# SSAE Newsletter

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## // ABOUT

The Strategic Systems Analysis and Engineering (SSAE) directorate provides the decision science and analysis capabilities necessary to evaluate complex energy systems. The directorate's capabilities address technical, economic, resource, policy, environmental and market aspects of the energy industry. These capabilities are critical to strategic planning, direction and goals for technology R&D programs and the generation of market, regulatory and technical intelligence for NETL senior management and DOE. SSAE offers a range of multi-criteria and multi-scale decision tools and approaches for this support:

- Process systems engineering research: advanced modeling, simulation and optimization tools for complex dynamic systems
- Process and cost engineering: plant-level synthesis, process modeling and simulation of energy systems with performance estimates
- Resource and subsurface analysis: evaluation of technologies, approaches and regulations for subsurface energy systems and storage
- Market and infrastructure analysis: economic impacts and program benefits
- Environmental life cycle analysis: cradle-to-grave emissions and impacts

These tools and approaches provide insights into new energy concepts and support the analysis of energy system interactions at the plant, regional, national and global scales.

# // HIGHLIGHTS

## Recent Paper Discusses New Optimization Tools

Development of a suite of new optimization-based computational modeling tools for increasing the efficiency and flexibility of power plants was discussed in a recent paper co-authored by SSAE researchers John Eslick*, Miguel Zamarripa*, Jinliang Ma*, Maojian Wang, Steve Zitney, Tony Burgard and David Miller and researchers from West Virginia University and Tri-State Generation and Transmission Association, Inc.

The modeling tools were used to construct a predictive, physics-based model of the Escalante Generating Station, a 245-MW subcritical power plant in New Mexico, that was tuned with extensive plant operating data (86 measurement tags) and remains accurate over the broad range of operation encountered during load following. The model was successfully applied to generate meaningful insights for reducing the plant's minimum operating load and improving its efficiency. Operating data, models and tools are made available as supplementary material for the paper, which was published in *Applied Energy* (impact factor: 9.746).

## Study Analyzes $CO_2$ Utilization Terminology

An article to help clarify terminology in carbon dioxide ($CO_2$) utilization (CO2U) research, co-authored by SSAE researcher Michele Mutchek* and the Global $CO_2$ Initiative (GCI), was published in the May 2022 edition of *Frontiers in Climate*. GCI is a research organization at the University of Michigan that supports carbon capture and utilization (CCU) technology development.

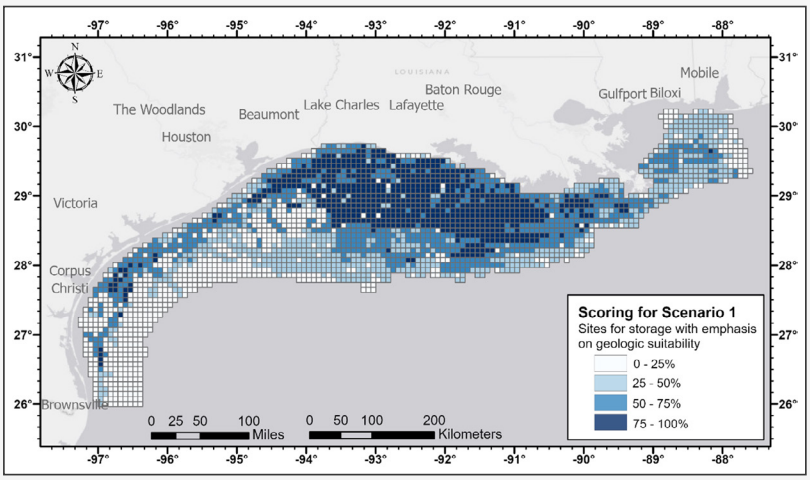
After identifying common terms in CO2U literature, several inconsistencies and ambiguities in terminology were highlighted. For example, carbon capture, utilization and storage (CCUS) could be interpreted as carbon storage, carbon utilization or a combination of the two. Similarly, $CO_2$ removal is ambiguous because it may refer solely to $CO_2$ extraction or also include sequestration.

To help unify vocabulary, glossaries developed by the GCI International CCU Assessment Harmonization Group, the University of Pennsylvania and the nonprofit CarbonPlan as well as those being developed by the German Institute for Standardization were referenced. Findings of this article suggested avoiding abbreviations or explaining and precisely defining them.

## Paper Screens Gulf of Mexico Outer Continental Shelf for Potentially Viable $CO_2$ Storage and Enhanced Oil Recovery Sites

A methodology that incorporates disparate sets of quantitative, spatially variable data into a decision-making framework for screening the Gulf of Mexico outer continental shelf for potentially viable $CO_2$ storage and enhanced oil recovery sites was described in a recent paper published in the *International Journal of Greenhouse Gas Control*.

Data was compiled for 14 criteria from several publicly available geographic information system (GIS) layers and aggregated over 2,559 spatially balanced points across the study area using the NETL-developed Cumulative Spatial Impact Layers™ GIS tool. Criteria considered both technical and non-technical considerations and were weighted by qualitative expert opinion relative to their perceived importance to given scenarios — the output of combined criteria values and weights enables regional $CO_2$ storage suitability differentiation. The flexible methodology enables a systematic approach to regional ranking at high spatial resolution over a large study domain. Additionally, the framework enables high grading of priority sites that warrant further characterization and follow-on analysis.




Results of general scoring binned by quartiles for scenario one highlighting long-term storage in the most favorable geologic settings

The results of the study showed that areas along the Louisiana coast and Mississippi River Delta consistently ranked higher in all scenarios (example results shown in figure above). These areas not only have favorable geology with the potential for stacked storage but also existing infrastructure and are in close proximity to several onshore $CO_2$ sources.

## Paper Assesses Renewable Natural Gas Production Pathways

Life cycle global warming potential (GWP) impacts of renewable natural gas production pathways was evaluated in a paper published in June 2022 in *Environmental Science and Technology*. This study is intended to help communities assess options for managing waste while producing renewable fuel.

Co-authored by SSAE researchers Timothy Skone and Gabrielle Yanai*, the study analyzed anaerobic digestion (AD), thermal gasification (TG) and power-to-gas (P2G) pathways including various feedstocks and technologies. The AD pathway considered animal manure, landfill gas, municipal solid waste and wastewater sludge as feedstocks. For the TG pathway, air, catalyst and steam thermal gasification technologies were evaluated with waste wood feedstock. The P2G pathway incorporated hydrogen production from wind-powered electrolysis.

* NETL Support Contractor

# // HIGHLIGHTS cont'd

GWP impacts depended strongly on production pathway and feedstock. AD of animal manure and TG using air and catalyst technologies yielded net negative carbon emissions, while AD of landfill gas and TG using steam yielded net emissions that were positive but lower than those of fossil natural gas (FNG). The other pathways produced higher emissions than FNG.

### Turbine Design for $sCO_2$ Plant Discussed in Recent Study

Details of the design process of a 950-MW rated supercritical $CO_2$ ($sCO_2$) turbine for a direct fired $sCO_2$ power plant are described in a recently released manuscript in *Energy Conversion and Management* (impact factor: 11.53). Meanline turbomachinery design code development is presented and then used in a design optimization process using a mixed integer distributed ant colony algorithm. Turbine blade and disk designs and key turbomachinery design metrics are optimized. A single-flow and a double-flow turbine design are each presented using the optimization procedure.

The work represents the first publicly available information on detailed turbine parameters for a large-scale $sCO_2$ turbine, which has unique temperature and pressure design requirements compared to the turbine design conditions used in comparable $sCO_2$ cycle literature. The results of the turbine design were used in a full power plant optimization procedure and detailed in another recently published *Energy Conversion and Management* publication.

### NETL-Led Study Examines Novel DPE Systems and Concepts

NETL's interest in magnetohydrodynamic (MHD)-based direct power extraction (DPE) technology as part of advanced power systems that meet DOE transformational efficiency and cost of electricity goals led to a detailed scoping study to identify candidate power generation processes that make use of DPE technology and have the potential to either exceed the efficiency or lower the cost of electricity compared to plants only using conventional technology. In this recently released study, computer modeling for some designs was performed along with quantitative techno-economic analysis of selected systems which use MHD power generators.

Because major advancements towards commercialization of MHD projects have remained mostly stagnant and DOE's legacy MHD program did not consider carbon capture and storage (CCS) as a management strategy to reduce $CO_2$ emissions, a detailed assessment of this technology can cause a potential revisit for CCS applications. In fact, the NETL and academic researchers that worked on this study were familiar with the legacy DOE MHD program and could provide insight into the lessons learned from that program to this study.

### Staff Spotlight

Since joining NETL as a site support contractor for the Energy Markets Analysis Team, Ivonne Pena-Cabra* has been evaluating the role of fossil energy (FE) in a decarbonized future. She conducts analyses on decarbonization pathways with hybridized, re-purposed or retrofitted fossil power technologies and storage technologies (e.g., hybrid FE power plants with energy storage, retrofitted FE power plants with CCS technologies and fully re-purposed FE assets). Ivonne has supported NETL in assessing demand response mechanisms that use natural gas and can be another tool to support a decarbonized future. Her motivation is to contribute to an energy transition that is feasible and equitable in the long-term, and that spills over to other sectors and economies. Ivonne's role as current president of the local Three Rivers Chapter of the United States Association for Energy Economics helps toward this goal.

Ivonne's past experience includes a regulatory advisor of the electricity and gas market in Colombia focusing on rooftop solar photovoltaic rate design and auction design for variable renewable power plants; rate impact analyst for wind energy integration in Portugal; modeler of the operation of wholesale electricity markets under scenarios of high renewable penetration using Plexos and cybersecurity analyst for the National Renewable Energy Laboratory; and consultant for Westeva (an American company focusing on solar-battery-wind solutions for non-interconnected zones of Latin America).

She has a bachelor's degree in Electronics Engineering from the Javeriana University of Colombia with a Math major; a master's degree in International Development from the University of Pittsburgh; and a Ph.D. in Engineering and Public Policy from Carnegie Mellon University and the Technical University of Lisbon, Portugal. On top of her educational background, Ivonne is proficient in English, Spanish, Portuguese and French.

# // NOTICES

### LCA Team Reviews LPO Projects

A team of NETL life cycle analysis (LCA) researchers, led by Michele Mutchek*, conducts screening-level greenhouse gas (GHG) emissions studies for DOE's Loan Programs Office (LPO). As of May 31, 2022, 77 active applications had been submitted to the LPO including those that may be eligible under the Title 17 Innovative Energy Loan Guarantee Program.

NETL reviews applications for the Title 17 Program, which provides loan and loan guarantees to innovative and large-scale energy infrastructure projects that avoid, reduce or sequester GHG emissions.

For each application it reviews, NETL assesses the environmental impact associated with GHG emissions from the proposed system and compares them to a baseline. To do so, NETL defines upstream and downstream flows and processes for the proposed and baseline systems based on a reference flow, called the functional unit.

In 2021, NETL reviewed a project submitted by Monolith Nebraska to expand one of its facilities in Hallam, Nebraska, to convert natural gas into carbon black and hydrogen using methane pyrolysis. LPO issued a conditional commitment to guarantee a loan of up to $1.04 billion to finance this project.

### Tarka Engages in Pittsburgh Energy Innovation Discussion

SSAE's Thomas Tarka was invited by the Pennsylvania Department of Community and Economic Development in collaboration with the Energy Innovation Center to participate in a lunch roundtable on energy innovation and decarbonization with representatives from the Kingdom of Denmark. Held on June 2, 2022 in Pittsburgh, PA, the meeting built upon over four years of engagement between NETL and Pittsburgh-area energy experts with the Danish government under the Pittsburgh-Danish Energy Exchange initiated in April 2018.

Tarka discussed NETL's research, development and commercialization activities in support of America's Energy Transition to a decarbonized economy, while Danish experts provided experiences on innovations in several areas including decarbonization, renewable natural gas and grid modernization. This roundtable aimed to update Danish experts on advances happening in the Pennsylvania energy and energy adjacent sectors, initiate future conversations about prospective transatlantic collaboration and innovation and identify future business opportunities for both Pennsylvanian and Danish companies in this area.

### SSAE Represented at ASME Power Conference

SSAE researchers Chad Able* and Eric Grol provided a project overview and professional insights, respectively, at the ASME Power Conference held in July 2022.

Chad discussed a market assessment to estimate the total volume of wastewater that could be subject to regulation and treatment and an evaluation on the cost to treat. This study projects those heavy metals, which can be challenging to detect in resulting wastewater due to their trace amounts in coal, that are most likely to be present in combustion residual leachate, based on the type of coal that was burned at the power plant. Given the wide variation in heavy metal concentration in wastewater, characterizing which pollutants are most likely to be present is a critical step to understanding the treatment technology research and development needs.

During the Student Panel session, Eric engaged with undergraduate, master and doctorate students across various research areas providing expertise and insights in the energy field to help guide their future career paths.

# // PERSPECTIVES

### Reforming-based IES for Low Carbon Power and $H_2$

Hydrogen ($H_2$) has significant strategic importance in the pursuit of a decarbonized, more sustainable energy sector. Achieving the DOE Hydrogen Energy Earthshot Initiative (HEEI) goal of reducing the cost of clean $H_2$ to $1/kg in one decade will likely require a multi-faceted approach that includes leveraging technology innovation, byproduct sales and several additional external factors (e.g., plant scale, site location, feedstock price, transport and storage, emissions reductions, etc.).

Integrated energy systems (IES) based around $H_2$ production and use have the potential to reduce production costs by synergistically providing multiple services such as electricity, high value heat and chemicals as part of dynamic, tightly coupled hybrid systems. SSAE personnel, utilizing the Institute for the Design of Advanced Energy Systems (IDAES) Integrated Platform, are currently evaluating several IES's capable of generating nearly carbon-free $H_2$ and power. One particularly promising IES design entails integrating steam methane reforming (SMR) with a gas turbine (GT) to create a system that uses the same feedstock to generate both $H_2$ and power while sharing the same carbon capture system (Figure 1). The GT provides stable, reliable, low-carbon power for on-site use, thus avoiding the operating cost of grid electricity and its uncertainty due to price oscillations in the power market. The IES power can also serve as an additional revenue stream if sold to external consumers or to the grid.

# // PERSPECTIVES cont'd

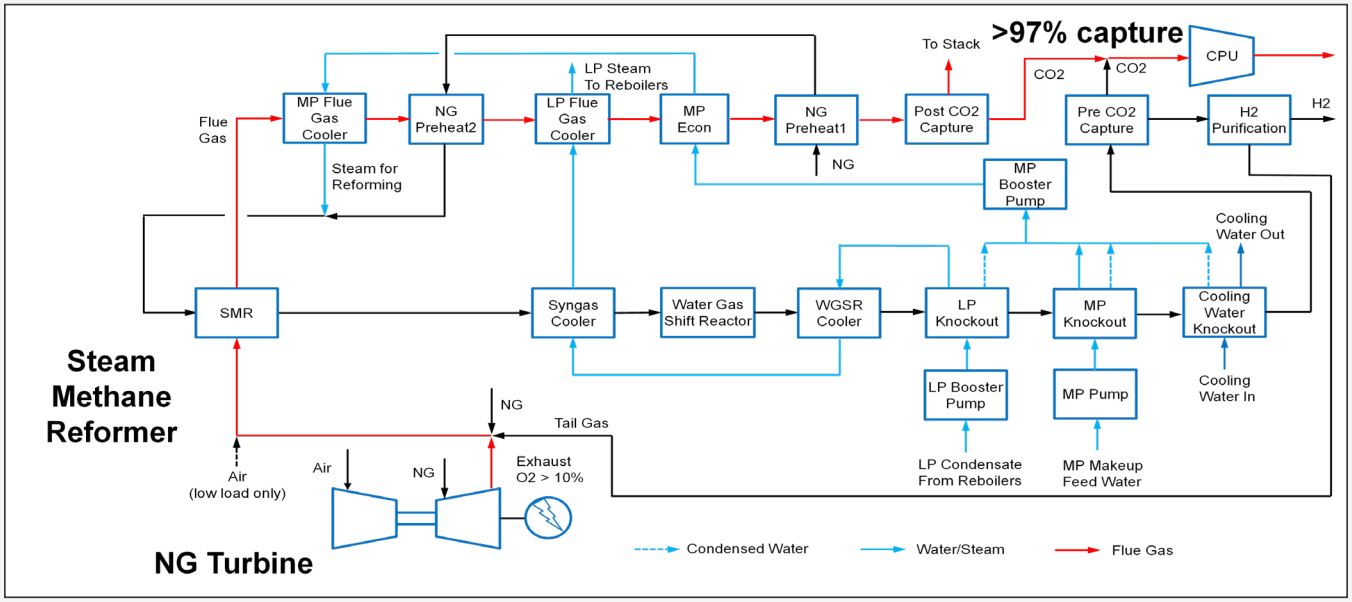



*Figure 1. Block flow diagram for an IES consisting of SMR and GT with carbon capture*

*Baseline Performance and Cost*

A preliminary assessment of the IES was recently conducted to demonstrate how the concept might reduce the levelized cost of $H_2$ (LCOH) relative to a more standard SMR process with carbon capture. Performance was compared to standalone systems (i.e., natural gas simple cycle + capture and SMR + capture) that produce the same amount of power (115 MW gross) and $H_2$ (20,100 kg/hr). In all cases considered, at least 97% of the produced $CO_2$ is captured. The IES gas turbine generates sufficient power for the SMR process (~40 MW) as well as an additional 75 MW that can be sold for additional revenue.

The required natural gas flow rates for the IES and standalone systems are shown in the left-hand chart of Figure 2. While the natural gas flow rates for the GT and the SMR reactor are identical, the flow rate for the supplemental natural gas to the SMR furnace is reduced from 13,850 kg/hr to 3,300 kg/hr, resulting in a reduction of approximately 11% in the total natural gas flow rate. If the natural gas fed to the SMR reactor and the SMR furnace is considered as the feedstock to produce low carbon $H_2$, the cold gas efficiency is increased from 72.5% to 84.4% on a higher heating value (HHV) basis and from 68.3% to 79.4% on a lower heating value (LHV) basis. The total flue gas flow rates of the IES and the standalone systems are shown in the right-hand chart of Figure 2. The total flow rate of the IES is that of flue gas leaving the SMR furnace, while for the standalone systems, it is the sum of the GT exhaust and the SMR flue gas. The overall flue gas flow rate is reduced by 604,700 kg/hr, or 42%, from 1,445,400 kg/hr to 840,700 kg/hr leading to a much smaller $CO_2$ absorber design for the integrated system than if the two systems were to operate independently.

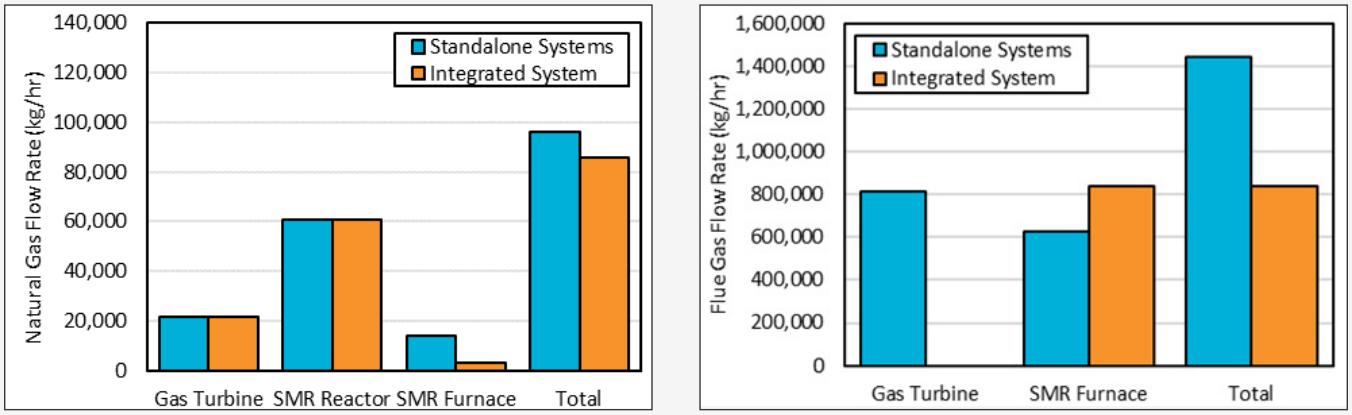



*Figure 2. Comparison of performance of IES versus standalone plants based on natural gas flow rates (left) and flue gas flow rates (right)*

# // PERSPECTIVES (cont'd)

The LCOH for the standalone SMR and the SMR + GT IES is shown in Figure 3. The standalone SMR with capture process has an LCOH of $1.64/kg assuming an electricity purchase price of $71.7/MWh and a natural gas price of $4.19/GJ ($4.42/MMBtu) on an HHV basis in 2018 U.S. dollars as reported in a 2022 study by Lewis et al.[1] The LCOH calculated for the IES is $1.52/kg $H_2$ assuming electricity sale price of $71.7/MWh. The bar chart in Figure 3 compares the individual components of LCOH for the IES with those of the standalone SMR at the same $H_2$ production rate of 20,100 kg/hr.

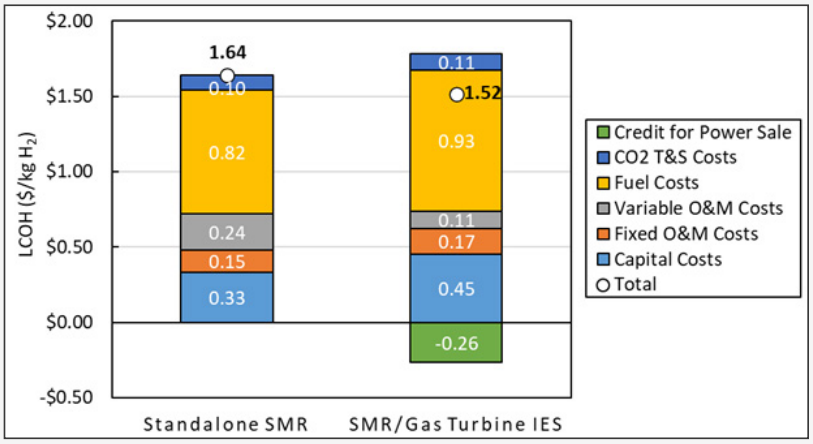



Figure 3. LCOH results for standalone SMR and SMR IES

*Sensitivity to Price of Electricity*

Figure 4 shows how the LCOH for the standalone SMR varies with the purchase price of electricity and how the LCOH for the IES varies with the electricity sale price. The vertical orange line denotes the baseline electricity price of $71.7/MWh. Since the standalone SMR consumes electricity, its LCOH increases with electricity price. On the other hand, the IES produces electricity and its LCOH decreases with an increase in electricity sale price. As expected, the benefit of the IES over the standalone SMR plant becomes far more pronounced at higher electricity prices, thereby insulating the system from potential future scenarios where the price of electricity is high.

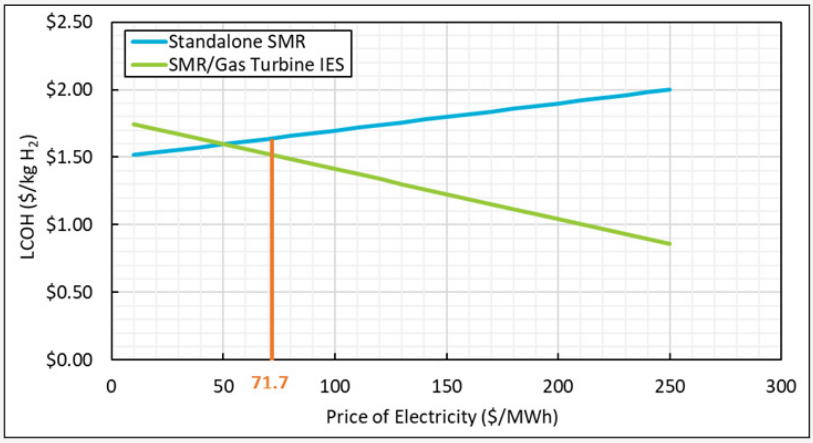



Figure 4. Sensitivity of LCOH to price of electricity for standalone SMR and SMR IES

This collaborative work between SSAE's Energy Process Analysis Team, Energy Markets Analysis Team and Process Systems Engineering Research Team (PSERT) is also exploring alternative IES process configurations and scales as well as dispatchability of such systems in existing energy markets in order to reduce the cost of low-carbon $H_2$ and achieve the DOE HEEI goal. – Contributed by Anthony Burgard, SSAE's PSERT and Jinliang Ma* in support of SSAE's PSERT

Reference

[1] E. Lewis, S. McNaul, M. Jamieson, M. Henriksen, H. S. Matthews, J White, L. Walsh, J. Grove, T. Shultz, T. J. Skone and R. Stevens, "Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies," National Energy Technology Laboratory, DOE/NETL-2022/3241, Pittsburgh, PA, April 12, 2022.

# // UPCOMING CONFERENCES AND EVENTS

**SSAE Federal staff and NETL support contractor personnel will attend or present at the following conferences and events in August 2022:**

- 46th International Technical Conference on Clean Energy
  Presenters: Timothy Fout–1) Update to Technoeconomic Analysis of BECCS Systems, 2) Direct Air Capture Case Studies: Sorbent System and 3) High $CO_2$ Capture Rate Cost and Performance Baseline Results for Natural Gas Combined Cycles (NGCC); Sydney Hughes*– Updated Cost and Performance of $CO_2$ Capture and Compression from Industrial Sources and Robert Stevens–Comparison of Commercial State-of-the-Art, Fossil-Based Hydrogen Production Technologies
  Moderator: Robert Stevens–Chemical Looping Session
  Hybrid (Virtual and Clearwater, FL), August 1–4, 2022
- Produced Water Society Permian Basin 2022
  Panelist: Markus Drouven–Panel – State of the consortiums: What are Texas and New Mexico stakeholders working on?
  Participants: Miguel Zamarripa-Perez*, Melody Shellman*, Naresh Susarla*, Travis Arnold* and Sitoshna Jatty*
  Midland, TX, August 15–17, 2022
- PARETO Stakeholder Board Meeting
  Participants: Markus Drouven, Miguel Zamarripa-Perez*, Melody Shellman*, Naresh Susarla*, Travis Arnold* and Sitoshna Jatty*
  Midland, TX, August 17, 2022
- 2022 Carbon Management Project Review Meeting
  Presenters: Kolawole Bello*–Application of Dimensionality Reduction in Machine Learning Modeling of $CO_2$ Storage; Derrick Carlson*–Life Cycle Analysis Tools for Capture and CDR; Tim Fout–Case Study of Sorbent Based Direct Air Capture; Amanda Harker Steele–Development of a Tool to Calculate the System Cost of Replacement Energy; Sally Homsy*–Recent Point Source Capture Techno-economic Analysis; Michelle Krynock–Overview of Carbon Utilization Life Cycle Analysis at NETL; David Morgan–Updates of the CO2_T_COM and CO2_S_COM Models ($CO_2$ transport and storage costs); Clint Noack*–Supply Chain Vulnerabilities of the Energy Transition with a Focus on Carbon Capture, Transportation, and Storage; Derek Vikara*–1) Cost Impacts of Risk-Based Methods for Defining AoR and PISC Duration of a $CO_2$ Storage Project Using NRAP Tools and FECM/NETL $CO_2$ Saline Storage Cost Model and 2) Pathways to $CO_2$ Utilization and Storage for the Intermountain West Region and Nur Wijaya*–1) Numerical Simulation of Commercial-Scale $CO_2$ Storage in a Saline Formation Evaluating Basin-Scale Pressure Interference and $CO_2$ Plume Commingling and 2) Site Selection and Cost Estimation of Pilot-Scale $CO_2$ Saline Storage Study in the Gulf of Mexico
  Participants: Peter Balash, Luciane Cunha, Timothy Grant, Eric Grol, Allison Guinan*, Gregory Hackett, Matthew Jamieson, Mike Marquis*, Alana Sheriff*, Taylor Vactor* and Travis Warner*
  Pittsburgh, PA, August 15–19, 2022
- Alaska's Minerals: A Strategic National Imperative
  Presenter: Thomas Tarka
  Fairbanks, AK, August 22–23, 2022
- The International Meeting for Applied Geoscience & Energy
  Participant: Luciane Cunha
  Houston, TX, August 28–September 1, 2022
- NERC Reliability Assessment Subcommittee Third Quarter Meeting
  Participant: John Brewer
  Hybrid (Virtual and Montreal, Canada), August 31–September 1, 2022



* NETL Support Contractor

# // RECENT PUBLICATIONS

### Articles/Manuscripts

- B. Olfe-Kräutlein, K. Armstrong, M. Mutchek, L. Cremonese and V. Sick, "Why Terminology Matters for Successful Rollout of Carbon Dioxide Utilization Technologies," *Frontiers in Climate*, May 30, 2022.
- S. Rai, D. Hage, J. Littlefield, G. Yanai and T. Skone, "Comparative Life Cycle Evaluation of the Global Warming Potential (GWP) Impacts of Renewable Natural Gas Production Pathways," *Environmental Science & Technology*, vol. 56, issue 12, pp. 8581-8589, June 2, 2022.
- J. C. Eslick, M. A. Zamarripa, J. Ma, M. Wang, I. Bhattacharya, B. Rychener, P. Pinkston, D. Bhattacharyya, S. E. Zitney, A. P. Burgard and D. C. Miller, "Predictive Modeling of a Subcritical Pulverized-Coal Power Plant for Optimization: Parameter Estimation, Validation, and Application," *Applied Energy*, vol. 319, article 119226, August 2022.
- S. Can Uysal and N. Weiland, "Turbomachinery design of an axial turbine for a direct fired $sCO_2$ cycle," *Energy Conversion and Management*, vol. 267, article 115913, September 2022.

### Models/Tools/Databases

- National Energy Technology Laboratory, "NETL CO2U LCA Documentation Spreadsheet (Version 2.1)," National Energy Technology Laboratory, Pittsburgh, PA, June 17, 2022.
- National Energy Technology Laboratory, "NETL CO2U LCA Guidance Toolkit – Version 2.1," National Energy Technology Laboratory, Pittsburgh, PA, June 17, 2022.
- National Energy Technology Laboratory, "NETL CO2U openLCA LCI Database Version 2.1," National Energy Technology Laboratory, Pittsburgh, PA, June 17, 2022.

### Reports/Supporting Documentation

- N. Weiland, C. Rigel Woodside, C. White and J. Mazzoccoli, "Scoping Study for Direct Power Extraction (DPE) Systems: Final Report," National Energy Technology Laboratory, DOE/NETL-2021/2751, Pittsburgh, PA, May 13, 2021.
- M. Verti, C. Charlton, L. Cooper and A. Richardson, "High Performance Alloy Technology to Market Support," National Energy Technology Laboratory, DOE/NETL-2021/3216, Pittsburgh, PA, August 27, 2021.
- C. Pechman, K. Kline, S. Lichtenberg, J. Loiter, B. Neenan, E. Nethercutt and T. Stanton, "Economics of Carbon Capture and Sequestration", National Energy Technology Laboratory, DOE/NETL-2021/3215, Morgantown, WV, February 1, 2022.
- H. Singh, C. Charlton, K. Krulla and C. Talarico, "Advanced Sensors for Hydrogen Technology," National Energy Technology Laboratory, DOE/NETL-2020/2613, Pittsburgh, PA, February 5, 2022.
- E. Shuster, R. Hoesly and A. Pizel, "Estimating Fresh Water Needs to Meet Future Thermoelectric Generation Requirements and Program Water Savings Benefits – 2022 Update," National Energy Technology Laboratory, DOE/NETL-2022/3786, Pittsburgh, PA, March 31, 2022.
- A. Harker Steele, R. Jackson, P. Járosi, S. Sharma and J. Adder, "WVU/NETL Econometric Input-Output (ECIO) Model Documentation Update," National Energy Technology Laboratory, DOE/NETL-2022/3781, Pittsburgh, PA, April 22, 2022.
- C. Shih, S. Lin, M. Milligan, A. Wendt, M. Marquis, J. Eppink and T. Grant, "Benefit Analysis of $CO_2$ Delivery Options for Offshore Storage or Enhanced Oil Recovery," National Energy Technology Laboratory, DOE/NETL-2022/3792, Pittsburgh, PA, May 22, 2022.
- B. Turner, C. Callahan, V. Toetz and J. Brewer, "2022 Summer Resource Adequacy in the ERCOT Region," National Energy Technology Laboratory, DOE/NETL-2022/3801, June 1, 2022.

### Presentations

- E. Shuster, K. Kern and P. Balash, "NETL Energy Related Diagrams – 2021 Edition," National Energy Technology Laboratory, DOE/NETL-2022/3260, Pittsburgh, PA, May 2022.
- E. Lewis, "Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies," June 15, 2022.

### Conference Proceedings and Events

- M. Drouven, "An Optimization Framework for Produced Water Management and Beneficial Reuse," presentation at the Texas Water and Energy Institute (TWEI): Virtual Water Lecture Series, Virtual, August 27, 2021.
- A. S. Chinen and E. Liese, "Dynamic Modeling and Simulation of a Large Scale Direct-Fired Supercritical $CO_2$ Power Cycle for Off-Design Operating Conditions," presentation at the 7th International $sCO_2$ Power Cycles Symposium, Hybrid (Virtual and San Antonio, TX), February 23, 2022.
- W.M. Summers, "Utilizing Coal as a Source for REE/CMs, Understanding Demand and Supply Chains," presentation at the 26th Annual ACS Green Chemistry and Engineering Conference, Reston, VA, June 8, 2022.

# // REFERENCE SECTION

**Models / Tools / Databases**

Carbon Capture Simulation Initiative (CCSI) Toolset

FE/NETL $CO_2$ Transport Cost Model

FE/NETL $CO_2$ Saline Storage Cost Model

FE/NETL $CO_2$ Prophet Model

FE/NETL Onshore $CO_2$ EOR Cost Model

Life Cycle Analysis Models

NETL LCA CO2U toolkit

IDAES Integrated Platform

IDAES Power Generation Model Library

Pulverized Coal Carbon Capture Retrofit Database (CCRD)

Natural Gas Combined Cycle CCRD

Industrial Sources CCRD

**Key Reports**

Baseline Studies for Fossil Energy Plants

Cost of Capturing $CO_2$ from Industrial Sources

Quality Guidelines for Energy System Studies

Life Cycle Analysis

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Life Cycle Analysis webpage

$CCSI^2$ webpage

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