared to conventional heating methods. These findings support the potential of microwave-integrated gasifiers to process heterogeneous feedstocks efficiently, paving the way for further optimization and scalability of the technology.

In summary, as pursued in a combination of NETL's sophisticated modeling and advanced simulations, experimental testing, and novel heating techniques, technology for a next-generation gasifier capable of efficiently processing diverse feedstocks with improved energy efficiency and reduced emissions can be advanced.

technology advantages

- MFiX models and simulations accelerate technology maturation by allowing virtual reactors and systems to be explored quickly and cheaply, versus costly physical systems.
- A large base of MFiX modeling experience can be leveraged in new reactor systems development.

R&D challenges

- Experimental validation of modeling is required, demanding sophisticated laboratory work and expertise.
- Computational demands of increasingly granular and realistic simulations.

status

Further refining and scaling microwave heating integration in fluidized bed gasifiers is in scope. Additional experimental testing to validate the liquid bridge model for preventing agglomeration during pyrolysis of waste plastics is in process. Ongoing efforts will focus on optimizing the gasifier design for modular and scalable applications, with the goal of demonstrating improved energy efficiency and operational stability in larger-scale systems. These advancements aim to position microwave-integrated gasifiers as a viable solution for processing heterogeneous feedstocks in sustainable hydrogen production.

available reports/technical papers/presentations

“Advanced Reaction Systems,” Eric Lewis, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Lewis.pdf*.

EY23 Field Work Proposal, Advanced Reaction Systems FWP Number: 1022405.

Microwave Reactions for Gasification

primary project goal

The National Energy Technology Laboratory (NETL) is developing microwave-based concepts for feedstock-flexible gasification at a modular scale for hydrogen (H_2)-rich syngas production. Utilizing blended feed streams of biomass, waste plastics, coal fines and/or municipal solid waste (MSW), gasification-based coproduction of energy, value-added chemicals and carbon materials at low temperature are enhanced with microwave application. Microwave technology integration into not just the gasification reactor itself, but also into different steps in the gasification process (e.g., feed pretreatment, tar conversion), is also under consideration. Scope includes scale up of a microwave reactor through numerical modeling and laboratory testing, system analysis studies to understand the economic feasibility of the microwave reaction systems, and development of a larger-scale continuous reactor prototype. Mechanistic studies will evaluate the effect of catalysts on the reaction pathways in microwave-assisted gasification of waste plastics/biomass.

technical goals

- Develop microwave technology to enhance reaction efficiency in gasifiers.
- Investigate the interaction of microwave energy with biomass, plastics and mixed feedstocks to improve gasification rates.
- Optimize microwave energy distribution for uniform heating and reduced energy consumption.
- Evaluate microwave technology impact on syngas quality and gasification system efficiency.

technical content

NETL is advancing gasification technologies through research and development (R&D) in several areas aimed at enabling the utilization of diverse feedstocks for hydrogen and value-added products.

The current Multiyear Research Plan (MYRP) includes an area focusing on leveraging microwave technology to enhance the efficiency and performance of gasification systems. Unlike traditional gasifiers that rely on partial fuel consumption to meet thermal energy demand for gasification reactions, microwave heating offers a novel approach by direct energization of specific feedstock components at the molecular level. Even renewable energy could be used in this context, creating expanded systems options for gasification processes (see Figure 1). This selective heating capability can allow for improved energy efficiency, faster reaction rates, and better control over the gasification process. Developmental work aims to integrate microwave heating into gasifiers to process

program area:
Gasification Systems

ending scale:
Bench scale

application:
Hydrogen Production

key technology:
Process Intensification for Syngas and Hydrogen

project focus:
Developing microwave-based concepts for varied feedstock gasification

participant:
National Energy Technology Laboratory (NETL)

project number:
Gasification Systems MYRP-4

predecessor projects:
FWP-1022405-06

NETL project manager:
Jennie Stoffa
Jennie.Stoffa@netl.doe.gov

principal investigator:
Dushyant Shekhawat
dushyant.shekhawat@netl.doe.gov

partners:
N/A

start date:
04.01.2023

percent complete:
60%

complex feedstocks such as coal, biomass and waste plastics, which often present challenges in conventional systems.

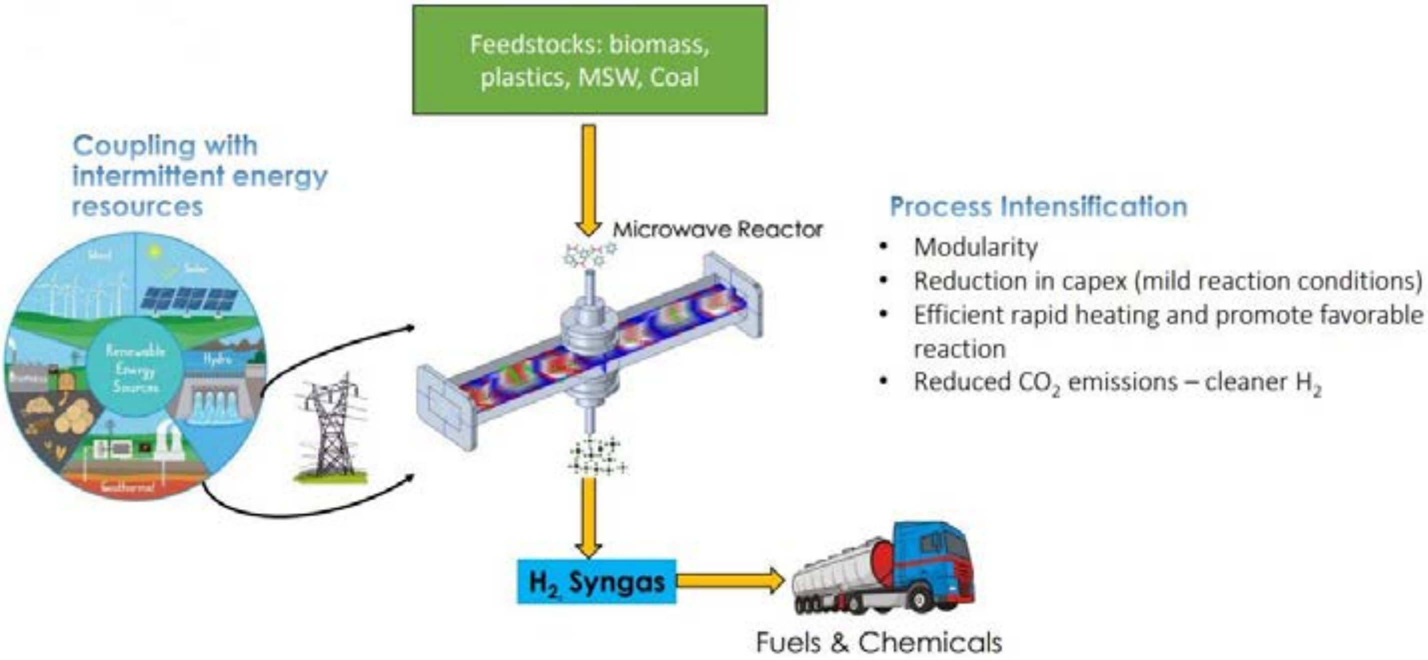


Figure 1: Concept diagram demonstrating microwave reactor position within a value-added production network.

Microwave heating introduces unique advantages for gasification. By selectively heating microwave-absorbing components within a feedstock, microwave energy can provide localized, high-temperature zones that accelerate reaction kinetics and enhance the breakdown of carbonaceous materials. This feature is particularly beneficial for processing mixed feedstocks, where uneven heating or the presence of low-reactivity materials can hinder gasifier performance (some detail of an iron oxide catalyst-enhanced microwave conversion of mixed plastics and biomass is depicted in Figure 2). Additionally, microwave heating has the potential to reduce overall energy consumption by minimizing heat losses typically associated with traditional gasification methods. The technology development approach combines experimental studies with advanced modeling to understand the interactions between microwave energy and various feedstock materials. This includes exploring how different feedstock compositions respond to microwave energy and optimizing energy distribution within the gasifier.

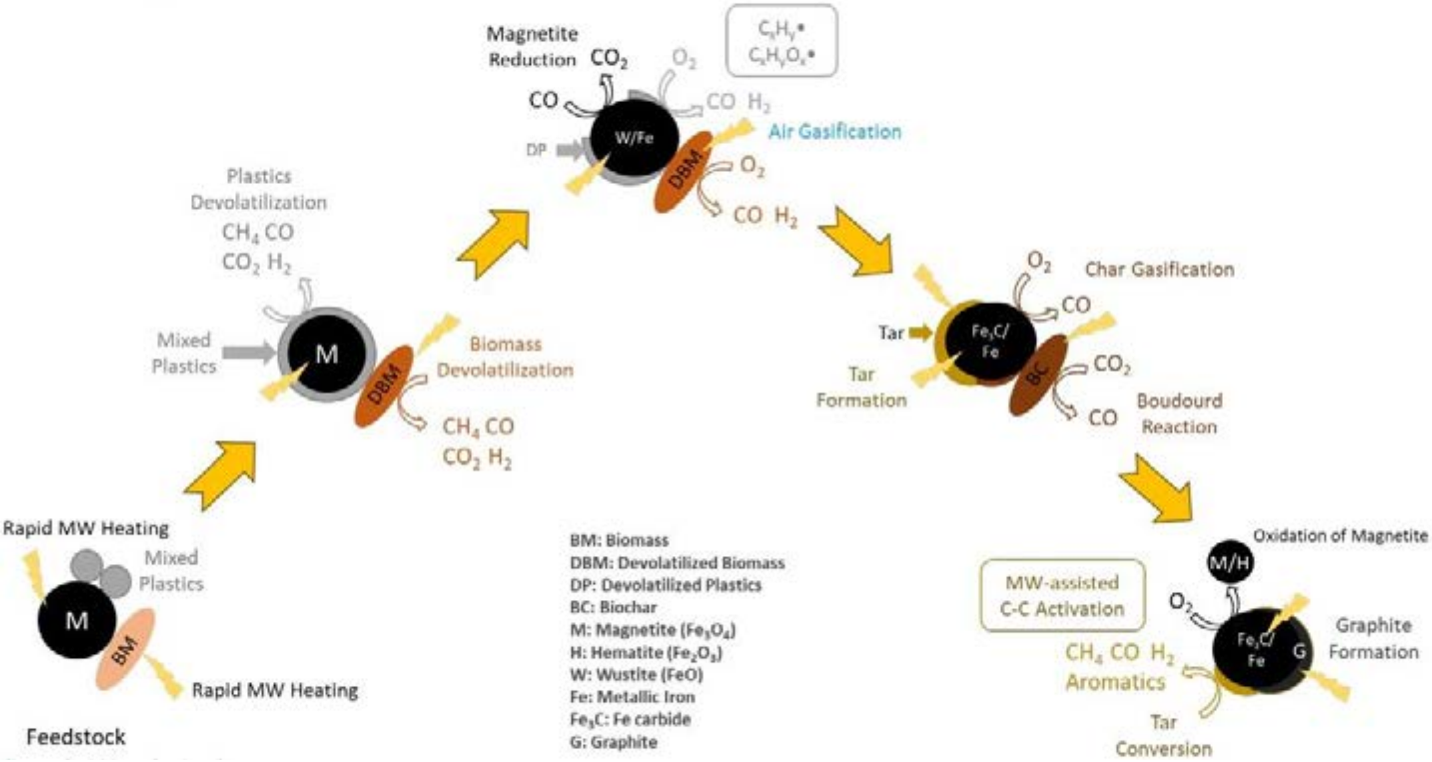
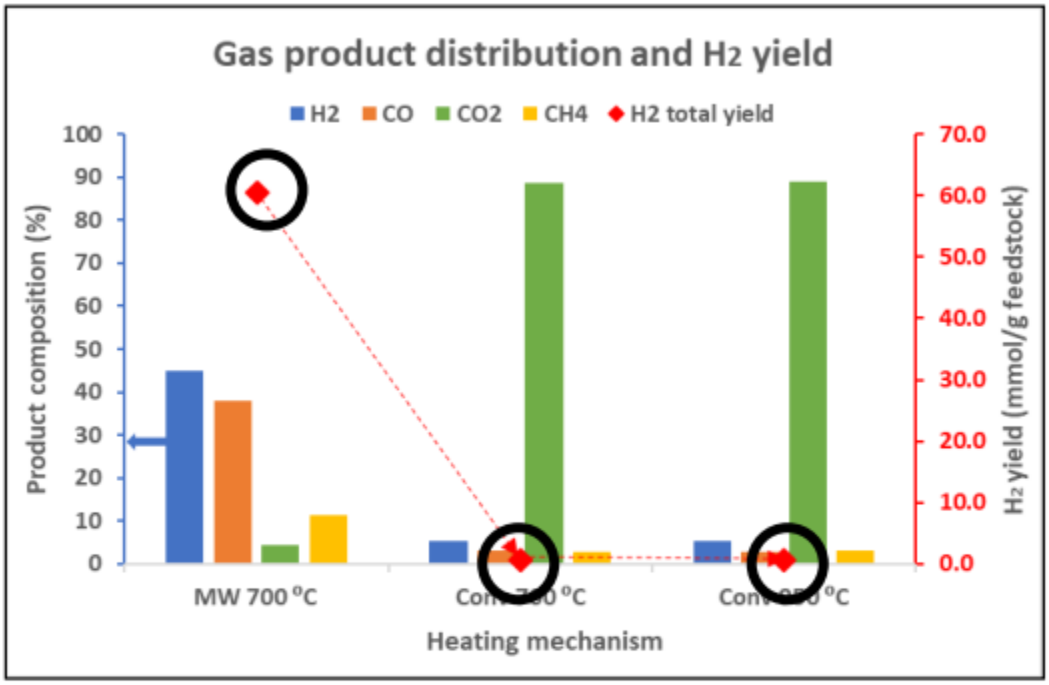


Figure 2: Microwave heating chemical process visualization.

The project has achieved notable advancements in microwave-assisted co-gasification of plastics and biomass feedstocks. Experimental results indicate that microwave heating significantly enhances hydrogen production, yielding four times higher hydrogen output and approximately 20% greater syngas yields compared to conventional heating methods. Additionally, the process effectively minimizes tar generation to less than 2%, indicating a cleaner gasification process (see Figure 3). The incorporation of iron oxide catalysts has been found to enhance the synergistic effects between plastics and biomass under microwave conditions, further improving gasification efficiency.



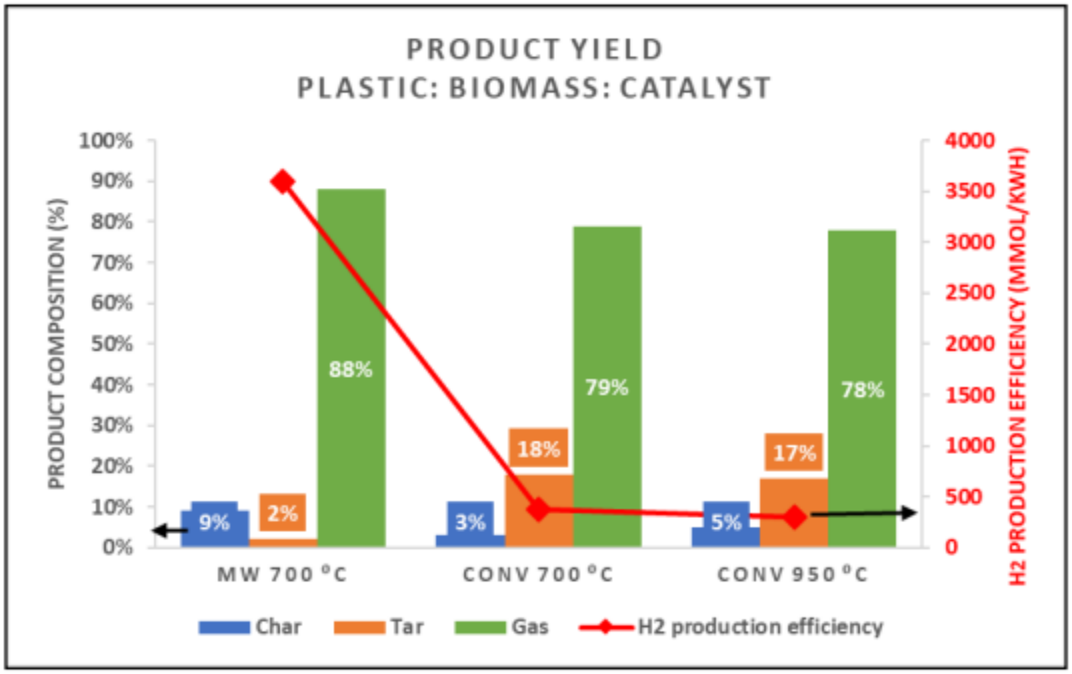


Figure 3: Improvements in H_2 yield and production efficiency with microwave versus conventional approaches.

These findings suggest that microwave-assisted gasification, particularly when combined with suitable catalysts, offers a promising pathway for efficient hydrogen production from mixed waste feedstocks. The reduction in tar formation and the significant increase in hydrogen yield highlight the potential of this technology to contribute to high-value energy production markets.

technology advantages

- Microwave-assisted gasification produces up to four times more hydrogen compared to conventional methods, improving overall process efficiency.
- The technology achieves approximately 20% higher syngas yields, maximizing the utilization of feedstock resources.
- Tar production is minimized to less than 2%, resulting in cleaner syngas and reducing downstream processing challenges.
- Enables efficient co-gasification of mixed feedstocks, such as plastics and biomass, supporting waste valorization and circular economy goals.
- Incorporation of iron oxide catalysts enhances reaction kinetics and further boosts gasification efficiency under microwave conditions.

R&D challenges

- Achieving uniform heating of diverse feedstocks under microwave conditions remains a challenge, particularly with heterogeneous mixtures.
- Ensuring consistent particle size and composition for efficient microwave energy absorption is critical but complex.
- Demonstrating the effectiveness of microwave-assisted gasification at industrial scales while maintaining performance improvements.
- Ensuring long-term stability and performance of iron oxide and other catalysts in continuous operation.
- Balancing microwave energy input to maximize process efficiency while minimizing operational costs.
- Adapting microwave technology for seamless integration into existing gasification infrastructure.

status

The team is developing a fluidized bed microwave reactor to demonstrate a lab-scale microwave gasifier capable of gasifying mixed feedstock for H_2 production.

available reports/technical papers/presentations

“Advanced Reaction Systems,” Eric Lewis, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Lewis.pdf*.

EY23 Field Work Proposal, Advanced Reaction Systems FWP Number: 1022405.

Refractory Materials for Gasification Systems

primary project goal

The National Energy Technology Laboratory (NETL) is developing durable refractory materials for gasification applications, with a current focus on refractories that have extended service life in challenging co-gasification environments with unusual ash chemistries stemming from utilization of alternative feedstocks such as biomass, plastics and municipal solid waste (MSW), along with the standard coal and petcoke feedstocks.

technical goals

- Develop refractory materials resistant to high-temperature corrosive conditions occurring during gasification.
- Test ceramic-bonded refractories for slag resistance and durability at temperatures up to 1,500°C.
- Optimize material formulations for cost and performance with diverse feedstocks.

technical content

NETL is advancing gasification technologies through research and development (R&D) in several areas aimed at enabling the utilization of diverse feedstocks for hydrogen and value-added products.

One key technology being advanced involves identifying and/or developing advanced refractory materials capable of withstanding the extreme conditions present in multifuel gasifiers. Refractories are subjected to severe gasification conditions and must resist temperatures ranging to at least 1,100°C; resist both reducing and oxidizing environments; resist carbon and mineral impurities from the feedstock material (ash) and slag infiltration; resist mechanical abrasion from high-velocity particulates; and resist thermal cycling. These harsh conditions can significantly degrade conventional refractory materials, leading to increased maintenance costs and reduced gasification system operational reliability/availability. If existing refractory materials do not have adequate performance, the designing and testing of new refractory formulations that offer superior resistance to these challenges may be necessary to ensure longevity and efficiency of gasifiers for these applications. Also, refractory materials must be adaptable to redesign and rapid repair/replacement as needed during servicing of gasifier systems.

program area:
Gasification Systems

ending scale:
N/A

application:
Co-gasification for production of hydrogen and other value-added products

key technology:
Process Intensification for Syngas and Hydrogen

project focus:
Refractory materials for co-gasification for diverse feedstocks

participant:
National Energy Technology Laboratory (NETL)

project number:
Gasification Systems MYRP-2

predecessor projects:
FWP-1022405-04

NETL project manager:
Jennie Stoffa
Jennie.Stoffa@netl.doe.gov

principal investigator:
David Alman
David.Alman@netl.doe.gov

partners:
Harbison Walker International;
Allied Mineral Products;
Eastman Chemical

start date:
04.01.2022

percent complete:
60%

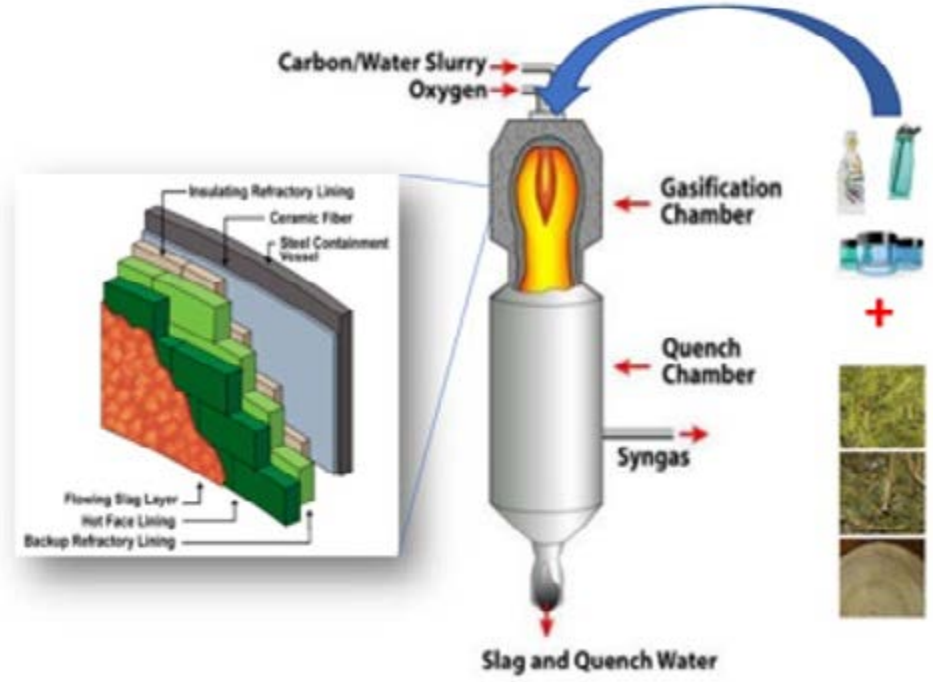


Figure 1: Diagram of refractory materials within the context of a gasifier.

Past NETL research on refractory liner materials has been directed toward evaluating a range of commercially available ceramic-and refractory cement-bonded refractory materials, including low to high chromia, alumina and magnesia-based pre-sintered materials. To date, six ceramic-bonded refractory materials have been tested (see Figure 2), including formulations with low to high levels of chromia, alumina and magnesia. These materials were exposed to molten synthetic high density propylene plastic ash at 1,500°C in a 10-6 oxygen atm to simulate the operational environment of gasifiers processing complex feedstocks. The resistance of the refractory materials to corrosion and degradation by slag penetration, chemical dissolution and physical degradation is being evaluated. Advanced analytical techniques such as scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX) analysis, and X-ray diffraction (XRD) were used to characterize the microstructural changes, chemical interactions, and identify degradation mechanisms. Preliminary results indicate that chromia- and alumina-based materials did not perform significantly better than other tested refractory formulations, prompting further investigation into alternative compositions.

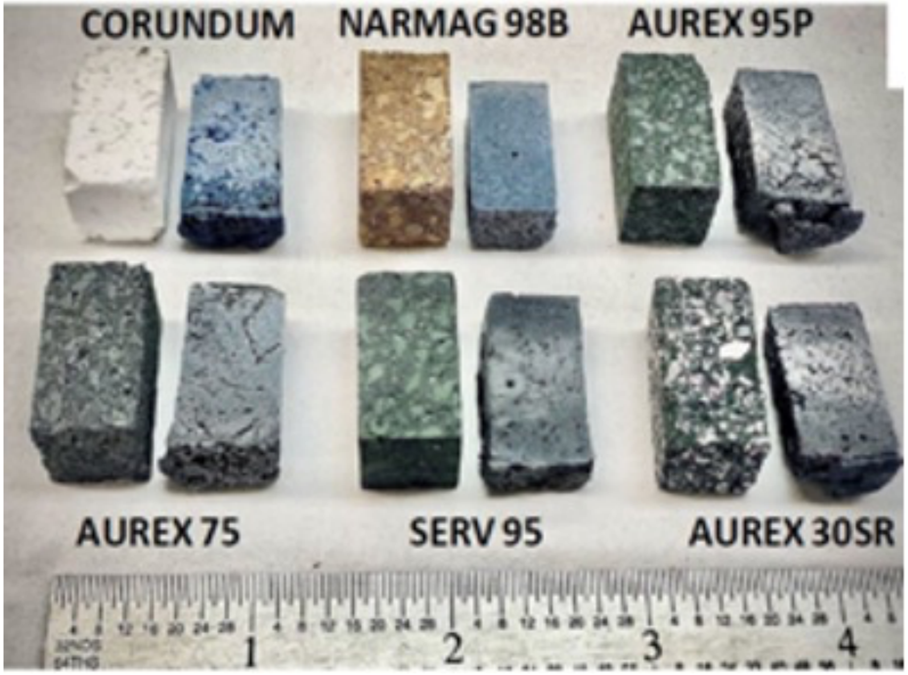


Figure 2: Tested refractory materials.

Another critical aspect of refractory development is understanding the mechanisms of slag infiltration and chemical degradation in refractory liners. NETL is utilizing computed tomography (CT) imaging (see Figure 3) to visualize the extent of slag penetration, providing a detailed view of the material's structural integrity and revealing varying levels of resistance among the tested materials. This approach offered a clearer understanding of how different refractory formulations interact with molten ash and enabled the identification of areas for improvement in material design.

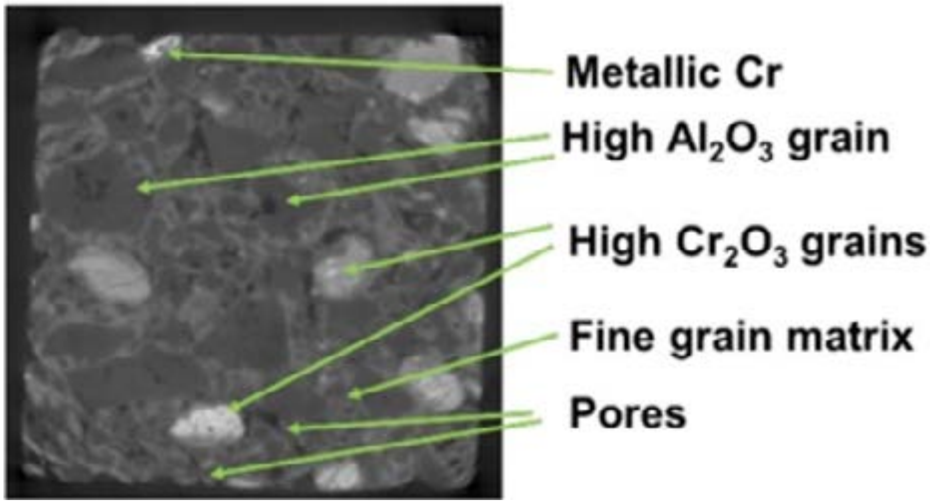


Figure 3: Computed tomography of refractory material.

These experiments represent an important step in determining the suitability of refractory materials for diverse feedstocks, particularly waste plastics and biomass, in gasification systems. While specific materials showed promising results, additional testing and optimization are required to develop refractories that can consistently withstand the challenging operational conditions of multifuel gasifiers. Future efforts will focus on refining material formulations and further evaluating their long-term performance.

technology advantages

- Improved refractory materials should withstand extreme gasification environments, including temperatures up to 1,100°C, ensuring durability in these new gasification environments expected with mixed carbon feedstocks.
- The development of improved refractory formulations targets the reduction of ash/slag penetration and chemical degradation, increasing the reliability and operational service life of gasifiers.
- Improved refractory materials should handle the chemical and thermal challenges posed by diverse gasification carbon feedstocks that include biomass, waste plastics, MSW, coal and/or petcoke, enabling flexible and sustainable gasification processes with acceptable system on-line performance.
- Advanced characterization techniques, such as SEM, EDX, XRD and CT imaging, provide deep insights into material performance, guiding the testing and development of optimized, high-performance refractories.
- Improved material longevity and reduced maintenance needs can lower operational costs for multifuel gasification systems.

R&D challenges

- Identifying optimum formulations and material compatibilities that resist chemical attack and physical wear from varied abrasive and corrosive compounds in a variety of carbon feedstock materials.
- Mitigating slag infiltration/penetration and the physical wear of carbon feedstock impurities in or to refractory liners, which compromises structural integrity and reduces lifespan.
- Achieving consistent performance of refractory materials under prolonged exposure to high temperatures up to 1,100°C.
- Balancing material service life performance with affordability to ensure commercial viability for widespread use and adoption in gasification systems.

status

Results are being published on the six refractory materials having potential for use as high-temperature (1,500°C) gasifier liner materials with high-density polyethene plastic gasifier feedstock.

Critical chemical and physical properties needed in low-temperature monolithic refractory liners using mixed carbon feedstock gasification in a projected service environment between 500–1,000°C are now being identified. When critical gasification conditions are identified, severe service material needs will be used to identify potential gasifier monolithic liner materials for simulated gasifier environment testing through discussions with refractory manufacturers.

available reports/technical papers/presentations

"Advanced Reaction Systems," Eric Lewis, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Lewis.pdf*.

EY23 Field Work Proposal, Advanced Reaction Systems FWP Number: 1022405.

Maturing Oxygen Carrier and Catalyst Technologies for Hydrogen Production

primary project goal

The National Energy Technology Laboratory (NETL) is developing optimized systems that can be used in low-cost hydrogen (H_2) production from solid fuels such as coal, biomass, plastics or municipal solid waste (MSW). Two novel patented/patent-pending processes are being pursued: an iron (Fe)-based catalytic process and a metal ferrite-based noncatalytic process. Information and parameters are being identified for use in developing integrated H_2 production systems, a scaled-up reactor design based on sub-pilot scale and pilot-scale test data, and for supporting techno-economic analyses (TEAs) and commercialization.

technical goals

- Define parameters to develop integrated H_2 production systems.
- Scale-up reactor design based on sub-pilot scale and pilot-scale test data.
- Obtain parameters necessary for TEA and commercialization.

technical content

NETL is advancing gasification technologies through its Gasification Systems Multiyear Research Plan, which encompasses several key tasks aimed at enabling the utilization of diverse feedstocks for hydrogen and value-added product generation.

Task 4-2 focuses on advancing oxygen carrier and catalyst technologies to enhance hydrogen production from solid fuels such as coal, biomass, plastics or MSW. Two innovative processes are under development: an Fe-based catalytic process and a metal ferrite-based noncatalytic process.

The Fe-based catalytic process utilizes iron-based materials to facilitate the conversion of solid fuels into hydrogen-rich syngas with steam. This approach aims to enhance reaction kinetics and improve overall system efficiency. The metal ferrite-based noncatalytic process employs metal ferrite oxygen carriers for supplying oxygen for the process to produce pure H_2 without the need for an external oxygen and heat source, potentially simplifying the system and reducing costs. These processes are conceptually illustrated in Figure 1. Both processes do not require an expensive air separation unit.

program area:
Gasification Systems

ending scale:
Sub-pilot scale

application:
Hydrogen Production

key technology:
Air Separation Technology

project focus:
Developing Fe-based catalytic and ferrite-based noncatalytic gasification technologies

participant:
National Energy Technology Laboratory (NETL)

project number:
Gasification MYRP 4-2

predecessor projects:
FWP-1022405-11

NETL project manager:
Jennie Stoffa
Jennie.Stoffa@netl.doe.gov

principal investigator:
Ranjani Siriwardane
ranjani.siriwardane@netl.doe.gov

partners:
N/A

start date:
04.01.2023

percent complete:
60%

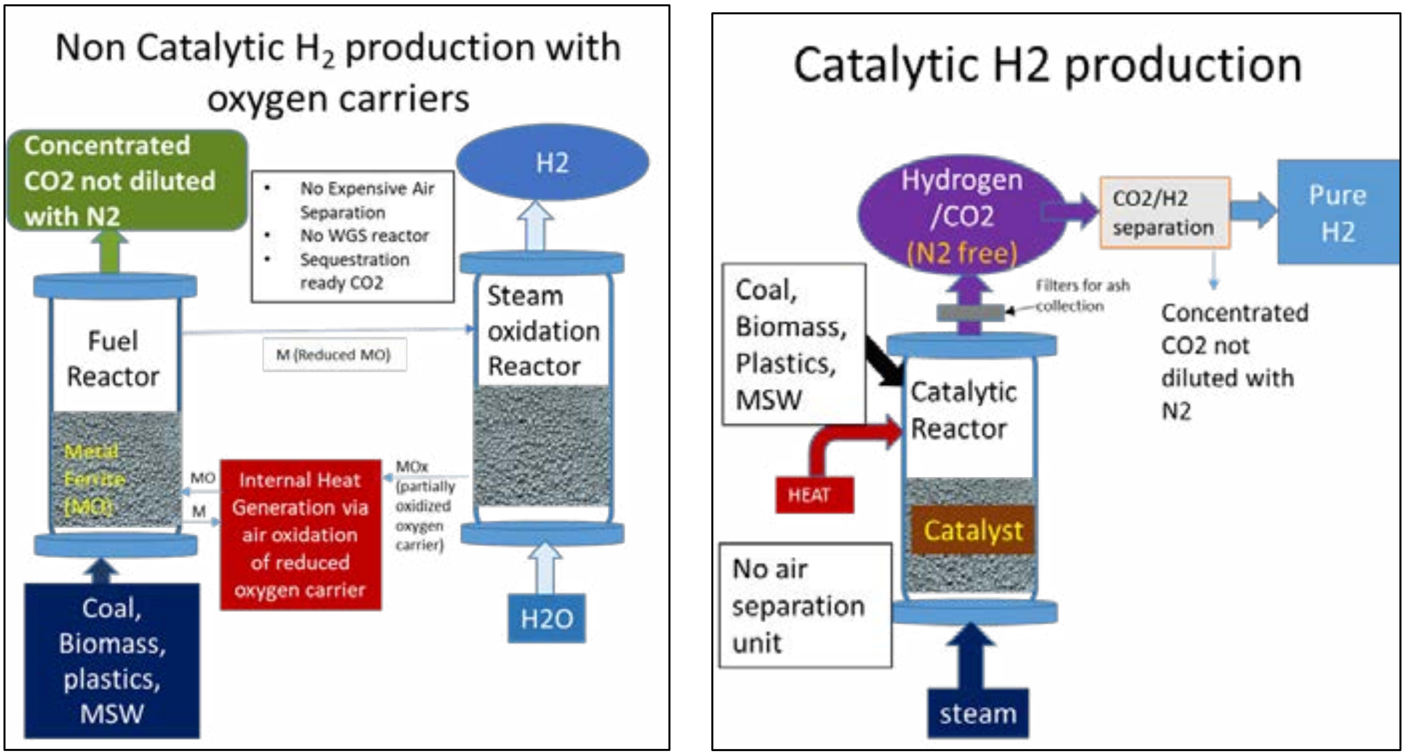


Figure 1: Concept process diagrams for noncatalytic and catalytic hydrogen production.

Development work to mature these oxygen carrier and catalyst technologies involves scaling up reactor designs based on sub-pilot and pilot-scale test data, as well as conducting TEAs to support commercialization efforts.

The Fe-based catalytic process shows strong performance in converting solid fuels into hydrogen-rich syngas not diluted with nitrogen (N_2). Enhanced reaction kinetics have been observed, contributing to higher system efficiency. The noncatalytic metal ferrite oxygen carrier process showed pure H_2 production while producing a concentrated carbon dioxide (CO_2) stream that can be used for various applications such as enhanced oil recovery (EOR). Figures 2 and 3 show some results for the noncatalytic metal ferrite-based oxygen carrier process. High-hydrogen production rates (approximately 85%) and stable performance during bench-scale multicycle tests were demonstrated with a calcium (Ca) ferrite oxygen carrier reduced with plastic (polypropylene), as shown in Figure 2. Feasibility of scaling the H_2 production noncatalytic process with Ca ferrite (2.5 kg) and woody biomass was demonstrated in the sub-pilot-scale tests (as shown in Figure 3).

Both approaches proved compatible with diverse feedstocks, including biomass and waste-derived materials, showcasing their flexibility and adaptability.

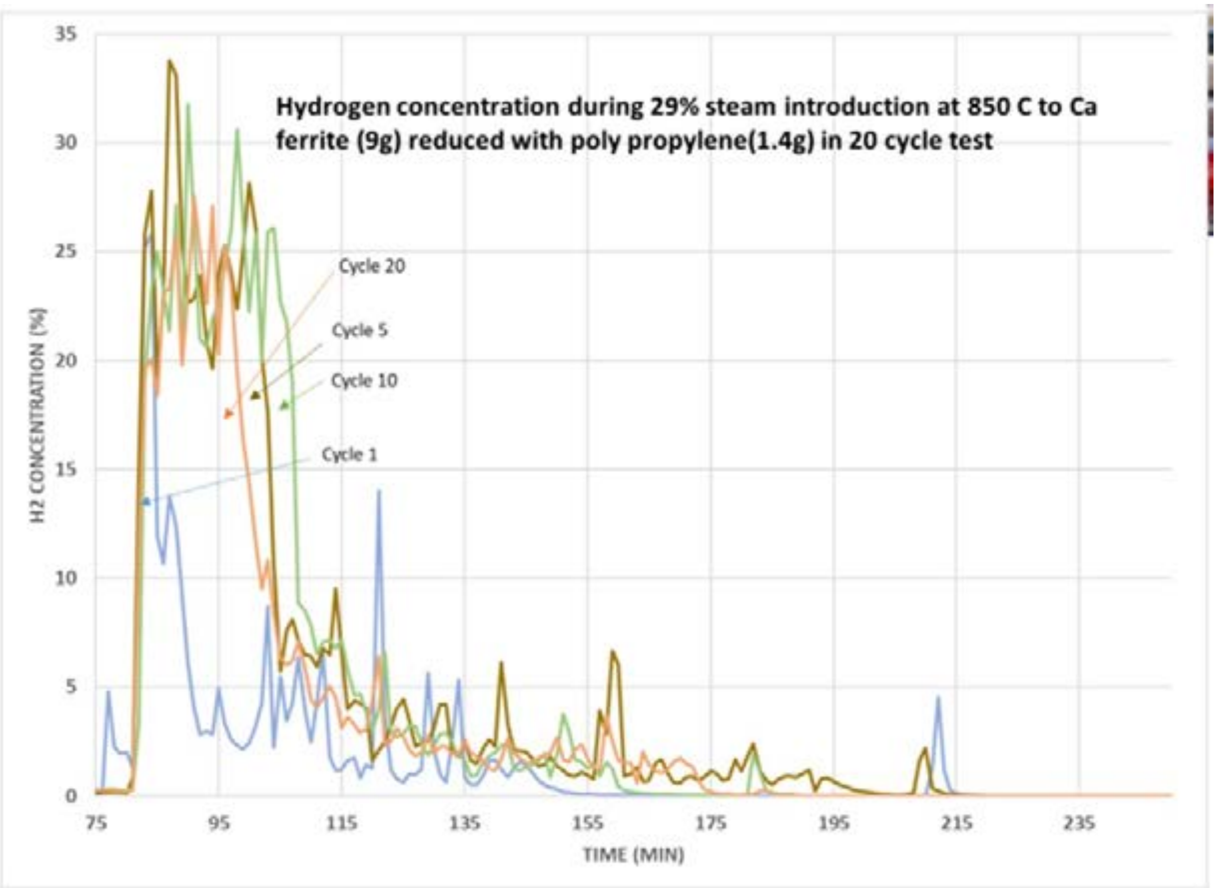


Figure 2: Hydrogen concentration while cycling a ferrite catalyst-based reactor for polypropylene conversion.

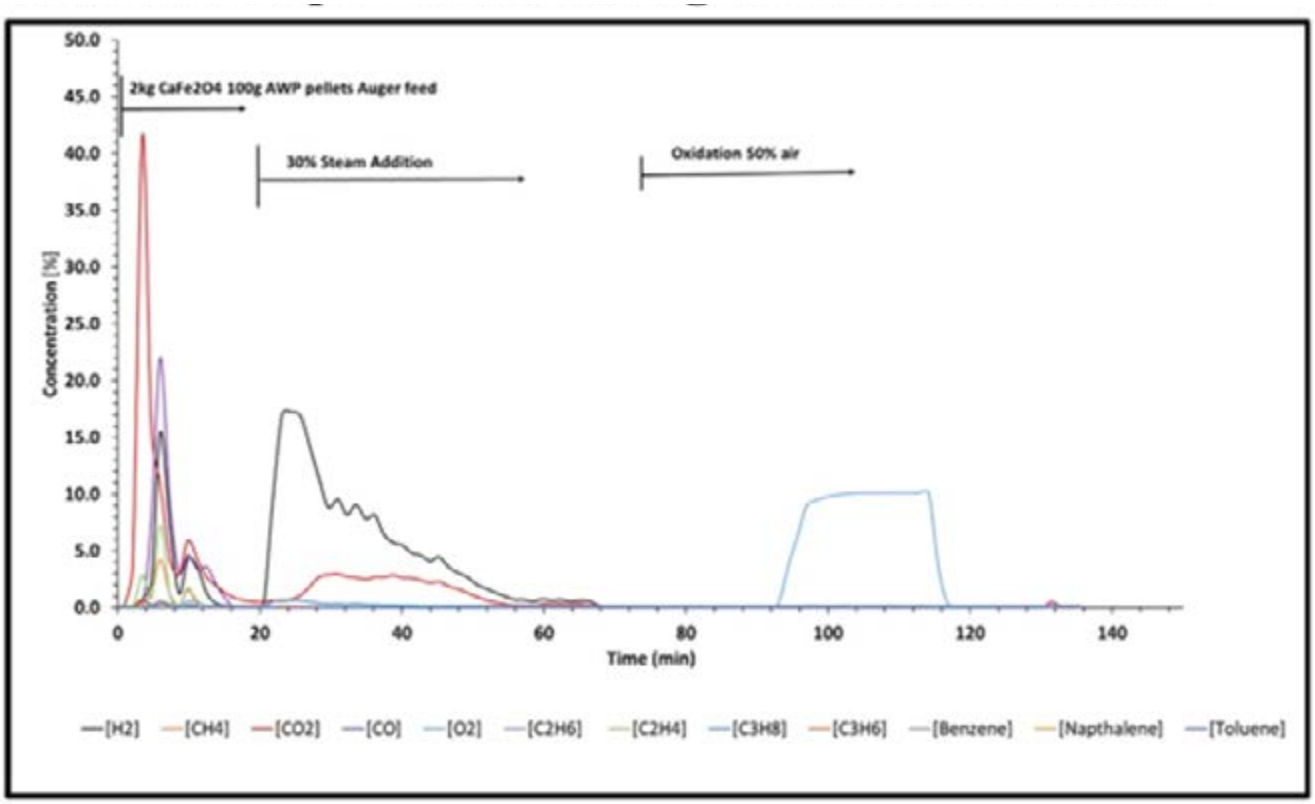


Figure 3: Effluent gas concentrations during test of 100 g biomass wood pellets and 2.5 Kg of Ca ferrite at 850°C.

Sub-pilot-scale testing validated the scalability of these technologies, providing critical data to inform reactor design and optimize system configurations for commercial deployment. Preliminary energy analysis indicated promising cost-competitiveness of these processes compared to traditional hydrogen production methods.

technology advantages

- Both the catalytic and noncatalytic processes have a potential to reduce hydrogen production cost.
- Compatible with diverse solid fuels, including coal, biomass, waste plastics and MSW, allowing for broad applicability.
- Both processes would not require expensive air separation units that are required in traditional gasification processes for H_2 production.
- Oxygen carriers demonstrated stable performance across multiple cycles, indictive of long-term reliability.
- Testing validated the feasibility of scaling up the processes, paving the way for commercial deployment.
- High attrition resistance of the oxygen carrier demonstrated during sub-pilot-scale tests.

R&D challenges

- Ensuring the long-term durability and reactivity of oxygen carriers under extended operational conditions.
- Refining reaction kinetics and improving system efficiency to maximize hydrogen yield while minimizing energy consumption.
- Addressing performance variations due to differing feedstock compositions and properties.
- Demonstrating consistent performance and efficiency at larger scales.
- Seamlessly integrating these technologies with existing hydrogen production infrastructure and gasification systems.

status

In process of refining cost models and further improving system efficiency.

available reports/technical papers/presentations

"Advanced Reaction Systems," Eric Lewis, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Lewis.pdf*.

EY24 Field Work Proposal, Gasification MYRP.

Ranjani Siriwardane, James Poston, Esmail Monazam, George Richards "Production of hydrogen by steam oxidation of calcium ferrite reduced with various coals," International journal of hydrogen energy, 2019, 44, 7158-7167, *https://doi.org/10.1016/j.ijhydene.2019.01.238*.

R. Siriwardane, J. Riley and C. Atallah, "Novel Process for Production of H_2-Rich Nitrogen-Free Syngas from Coal Using a Cu/Fe-Alumina Catalyst and Steam," Energy and Fuels 2024, 38, 15116–15130 *https://doi.org/10.1021/acs.energyfuels.4c01738*.

Process Development to Mature Oxygen Sorbent-Based Technology

primary project goal

The National Energy Technology Laboratory (NETL) is advancing technology toward a pilot-scale prototype of a fixed-bed, perovskite sorbent-based oxygen (O_2) separation unit. This task supports that effort through computational modeling of a modular-scale production unit coupled with material characterization and process optimization. The model includes both O_2 adsorption and desorption modes of operation along with thermal management of the fixed-bed system. Simulation predictions have been validated against bench-scale experimental data, and the model is being exercised over a range of operating conditions, including varying flows and operating temperature.

technical goals

- Develop a computational model to simulate oxygen storage and release capabilities of NETL-designed perovskite sorbents.
- Conduct thermogravimetric analysis (TGA) and bench-scale experiments to establish kinetic rates for oxygen adsorption and desorption.
- Validate experimentally derived kinetic data using computational modeling to ensure accuracy.
- Scale reactor designs from laboratory samples (50 mg) to modular-scale systems handling up to 5 kilograms of sorbent.
- Optimize adsorption swing times and reactor geometry to enhance oxygen production rates and minimize pressure drop.
- Design a modular, scalable oxygen separation system suitable for integration into gasification processes.

technical content

NETL is advancing gasification technologies through research and development (R&D) in several areas aimed at enabling the utilization of diverse feedstocks for hydrogen and value-added products.

This task is advancing oxygen sorbent-based air separation technologies by development of a computational model that accurately represents the oxygen storage and release capabilities of NETL-designed perovskite materials. This model has informed the design of a pilot-scale fixed-bed oxygen separation unit utilizing these perovskite sorbents. The basic process configuration of the unit is depicted in Figure 1. Oxygen produced in this way is needed as a key input to gasifiers producing syngas used in many varied energy systems and value-added production of fuels and chemicals.

program area:
Gasification Systems

ending scale:
Modular scale (1-5 kg perovskite sorbent)

application:
Hydrogen Production

key technology:
Air Separation Technology

project focus:
Computational modeling of perovskite sorbent-based O_2 separation unit to inform a modular-scale build

participant:
National Energy Technology Laboratory (NETL)

project number:
Gasification Systems MYRP-3

predecessor projects:
FWP-1022405-07

NETL project manager:
Jennie Stoffa
jennie.stoffa@netl.doe.gov

principal investigator:
Mary Ann Clarke
maryann.clarke@netl.doe.gov

partners:
N/A

start date:
04.01.2023

percent complete:
60%

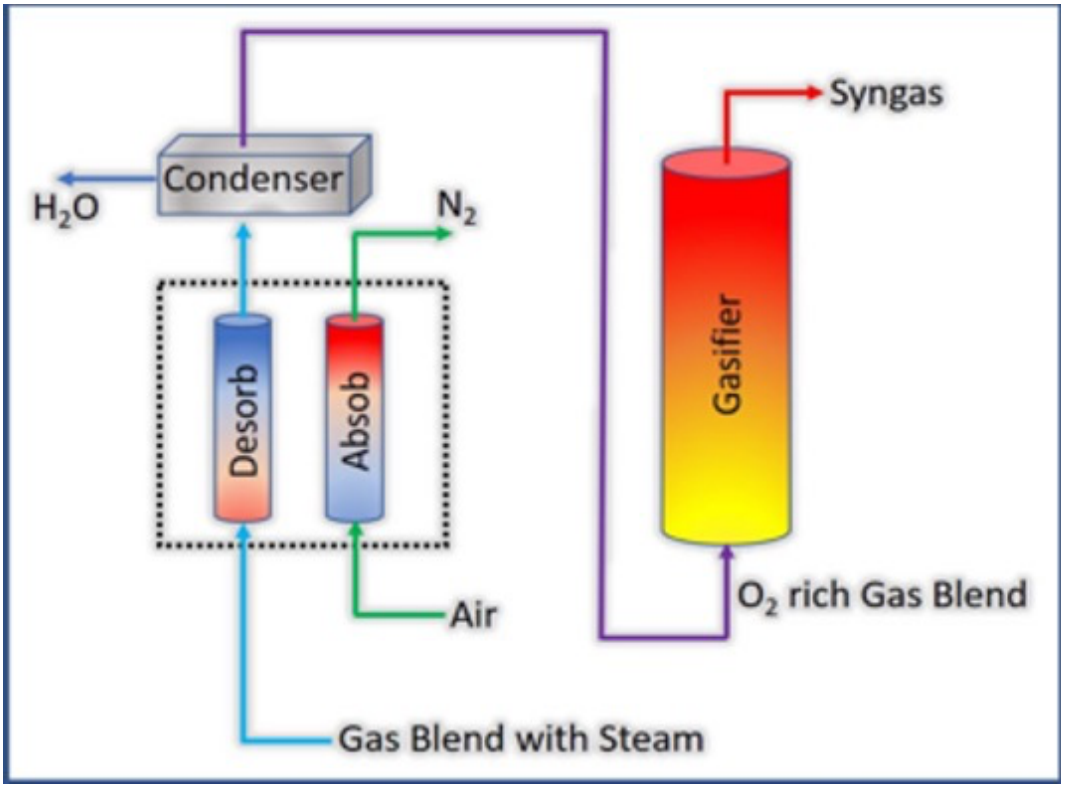


Figure 1: Simplified process flow diagram for NETL perovskite sorbent-based separation unit.

It is essential to establish detailed kinetic rates for oxygen adsorption and desorption to underpin an accurate air separation unit (ASU) model; these are being quantified through thermogravimetric analysis (TGA) and bench-scale experiments. Experimentally derived rates are being validated computationally to ensure their accuracy. Subsequently, the validated kinetic data is being applied to scale reactor models from small laboratory samples (approximately 50 mg) to larger systems handling up to 50 kilograms of sorbent material. This scaling process is crucial for designing reactors that can operate efficiently at a pilot scale.

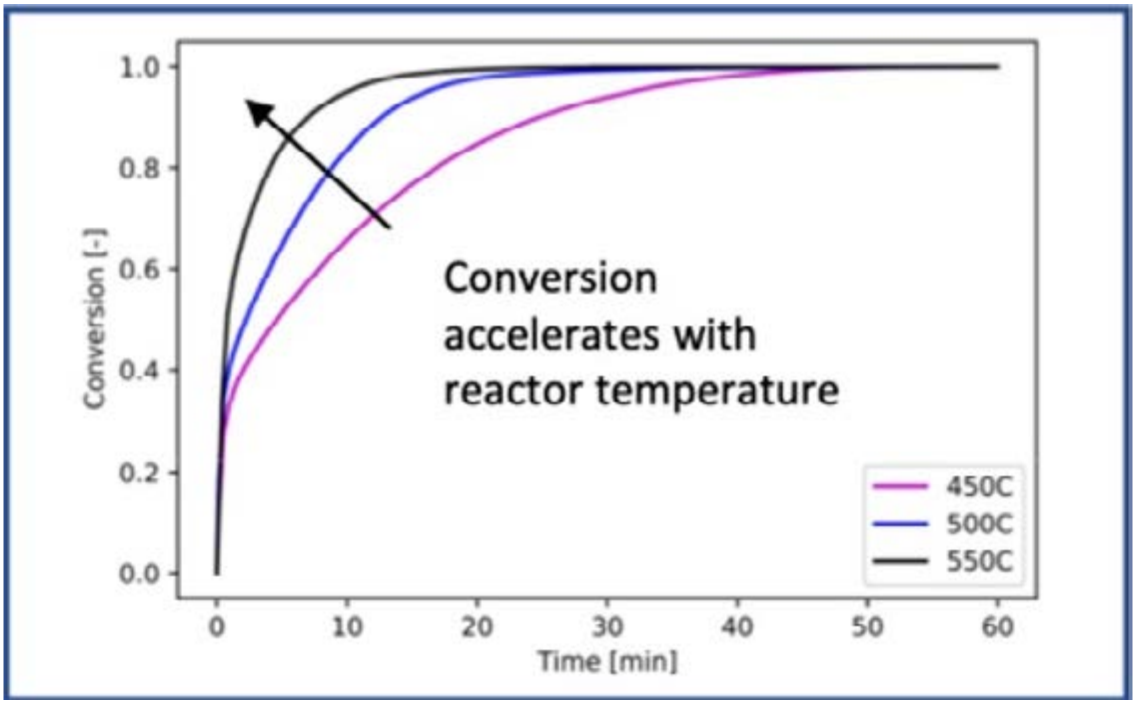


Figure 2: Experimental conversion of NETL perovskite over time, 450-550°C.

Optimization efforts are focusing on enhancing oxygen production rates by examining variables such as adsorption swing times and reactor geometry to minimize pressure drops and improve overall oxygen production rates.

The desorption mechanism of NETL's perovskite has been characterized kinetically through three stages: surface reaction, diffusion and random nucleation. In an optimized oxygen production environment, the surface reaction is most attractive, as the rate of oxygen release is considerably higher than in later stages (Figure 3, top right). However, the surface reaction mechanism accounts for only approximately 25% to 30% (Figure 3, top left) of desorption-available oxygen in the perovskite. It is also noted that required system energy to release surface oxygen is considerably lower than oxygen that must diffuse from the interior of the perovskite particles (Figure 3, lower left). Given these observations, NETL is engaging in an optimization study to minimize system energy requirements and to maximize oxygen production over an expected operating range of 450-500ºC.

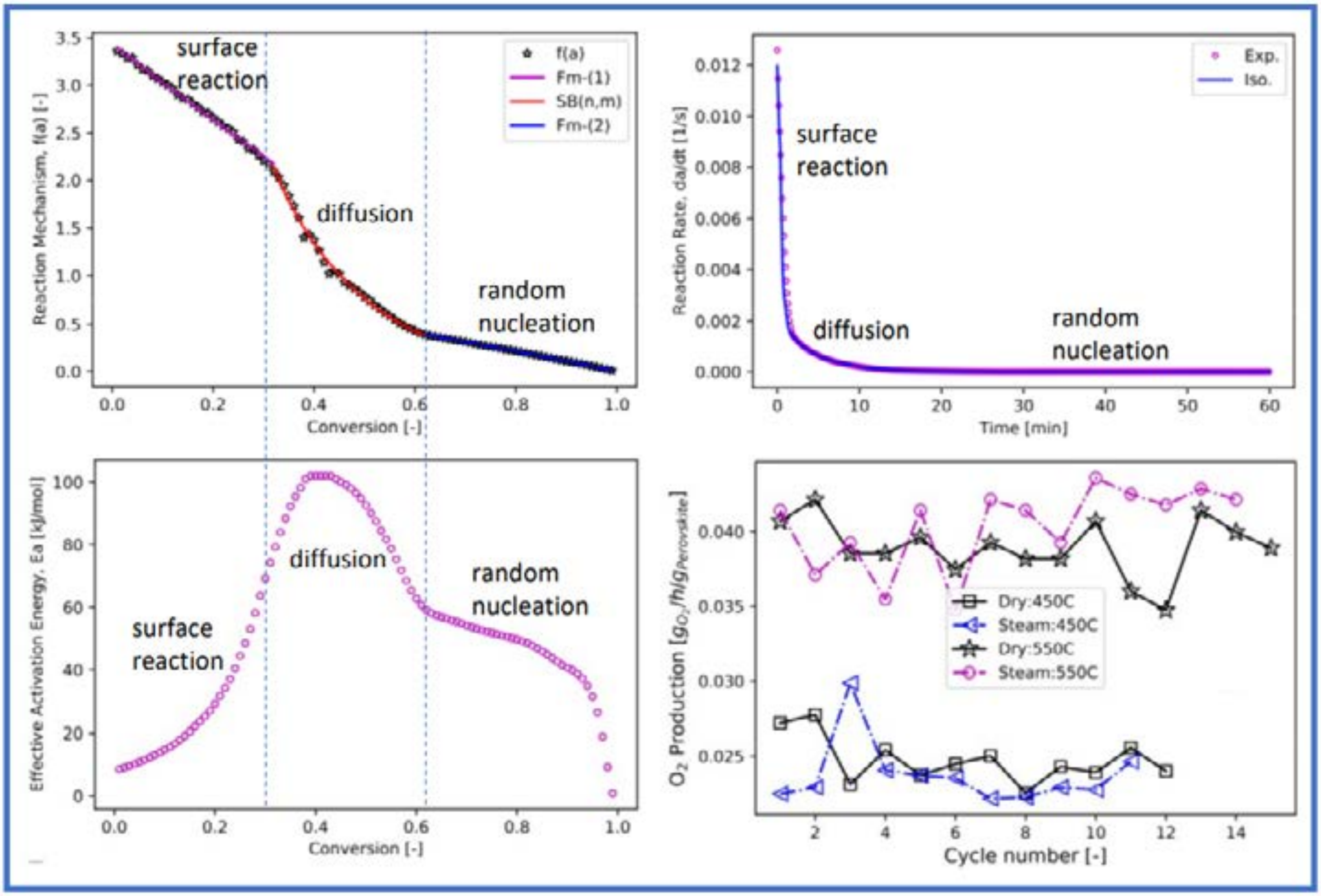


Figure 3: An examination of NETL perovskite kinetic mechanism, reaction rate, activation energy and O_2 production capacity.

In summary, significant progress to simulate oxygen production effectively while supporting development of a modular oxygen sorbent system based on the NETL-developed perovskite oxygen sorbents has been made. The results lay a strong foundation for further testing and development at pilot scale, leading the way to potential ASU commercialization.

technology advantages

- Models and simulations accelerate technology maturation by allowing virtual reactors and systems to be explored quickly and cheaply, versus costly physical systems.
- NETL's vast modeling experience can be leveraged in new reactor systems development.

R&D challenges

- Experimental validation of modeling is required, demanding sophisticated laboratory work and expertise.
- Computational demands of increasingly granular and realistic simulations.

status

Already, several key accomplishments in advancing oxygen sorbent technology for gasification processes have been achieved. A computational model simulating the oxygen storage and release behavior of NETL-designed perovskite sorbents has been developed. This model integrates data from thermogravimetric analysis (TGA) experiments and bench-scale experiments, which established initial adsorption and desorption kinetic rates for the sorbents under various operating conditions. These rates were validated against experimental data, ensuring the model's accuracy for predicting sorbent performance in different scenarios.

available reports/technical papers/presentations

"Advanced Reaction Systems," Eric Lewis, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Lewis.pdf*.

EY23 Field Work Proposal, Advanced Reaction Systems FWP Number: 1022405.

Co-Gasification of Waste to Generate Hydrogen

primary project goal

The National Energy Technology Laboratory (NETL) is exploring the gasification of alternative carbonaceous feedstocks (waste plastics, waste coal, biomass, municipal solid waste [MSW]) to generate hydrogen (H_2) and syngas. Co-gasification of waste plastics and waste coal is being studied, specifically evaluating the effects of operating conditions and catalyst compositions on H_2/syngas production and tar mitigation. The pyrolysis of waste plastics, biomass and their mixtures at different operational conditions (like temperature and residence time) is also in scope to support model development and validation. Kinetics and production distribution of pyrolysis and gasification are being studied in gasification simulations, with machine learning (ML) utilized to accelerate gasification technology development.

technical goals

- Characterize waste feedstocks to understand thermal properties, reaction kinetics and production distribution in gasification and pyrolysis.
- Optimize gasification parameters to maximize hydrogen and syngas production from waste feedstocks.
- Minimize tar and other by-product formation during the gasification of wastes.
- Develop strategies and validate the gasification process for various types of waste feedstocks to ensure feedstock flexibility.
- Demonstrate the potential for integrating wastes gasification into a circular economy framework.

technical content

NETL is advancing gasification technologies through its Advanced Reaction Systems portfolio, which encompasses several key tasks aimed at enabling the utilization of diverse feedstocks for hydrogen and value-added product generation.

This work focuses on developing advanced gasification processes specifically tailored for waste feedstocks, aiming to transform these materials into valuable products such as hydrogen and syngas. Investigation involves co-gasification of waste plastics and waste coal/biomass in a steam environment to generate H_2/syngas, specifically including study of the co-feeding of pelletized waste plastic and waste coal/biomass in a drop tube reactor (DTR) under nearly isothermal conditions (see Figure 1). Primary aims are to evaluate process conditions such as feed blend ratio, temperature and catalyst to optimize syngas conversion. Co-pyrolysis of waste plastics and/or biomass is being evaluated at different operating conditions, including temperature and gas/volatile residence time; results will support model development and validation in complementary tasks. Additionally,

program area:
Gasification Systems

ending scale:
N/A

application:
Syngas & Hydrogen Value-added Production

key technology:
Novel Technologies for Chemicals & Fuels

project focus:
Exploring alternative/waste feedstocks for gasification

participant:
National Energy Technology Laboratory (NETL)

project number:
Gasification Systems MYRP-5&6

predecessor projects:
FWP-1022405-08

NETL project manager:
Jennie Stoffa
Jennie.Stoffa@netl.doe.gov

principal investigator:
Ping Wang
ping.wang@netl.doe.gov

partners:
N/A

start date:
04.01.2022

percent complete:
50%

tar composition (hydrocarbons up to C_{45}) is being analyzed using gas chromatography-mass spectrometry (GC-MS) to understand mechanisms of pyrolysis and tar formation and cracking. Finally, pyrolysis kinetics are being studied in a thermal analyzer (simultaneous thermogravimetric analyzer-differential scanning calorimeter [TGA-DSC]) to determine kinetic triplets (i.e., apparent activation energy, pre-exponential factors and reaction mechanism).

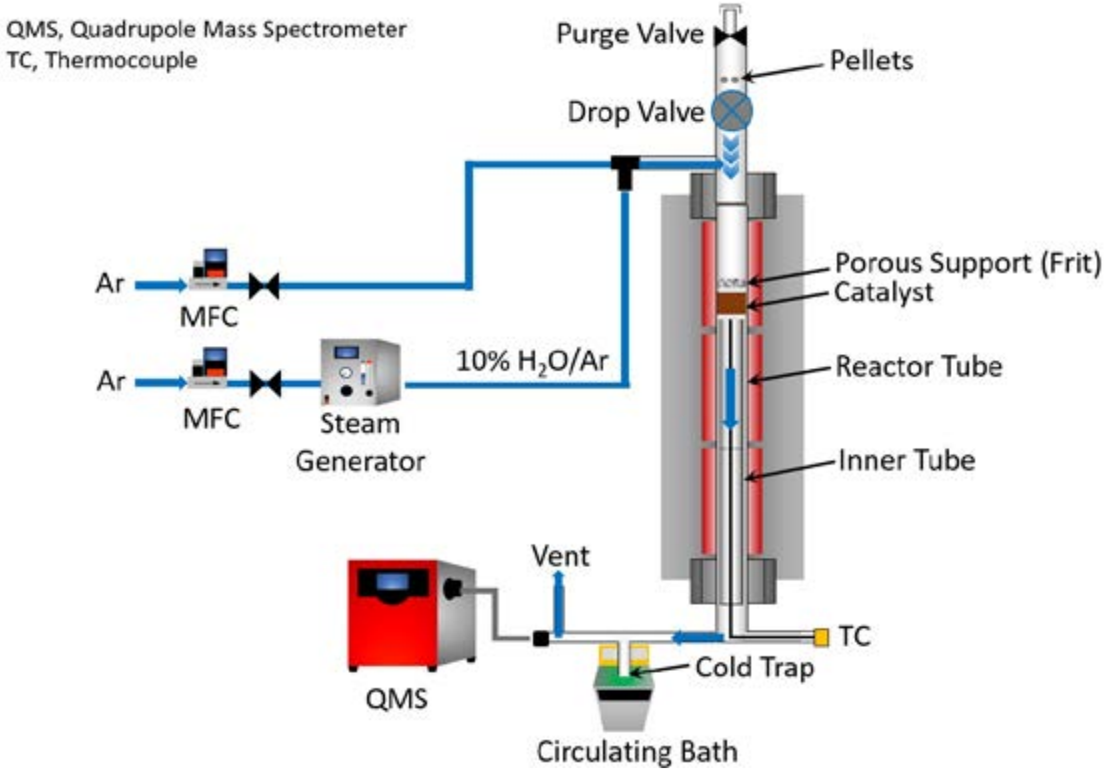


Figure 1: DTR equipped with quadrupole mass spectrometer.

Experiments utilizing steam co-gasification of pelletized low-density polyethylene (LDPE) and coal refuse (CR) in the DTR yielded three primary outcomes. First, the team completed optimization of syngas production and quality with various LDPE/CR feed blend ratios (0, 10, 20, 40, 60, 80 and 100 LDPE) and temperature (800–1,000°C) (Figure 2, left). Second, they demonstrated up to 100% tar reforming efficiency during catalytic co-gasification with Fe_2O_3 or coal ash (Figure 2, right). Finally, the team conducted co-gasification of LDPE and pine dust with select feed blends.

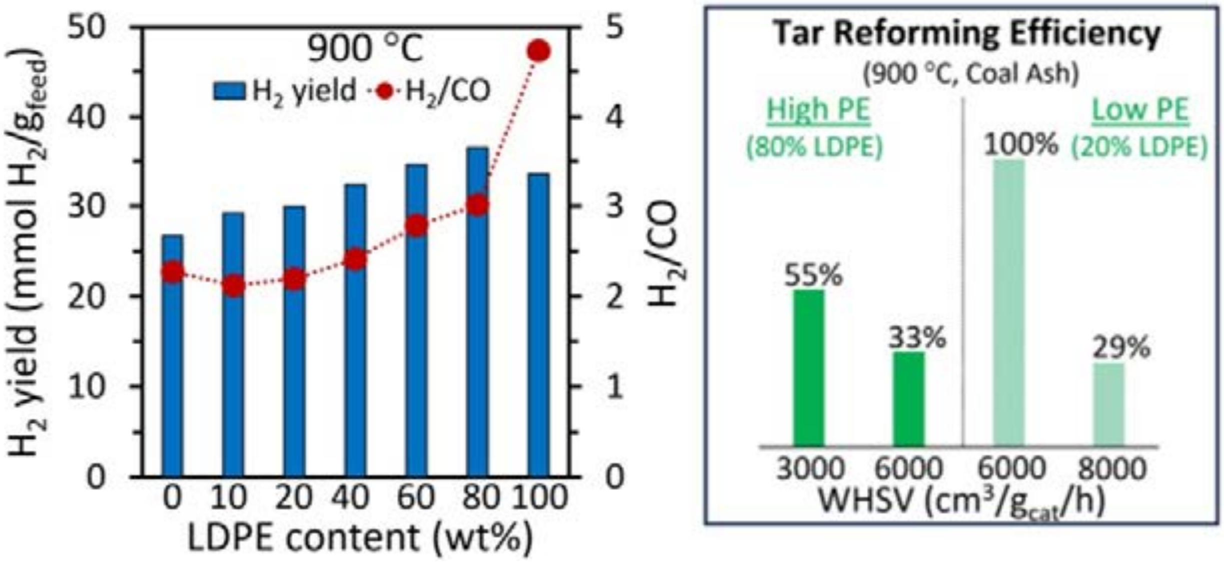


Figure 2: H_2 yield and tar reforming efficiency results from the steam co-gasification of LDPE and coal refuse.

Pyrolysis of high-density polyethylene (HDPE) pellets in the DTR involved completing an investigation of temperature (500–900°C) and gas/volatile residence time (four to 32 seconds) effects on carbon conversion and product distribution. The team utilized various analytical techniques, such as GC-MS, Raman spectroscopy and scanning electron microscopy/energy-dispersive X-Ray spectroscopy (SEM/EDS), to characterize HDPE pyrolysis products: gases (H_2, C_1-C_3), tars (C_{10}-C_{45}), and char and established correlations between their formation and process parameters. See Figure 3 for various results on HDPE pyrolysis.

Finally, the team determined pyrolysis kinetic parameters using non-isothermal TGA-DSC. This included developing standardized protocols to examine thermal degradation behaviors of pure and mixed feedstocks (plastics, biomass and MSW), as well as determining kinetic triplets from collected TGA data using a combination of isoconversional and master-plot methods.

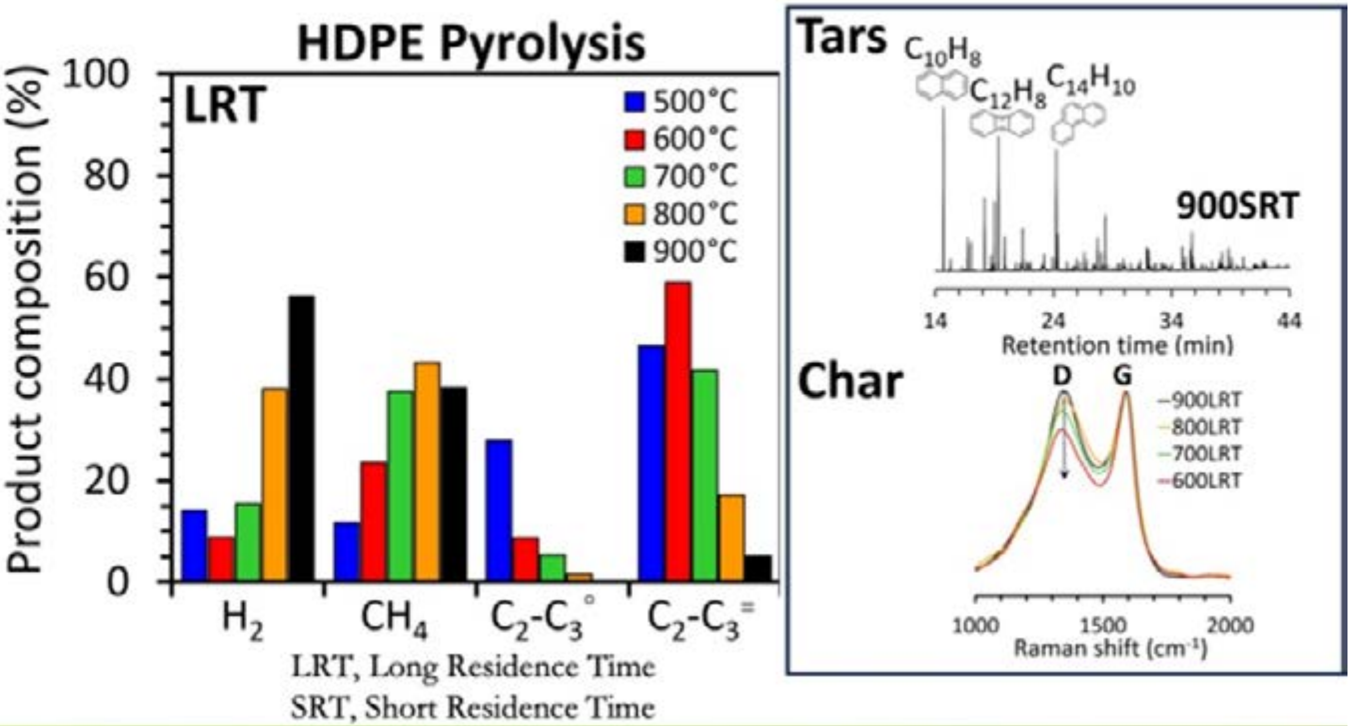


Figure 3: Testing and characterization results for HDPE pyrolysis.

technology advantages

- Supports methods for converting waste (like nonrecyclable waste plastics) into valuable products like hydrogen and syngas, reducing landfill dependency and environmental impact.
- Enables the processing of a wide range of wastes (e.g., different type, mixed and contaminated plastics), making the system versatile and scalable.
- Supports a sustainable approach by transforming waste into usable energy, closing the resource loop.
- Produces energy-rich, high-value syngas and hydrogen.
- Mitigates the risks associated with wastes, incineration or disposal by providing a cleaner, controlled gasification alternative.

R&D challenges

- Tendency of waste plastics and biomass to produce tars and other undesirable by-products during gasification.
- Developing strategies to handle contaminants released from wastes, such as chlorine and heavy metals, to protect gasifier components and maintain syngas quality.
- Managing the inconsistent composition and properties of waste feedstocks to ensure stable gasifier operation.
- Designing systems capable of efficiently feeding and processing mixed and heterogeneous waste materials.
- Ensuring seamless incorporation of waste gasification into existing gasification systems without compromising efficiency or reliability.
- Demonstrating the technology's performance and economic viability at industrial scales for broader adoption.

status

New test capacities are being established by installing micro-GC for comprehensive analysis of C_1-C_{45} products of gasification and pyrolysis, thereby helping to investigate mechanisms of gasification and pyrolysis. Ongoing work is developing kinetic models and product distribution calculations for gasification and pyrolysis of waste feedstocks by individual feedstock constituents, supporting gasification modeling/ML and gasifier design.

available reports/technical papers/presentations

"Advanced Reaction Systems," Eric Lewis, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Lewis.pdf*.

EY23 Field Work Proposal, Advanced Reaction Systems FWP Number: 1022405.

Muhammad Aamir Bashir, Tuo Ji, Jennifer Weidman, Yee Soong, McMahan Gray, Fan Shi, and Ping Wang, "Plastic Waste Gasification for Low-Carbon Hydrogen Production: A Comprehensive Review," Energy Advances, January 2025. https://doi.org/ 10.1039/d4ya00292j.

Muhammad Aamir Bashir, Sittichai Natesakhawat, Jennifer Weidman, Nicholas Means, Fan Shi, Jonathan Lekse, McMahan Gray, and Ping Wang, "Co-Gasification of Plastic, Coal Refuse, and Biomass for Hydrogen-Rich Syngas Production," AIChE Annual Meeting, San Diego, CA, October 2024.

Sittichai Natesakhawat, Jennifer Weidman, Muhammad Aamir Bashir, Nicholas Means, Fan Shi, Jonathan Lekse, McMahan Gray, and Ping Wang, "From Plastic Waste to Fuel: Pyrolysis and Gasification of Polyethylene for Hydrogen Production," ACS Fall 2024 Meeting, Denver, CO, August 2024.

Muhammad Aamir Bashir, Sittichai Natesakhawat, Mehrdad Shahnam, and Ping Wang, "Unraveling the Pyrolytic Behavior and Kinetics of Pure Polymers and Plastic-Rich Municipal Solid Waste Using Thermal Analysis," 2024 Multiphase workshop, Morganton, WV, August 2024.

Max Edelstein, Ping Wang, and Wei Shi, "Optimizing Process Conditions for H2 Production from Biomass and Plastic Waste Gasification Using Machine Learning and Genetic Algorithm," 2024 FECM/NETL Carbon Management Project Review Meeting, Pittsburgh, PA, August 2024.

Christopher Ge, Muhammad Aamir Bashir, and Sittichai Natesakhawat, "A Kinetic Study of Mixed Polyolefins and Biomass Pyrolysis Using Thermal Analysis," 2024 FECM/NETL Carbon Management Project Review Meeting, Pittsburgh, PA, August 2024.

Sittichai Natesakhawat, Jennifer Weidman, Stephanie Garcia, Nicholas C. Means, and Ping Wang, “Pyrolysis of High-Density Polyethylene: Degradation Behaviors, Kinetics, and Product Characteristics,” Journal of the Energy Institute, Volume 116, 2024, Article number 101738. https://doi.org/10.1016/j.joei.2024.101738.

Sittichai Natesakhawat, Nicholas Means, Victor Abdelsayed, Jennifer Weidman, Fan Shi, Jonathan Lekse, McMahan Grey, and Ping Wang, “Upcycling Plastic and Coal Wastes into Syngas by Steam Gasification,” 2023 AIChE Annual Meeting, Orlando, FL, November 2023.

Ping Wang, Sittichai Natesakhawat, Victor Abdelsayed, Jennifer Weidman, Nicholas Means, Yee Soong, Fan Shi, Jonathan Lekse, and McMahan Grey, “Thermochemical Conversion of Plastic Waste to Enable a Circular Economy,” ACS Fall 2023 Meeting, San Francisco, CA, August 2023.

Nicholas Means, Sittichai Natesakhawat, Fan Shi, Jonathan Lekse, McMahan Gray, and Ping Wang, 46th International Technical Conference on Clean Energy, Clearwater, FL, August 2022.

Feedstock Control for Gasification

primary project goal

The National Energy Technology Laboratory (NETL) is developing intelligent systems capable of controlling the blend of mixed plastic waste, biomass, municipal solid waste (MSW) and waste coal supplied to a modular gasification system for production of hydrogen (H_2) with carbon capture and storage (CCS). Actively controlling the blend of waste plastics and other materials fed to a gasifier will make its operation more stable and enable the optimization of its operation based on the feed stream composition.

technical goals

- Work with the National Renewable Energy Laboratory (NREL) to assess existing tools for imaging and spectroscopic characterization of biomass, MSW and fossil energy feedstocks.
- Collect data to link waste plastics to gasification properties.
- Develop a prototype system for actively controlling feed to small pilot gasifier.

technical content

NETL is advancing gasification technologies through research and development (R&D) in several areas aimed at enabling the utilization of diverse feedstocks for hydrogen and value-added products.

Gasification has the potential to convert diverse and low-value source materials, such as biomass, MSW and waste plastics, into valuable, hydrogen-rich syngas, supporting the U.S. Department of Energy's Hydrogen Earthshot initiative. Work in feedstock control for gasification focuses on comprehensive characterization to understand and control materials variability, which is critical for ensuring consistent performance in gasification systems. By developing advanced methods for feedstock analysis, preparation and blending, process efficiency, reliability and scalability can be enhanced. Improved gasification feedstock control will not only improve the economic viability of hydrogen production, but also contribute to the sustainability and environmental benefits of energy systems through the efficient use of waste-derived materials.

Figure 1 depicts the concept that considerable variation is present in one of the gasification wastes streams of interest (nonrecyclable waste plastic), which would require extensive sorting, preparation including size reduction/shredding, and finally blending with biomass before a suitably controlled feedstock mixture is ready for utilization in a gasifier.

program area:

Gasification Systems

ending scale:

Small Pilot

application:

Hydrogen Production

key technology:

Novel Technologies for Chemicals & Fuels

project focus:

Active control of gasification feedstocks for hydrogen production systems

participant:

National Energy Technology Laboratory (NETL)

project number:

Gasification Systems MYRP-5

predecessor projects:

FWP-1022405-1

NETL project manager:

Jennie Stoffa
Jennie.Stoffa@netl.doe.gov

principal investigator:

Benjamin Chorpening
benjamin.chorpening@netl.doe.gov

partners:

N/A

start date:

04.01.2023

percent complete:

50%

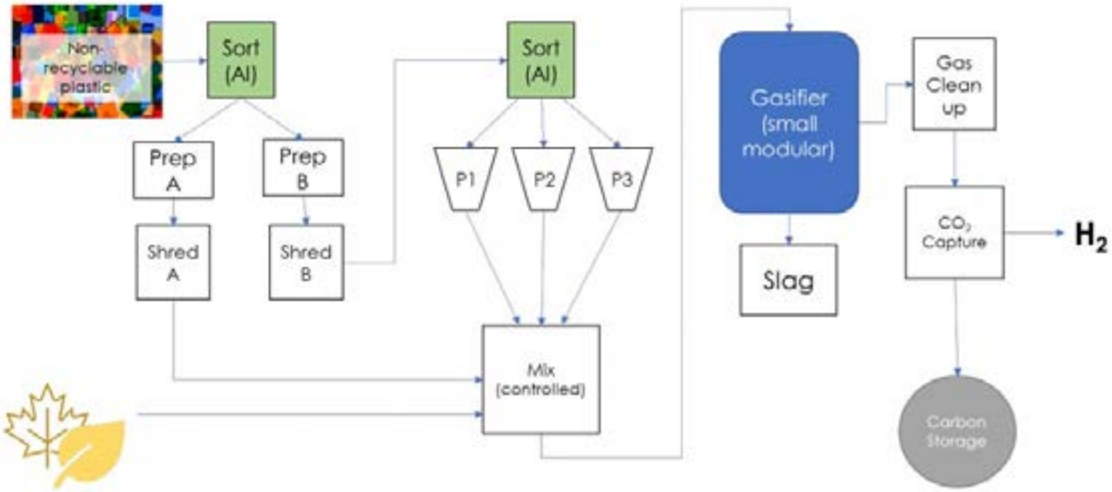


Figure 1: Process flow diagram for conversion of plastic waste to clean hydrogen.

technology advantages

- Enabling highly heterogenous alternative feedstock usage in gasification systems.

R&D challenges

- Application of machine learning (ML)/artificial intelligence (AI) to gasification feedstock control.
- Developmental challenge of extending support to active control of a small pilot gasifier.

status

State-of-Technology Report under preparation.

available reports/technical papers/presentations

“Advanced Reaction Systems,” Eric Lewis, 2024 FECM/NETL Spring R&D Project Review Meeting - Gasification Systems – PROCEEDINGS *https://netl.doe.gov/sites/default/files/netl-file/24FECM_GAS_Lewis.pdf*.

EY23 Field Work Proposal, Advanced Reaction Systems FWP Number: 1022405.

this page intentionally left blank

U.S. DEPARTMENT
of ENERGY

NATIONAL
ENERGY
TECHNOLOGY
LABORATORY

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

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

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

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

CUSTOMER SERVICE
1-800-553-7681

NETL.DOE.gov