SSAE Newsletter

NOVEMBER // 2022 VOLUME 2.10

2 HIGHLIGHTS

4 NOTICES

5 PERSPECTIVES

7 UPCOMING CONFERENCES AND EVENTS

8 RECENT PUBLICATIONS

// 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.

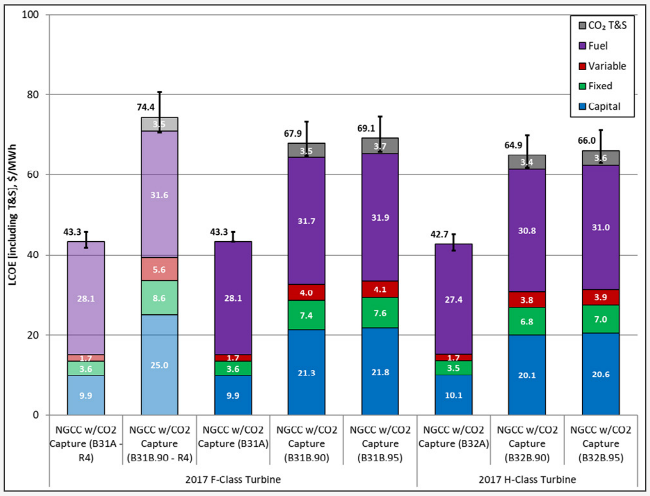
// HIGHLIGHTS

NETL Baseline Study Updated to Include the Performance and Cost of High CO_2 Capture Rates for Power Generation Systems

NETL recently updated its widely cited study on the performance and cost of fossil-fueled commercial power generation systems. The report, "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity (Revision 4A)," is used by industry, researchers and policy makers as a key reference for contemporary carbon dioxide (CO_2) capture systems applied to pulverized coal (PC) and natural gas combined cycle (NGCC) electricity generating units (learn more).

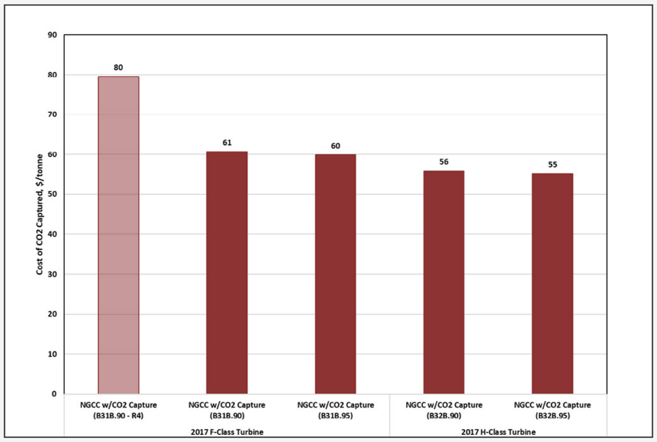
Compared to Revision 4, published in 2019, the revised study includes new cases for H-class NGCCs, updated (2021) quotes for the Shell CANSOLV post-combustion capture system and greater than 90% carbon capture rates for PC and NGCC cases. The latter is of particular interest given the Biden Administration's goal for a decarbonized power sector by 2035. Both 90% and 95% capture cases are presented for PC and NGCC plants as representations of the current state of the art. Technology suppliers and subject matter experts acknowledge that solvent-based post-combustion CO_2 capture technologies can achieve CO_2 removal rates beyond 95% for fossil-fueled combustion streams; however, the limited operational experience with such systems indicates that further data is required to ensure they can routinely, reliably and economically achieve very high removal rates. Consequently, 97% (NGCC) and 99% (PC) cases are included in appendices.

The levelized cost of electricity (LCOE, $/MWh) results for F- and H-class NGCC plants (2018$, 85% capacity factor) are shown in the figure below. Note that the F-class base plant is unchanged from Revision 4 to Revision 4A, and the H-class cases are new for Revision 4A. For the F-class cases with 90% capture, the updated post-combustion capture system results in an 8.7% reduction in LCOE from Revision 4 to Revision 4A. The LCOE increases by 1.8% to go from 90% to 95% capture. The new H-class cases have a slightly lower LCOE compared to the corresponding F-class cases, reflecting the more advanced base plant technology.



LCOE ($/MWh) results for F- and H-class NGCC plants (reported in real 2018$ with an 85% capacity factor)

The cost of capture (COC, $/tonne) results for F- and H-class NGCC plants (2018$, 85% capacity factor) are shown in the figure below. As a result of the updated performance and cost for the capture system, the COC for the 90% carbon capture and storage (CCS) F-class decreased from $80/tonne to $61/tonne (24%) from Revision 4 to Revision 4A and remains relatively unchanged as the capture rate is increased from 90% to 95%. The H-class COC is slightly lower compared to the corresponding F-class cases, a consequence of the larger scale.



COC ($/tonne) results for F- and H-class NGCC plants (reported in real 2018$ with an 85% capacity factor)

This work will serve as the basis for multiple follow-on analyses, including NGCC and PC retrofit studies and accompanying carbon capture retrofit databases, as well as an updated coal-biomass co-firing (up to 100% biomass) with CCS study.

SSAE Evaluates Greenfield Pulverized Coal Electricity Generating Unit Designs for Flexible Operation

The conceptual design of greenfield PC plants intended for flexible operation rather than high capacity factor baseload operation was addressed in a study recently published by SSAE. The United States (U.S.) has plentiful, low-cost natural gas resources—studies of aggressive decarbonization scenarios of the U.S. energy sector suggest that the variability of carbon-free power can be economically addressed using dispatchable natural gas-fueled generation. Globally, natural gas resources are not as plentiful or low cost. Consequently, some regions of the world are expected to continue to rely upon coal generation, even as they pursue decarbonization efforts. To support the increased utilization of variable renewable generation in these coal-dependent regions, plant designs must target low-capacity-factor coal plants with increased emphasis on flexibility attributes such as start-up times, ramp rates, minimum load and part-load heat rates. While much work has been performed on the improvement of flexibility for existing coal plants originally designed for baseload service, little public literature exists on clean-sheet design for flexible operation. This conceptual design study aims to define the features, performance characteristics and costs for greenfield coal plants intended for flexible operation. Quantifying these characteristics

// HIGHLIGHTS cont'd

provides critical information required by utility owners, grid planners, energy market modelers and energy policy decision makers in coal-dependent regions of the world to better understand how coal-fired power plants can support a transition to a low carbon power sector. Marc Turner*, one of the report's co-authors, will be presenting the study at the International Centre for Sustainable Carbon's workshop, "The Energy Transition – The Role for Sustainable Carbon," on November 17, 2022.

Case	Baseload Subcritical and Supercritical PC Plants	Tier 1 Flexibility Options	Tier 2 Flexibility Options	Tier 3 Flexibility Options
Start-up Time to Full Load				
Cold Start to Full Load, Hours	7 – 15	5 - 6		4 - 5
Warm Start to Full Load, Hours	3 – 6	1 - 2		
Hot Start to Full Load, Hours	1 – 3	0.5 – 1.0		
Ramp Rate, % Load/min	3 – 5	5 – 7	7 – 8	8 – 9
Minimum Stable Load (Emissions Compliant), %	40	20		
Minimum Achievable Load (Emissions Compliant), %	30	15		12.5
Design Life, Years	30	30+		
Availability/Reliability (New Construction)				
Equivalent Availability Factor, %	88 – 90	90 – 92	92 – 94	
Equivalent Forced Outage Rate, %	5 – 8	4 – 6	4 – 5	
Planned Plant Maintenance Outage (Spring/Fall)				
Frequency, Outage/Year	1 – 2	2 – 4		
Duration, Days	1 – 7	1 – 4		
Number of Starts Tolerable, Per Year	10 – 20	30 – 60		

Flexibility attribute results for baseload and flexible subcritical (150 MW gross) and supercritical (300 MW gross) PC plants

Staff Spotlight

Josh Redublo*, who joined the Life Cycle Analysis (LCA) Team in May 2021, has advanced work under the Loan Program Office (LPO) Support, 45Q LCA Support and National Institute of Standards and Technology (NIST) LCA Support.

Serving as LPO lead, he manages and 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 greenhouse gas emissions. Josh also assists in reviews of LCAs in 45Q tax credit applications ensuring they conform with International Organization for Standardization (ISO) standards and NETL CO_2 Utilization LCA standards of practice and provide a reasonable estimate of life cycle greenhouse gas emissions. On projects supported by NIST, he produces energy resource life cycle assessment results for use in building sustainability models.

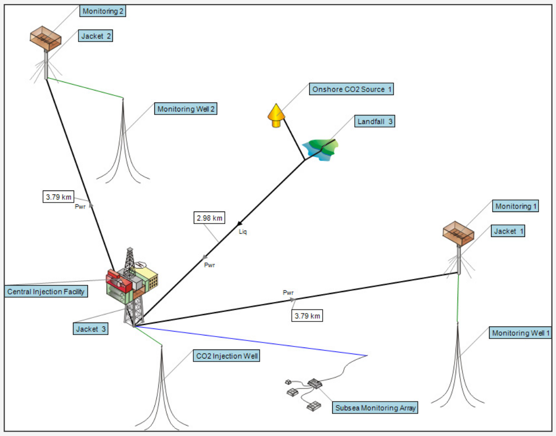
Josh graduated with an M.S. in Engineering from the University of Arkansas, a B.S. in Chemical Engineering from Texas A&M University – Kingsville and a B.S. in Biochemistry from the University of the Philippines. Before joining the LCA Team, he worked as a research engineer at Agricen Sciences advancing sustainable agriculture technology.

* NETL Support Contractor

// NOTICES

Subsurface Resource Analysis Team Explores Project Cost Magnitudes of Offshore CO_2 Storage Using QUE$TOR™

Although the offshore Gulf of Mexico (GoM) offers exceptional opportunities for a large-scale CO_2 storage ecosystem, several challenges remain in deploying the first offshore pilot-scale project in the nation. One of the primary challenges is the current absence of flexible tools to provide confident estimates of project costs. The Subsurface Resource Analysis Team under SSAE's Energy Systems Analysis Team has demonstrated the application of QUE$TOR™ software to estimate offshore CO_2 transport and storage costs. An example configuration produced by QUE$TOR is provided below. QUE$TOR is oil and gas cost estimation software that provides capital and operating costs for the lifecycle of an oil and gas project (from planning through decommissioning). The Subsurface Resource Analysis Team has successfully leveraged and modified QUE$TOR for CCS applications given some infrastructure and cost components unique to a CO_2 storage project lifecycle such as pipelines and platforms amenable to CO_2 transport and storage, implications of re-using existing platform/infrastructure, monitoring infrastructure or approaches (including seismic surveys), CO_2 handling equipment like compressors or pumps and post-injection site care costs. Details on the application and preliminary project cost estimates using QUE$TOR can be found in a presentation that was given at DOE-NETL's 2022 Carbon Management Project Review Meeting in August 2022.



Schematic of an infrastructure configuration in QUE$TOR to model pilot-scale CO_2 storage in Texas state waters in the GoM

SSAE Stakes Claims in USAEE/IAEE Conference

Several SSAE staff showcased their research at the 39th Annual United States Association for Energy Economics (USAEE)/ International Association of Energy Economics (IAEE) Conference in October 2022. The meeting featured presentations focused on the global energy consumption and production trends causing energy price fluctuations and the increase in decarbonization costs causing investors and governments to implement new strategies. Each presenter fielded questions during their session. Interest in certain aspects of projects was indicated. Publication is pending for all presentations. On another note, SSAE researchers Peter Balash and Christopher Nichols currently hold the President and Vice President for Government leadership roles, respectively, on USAEE's council.

- Organized and chaired by Amanda Harker Steele, the "Barriers & Opportunities for CCUS" session showcased barriers and opportunities for large-scale carbon capture, utilization and storage (CCUS) deployment in a net-zero energy future. The four SSAE presentations given during this session discussed drivers for CCUS technology investment: 1) a study that assessed the economic feasibility of offshore CCUS in the GoM was given by Timothy Grant, 2) results from examining CO_2 capture, transport and storage technologies and associated supply chains that will be required to support the U.S. decarbonization goals by 2050 was presented by Jack Suter*, 3) details on the System Cost of Replacement Energy (SCoRE) tool, which can be used to identify the least-cost technology substitution pathway to meet a decarbonization target within a U.S. operating region, was presented by Amanda Harker Steele and 4) the impact of economic, social and governance drivers on growing CCUS investment despite lack of environmental regulation and government financial incentives was given by Connie Zaremsky*.
- A study that investigated the current U.S. hydrogen industry level, potential importance of hydrogen to accelerate a net-zero future and challenges to overcome to make hydrogen an important part of the U.S. energy system was presented by Nadejda Victor* in "The Role of CCUS & Hydrogen in Decarbonization" session. Nadejda also chaired this session, which also featured presentations by other researchers from institutions such as Massachusetts Institute of Technology and the Colorado School of Mines.
- Chaired by Christopher Nichols, "The Infrastructure Investment and Jobs Act – the View from the Inside" session featured panelists from DOE, Center for Houston's Future and the Federal Energy Regulatory Commission. Macroeconomic and regulatory implications of the Infrastructure and Investment Jobs Act on the energy industry were discussed during this session.

NETL Training Explores Building Blocks of LCA Models

In August and September 2022, Matthew Jamieson, Michelle Krynock and Megan Henriksen* led the NETL LCA Team in multiple training sessions on unit process (UP) development including detailed spreadsheet and process documentation UP file formats. Topics included flow naming conventions, data quality indices, calculations and scenarios and data types. The training walked through example UPs "Illinois No. 6 Underground Coal Mine Assembly, Construction" and "Steam Methane Reforming with CCS" and methods for developing a new UP template.

In LCA models, UPs are the smallest pieces for which inputs and outputs are quantified (ISO 14040:2006). UPs are intended to feed into larger systems linking processes together with equations and assumptions and modeled in software like Microsoft Excel and openLCA.

The NETL Unit Process Library contains over 400 publicly available UPs developed over the span of a decade.

// PERSPECTIVES

Case Study Conducted to Evaluate Solvent-Based DAC System

In view of the Biden Administration's goals to achieve a fully decarbonized power sector by 2035 and a net-zero economy by 2050, research and development (R&D) into CCS technology is of vital interest to the country. To aid in the removal of CO_2 in sectors from which the emissions are difficult to abate and to address historical anthropogenic emissions, CO_2 removal (CDR) technologies have become a focal point of R&D in DOE's Office of Fossil Energy and Carbon Management. CDR technologies focus on addressing non-point-source CO_2 emissions through effectively removing CO_2 directly or indirectly from the environment. The capture and storage or conversion of CO_2 directly from the air is commonly referred to as direct air capture (DAC). DAC has been identified as an important tool to meet the Administration's goals; thus, it is a priority for DOE and figures prominently in the Bipartisan Infrastructure Law. In fact, $3.5 billion have been dedicated to the development of regional DAC Hubs that will each capture at least 1 million tonnes of CO_2 from the atmosphere. DOE also established Carbon Negative Shot to reduce the cost of CDR technologies within ten years to $100/net tonne CO_2 removed from the atmosphere and utilized or stored permanently.

In general, there are two categories of DAC contact media, solvents and sorbents. In August 2022, NETL released a report, "Direct Air Capture Case Studies: Sorbent System," that serves as an initial foray into the analysis of DAC systems . A parallel effort was completed to evaluate solvent-based DAC, focusing on the technology best represented by Carbon Engineering (CE) in their 2018 *Joule* paper and related NETL-funded project. The objective was to develop an independent assessment of the performance and cost of a solvent-based DAC system. This assessment also applied reporting standards similar to those used by SSAE's Energy Process Analysis Team (EPAT) in its other reports, including the Fossil Energy Baseline. This is an important feature of the DAC report, because much of the literature information available on the techno-economic evaluation of DAC is limited in detail. Most sub-systems were modeled directly from CE process data; vendor quotes and engineering, procurement and construction industrial experience were used to model the balance of the plant.

The study provides an extensive evaluation of a base case and optional cases to include costs for CO_2 purification and to evaluate the effect of economies of scale. The base case nominally removes 1 million tonnes CO_2/year net from the atmosphere, with CO_2 at 400 ppmv concentration. Because of residual emissions, primarily from the power system, total tonnes of CO_2 removed is higher.

Capital cost estimates were developed with an uncertainty range of +/- 50%, consistent with Association for the Advancement of Cost Engineering (AACE) Class 5 cost estimates (i.e., concept screening). Since DAC systems are an immature technology, the cost estimate methodology presented in this report does not fully account for the unique cost premiums associated with the initial complex integrations of established and emerging technologies in a commercial application. The costs in the report represent neither first-of-a-kind (FOAK) nor nth-of-a-kind (NOAK) costs. Nevertheless, the application of a consistent methodology—and the presentation of detailed equipment specifications and costs based on contemporary sources—facilitate comparison between cases as well as sensitivity analyses to guide R&D and complement the many publicly available estimates characterized by more opaque methods and less detailed sources.

Figure 1 highlights the results of the analysis in terms of COC. Case 1 is the system largely as modeled by CE. Case 1 with CO_2 purification unit (CPU) adds a CPU to Case 1 to have the product CO_2 meet the NETL quality guidelines for CO_2 purity. Case 1A illustrates the economies of scale by scaling the size of the DAC system down to the minimum requirement for 45Q (which was 100,000 tonnes/year net from the atmosphere at the time of the analysis). This report recommends that the DAC Net metric be utilized because it is the true cost for the removal of CO_2 from the atmosphere. COC DAC Net metric is defined as the cost per tonne of CO_2 removed from the atmosphere minus any quantity of CO_2 emitted by the DAC process, including energy for the process.

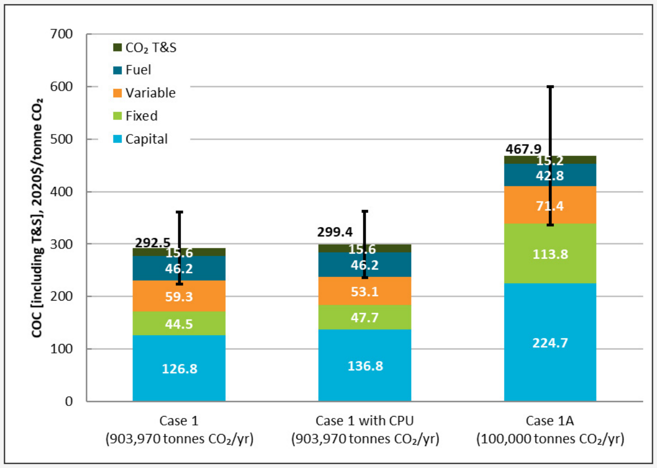


Figure 1. COC including capital cost uncertainty ranges

The report also presents sensitivities for the COC for Case 1. Since the overall system uses natural gas for power production and to calcine the capture material, the system COC is highly sensitive to the cost of natural gas. Other key parameters are the financial assumptions, capacity factor and capital cost. – Contributed by Timothy Fout.

DOE's WaterTAP

Water supply and wastewater management face significant stressors in the 21st century including climate change, aging infrastructure, growing wastewater production and rising awareness of human health and environmental impacts from current water management practices. These stressors have exposed vulnerabilities in securing resilient low-cost water supplies and managing wastewater. Since incremental technological advancements in the preceding decades have not overcome these mounting challenges, there has been growing interest in transforming the 20th century paradigm of a linear water economy

// PERSPECTIVES (cont'd)

to a circular water economy.[1] This radical transformation would shift the water economy from one in which water is extracted from the environment (primarily freshwater), treated and distributed for use with the resulting wastewater treated and discharged to the environment, to an economy where water is repeatably reused with fit-for-purpose treatment locally and its contaminants are recovered as valuable products. However, a circular water economy is not economically viable with current water treatment technologies and will require significant advancements through R&D.

To advance water treatment technologies, DOE has funded the development of the Water Treatment Technoeconomic Assessment Platform (WaterTAP; repository and documentation are downloadable). DOE seeks to use this software tool to provide decision support to some of its water research programs under the Office of Energy Efficiency & Renewable Energy (EERE), where it will be used to help prioritize R&D investment, identify high impact opportunities and set research targets for technologies. The EERE research program that conceptualized WaterTAP and initiated its development is the National Alliance for Water Innovation (NAWI), which is DOE's desalination hub. NAWI began in January 2020 and is a $110 million five-year research program spanning multiple national labs, universities and industry partners that is focused on advancing early-stage desalination technologies. After the first year of development by NAWI, two other EERE research programs chose to fund additional development of WaterTAP to support their objectives. One of these programs is managed by the Advanced Manufacturing Office (AMO) through DOE FOA-0002336, Research and Development for Advanced Water Resource Recovery Systems, which is a $27 million three-year program advancing wastewater resource recovery. The other program is managed by the Solar Energy Technology Office (SETO) through DE-LC-000L088, which is investigating the potential of solar-driven desalination technologies. These programs seek to further develop WaterTAP into a unified, flexible and powerful software tool not only to support their research programs but also to provide the capability to the broader water research community. Figure 2 provides the relationships between WaterTAP, the Institute for the Design of Advanced Energy Systems (IDAES) and DOE water research programs.

NETL SSAE researchers have been leading the development of WaterTAP due to their deep expertise in developing advanced process systems engineering software. Specifically, WaterTAP builds off the NETL-led IDAES Platform, the R&D 100 award-winning process systems engineering tool. WaterTAP's approach and core capabilities are as follows:

- Open-source – all WaterTAP code is publicly available for use, modification and redistribution.
- Modular – WaterTAP is composed of modular water treatment models, supporting users to assemble full treatment trains composed of multiple unit operations.
- Multi-hierarchical – WaterTAP provides models with multiple levels of detail, allowing users to select the appropriate detail for their analysis.
- Customizable – WaterTAP is designed to be customizable, encouraging users to modify standard models or create custom models for their needs.
- Equation oriented and IDAES compatible – WaterTAP is based on Pyomo, an algebraic modeling environment within Python, and the IDAES platform, providing users with a powerful simulation and optimization capability.

Within the past two years, WaterTAP has developed numerous water treatment modeling capabilities. The WaterTAP development team primarily consists of members from four national labs including NETL, Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory and Oak Ridge National Laboratory. This team has added water treatment models spanning broad categories including membrane, evaporative, physical, chemical, biological, ad/absorption and electrochemical-based technologies that range in detail from simple to complex. The team has demonstrated the use of these models by completing detailed technoeconomic assessments of emerging water treatment trains, such as multi-stage high-pressure reverse osmosis and low salt rejection reverse osmosis. The team has also successfully integrated detailed water chemistry predictions for mineral precipitation from OLI Systems commercial software.

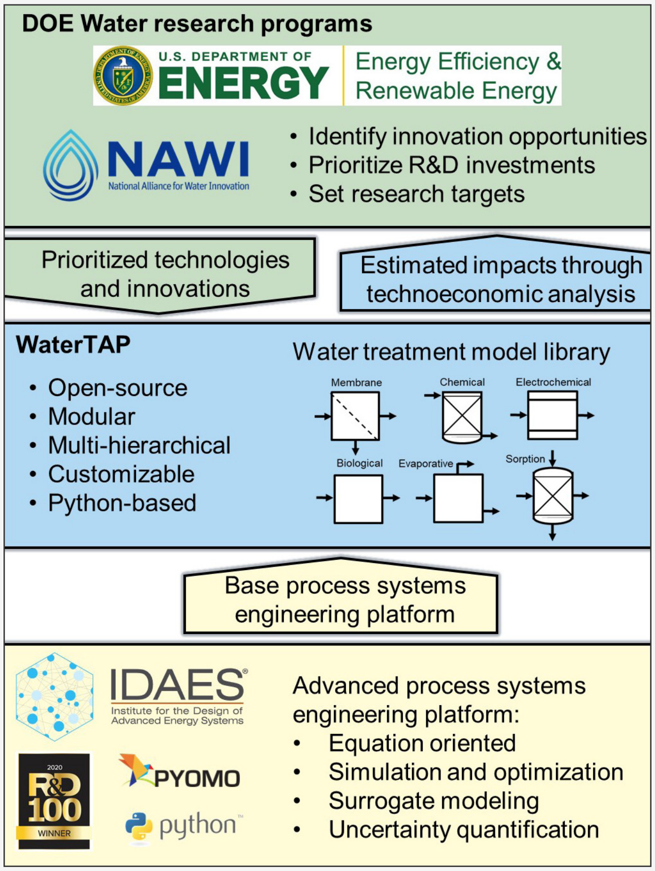


Figure 2. Illustration of the relationships between WaterTAP, IDAES and DOE water research programs

// PERSPECTIVES (cont'd)

WaterTAP development is funded for at least two more years (through fiscal year 2024) across the three EERE programs. In the short term, WaterTAP developers will focus on supporting more water treatment technologies, refining current models and creating publications that demonstrate the novel capabilities of the tool. In the long term, WaterTAP developers will assess opportunities for supporting advanced computational capabilities which could include dynamic modeling, mixed-integer programming, conceptual design, uncertainty quantification, stochastic programming and robust optimization. It is expected that WaterTAP development will continue to be funded beyond fiscal year 2024 through supporting new DOE water research programs and funding opportunity announcements. – Contributed by Timothy Bartholomew

Reference

[1]M. S. Mauter and P. S. Fiske, "Desalination for a circular water economy, "*Energy & Environmental Science*, vol. 13, issue 10, pp. 3180–3184, 2020.

// UPCOMING CONFERENCES AND EVENTS

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

- Ground Water Protection Council Annual Training Meeting
  Participant: Markus Drouven
  Austin, TX, November 2, 2022
- NERC Project 2022-03 Energy Assurance with Energy-Constrained Resources SAR Drafting Team Meeting
  Participant: John Brewer
  Hybrid (Virtual and Atlanta, GA), November 8–10, 2022
- ACLCA 2022 Conference
  Presenters: Joseph Chou* – Life Cycle Analysis of Microwave-Assisted Catalytic Conversion of CO_2 to Value-Added Chemicals; Tyler Davis* – A Next-Generation Toolset for the Life Cycle Analysis of Electricity Use and Sheikh Moni* – Life Cycle Analysis of CO_2-Derived Building Materials: CO_2-Cured Concrete and Building Aggregates
  Participants: Matthew Jamieson and Timothy Skone
  Virtual, November 7 (workshops), 8–11 (conference), 2022
- 2022 American Institute of Chemical Engineers (AIChE) Annual Meeting
  Presenters: Jaffer Ghouse* – 485a Multiscale Optimization of Integrated Energy Systems Using Machine Learning Models for Market Interactions; Ryan Hughes* – 649d Isotherm Modeling and Techno-Economic Optimization of Contactor Technologies for a New Tetraamine-Appended MOF for CO_2 Capture from Ngcc Plants; David Miller – 271a From Mfix to Ccsi to Exa: A Retrospective on the Career of Madhava Syamlal; Sheikh Moni* – 149e Life Cycle Analysis Tools to Determine Environmental Footprint of Carbon Utilization Projects; Naresh Susarla* – 692e Conceptual Design and Analysis of a Power Generator with Integrated Thermal Energy Storage and CO_2 Capture; Radhakrishna Tumbalam Gooty* – 1) 623g Technoeconomic Assessment of Coupling an Existing Nuclear Power Plant with a Low Temperature Electrolysis Unit and 2) 628b Incorporation of Market Signals for the Optimal Design and Operation of a Flexible Post-Combustion Capture System and Maojian Wang* – 692c Technoeconomic Analysis and Optimization of Low Carbon, Reforming-Based Integrated Energy Systems for the Co-Production of Hydrogen and Power
  Session Chair: Radhakrishna Tumbalam Gooty* – 1) Design, Analysis and Optimization of Sustainable Energy Systems and Supply Chains I and 2) Design, Analysis and Optimization of Sustainable Energy Systems and Supply Chains II
  Session Co-Chair: David Miller – 1) Design and Analysis of Sustainable Carbon Capture and Emissions Control Technologies, 2) Design and Optimization of Integrated Energy Systems and 3) Design and Optimization of Integrated Energy Systems II
  Participant: Stephen Zitney
  Phoenix, AZ, November 13–18, 2022
- National Carbon Capture Center Fall/Winter Meeting (Non-public)
  Participants: Timothy Fout, Eric Grol and Gregory Hackett
  Wilsonville, AL, November 15, 2022
- International Centre for Sustainable Carbon's workshop "The Energy Transition – The Role for Sustainable Carbon"
  Presenter: Marc Turner* – Conceptual Design of Pulverized Coal Electricity Generating Units for Flexible Operation
  Hybrid (Virtual and Sardinia, Italy), November 16–18, 2022

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* NETL Support Contractor

// RECENT PUBLICATIONS

Manuscripts

- J. Littlefield, S. Rai and T. J. Skone, "Life Cycle GHG Perspective on U.S. Natural Gas Delivery Pathways," *Environmental Science & Technology*, 2022.
- N. Victor and C. Nichols, "CCUS deployment under the U.S. 45Q tax credit and adaptation by other North American Governments: MARKAL modeling results," *Computers & Industrial Engineering*, vol. 169, article 108269, July 2022.
- C. O. Okoli, R. Parker, Y. Chen, A. Ostace, A. Lee, D. Bhattacharyya, A. Tong, L. T. Biegler, A. P. Burgard and D. C. Miller, "Application of an equation-oriented framework to formulate and estimate parameters of chemical looping reaction models," *AIChE Journal*, vol. 68, issue 10, e17796, October 2022.
- A. J. Harker Steele and J. C. Bergstrom, "Why is it still too warm or cold in my house? Examining the relationships between energy efficient capital and household energy insecurity," *Energy Research & Social Science*, vol. 93, article 102827, November 2022.

Models/Tools/Databases

- National Energy Technology Laboratory, "SubPC Baseline LCA Detailed Results," National Energy Technology Laboratory, Pittsburgh, PA, April 13, 2018.

Reports/Supporting Documentation

- R. A. Newby and D. L. Keairns, "Chemical Looping Combustion Sensitivity Analyses: CLOU Concepts," National Energy Technology Laboratory, DOE/NETL-2018/1879, Morgantown, WV, February 9, 2018.
- T. J. Skone, G. Schivley, M. Jamieson, J. Marriott, G. Cooney, J. Littlefield, M. Mutchek, M. Krynock and C. Shih, "Life Cycle Analysis: Sub-Critical Pulverized Coal (SubPC) Power Plants," National Energy Technology Laboratory, DOE/NETL-2018/1888, Pittsburgh, PA, April 13, 2018.
- R. A. Newby and D. L. Keairns, "NETL Gen-2 Oxygen Carrier Assessment," National Energy Technology Laboratory, DOE/NETL-2019/2082, Morgantown, WV, June 21, 2019.
- S. C. Uysal, "Comparative Study for Pressure Gain Combustion-Gas Turbine System Performance in NGCC Configurations," National Energy Technology Laboratory, DOE/NETL-2021/2644, Morgantown, WV, January 21, 2021.
- M. Turner, S. Pidaparti and E. Grol, "Advanced Water-Related Technology Performance Development," National Energy Technology Laboratory, DOE/NETL-2021/2755, Pittsburgh, PA, March 3, 2021.
- C. Able, " Techno-Economic Analysis of Chemical Precipitation Followed by Low Hydraulic Residence Time Biological Treatment, Including Ultrafiltration," National Energy Technology Laboratory, DOE/NETL-2021/2874, Pittsburgh, PA, March 5, 2021.
- S. Leptinsky and M. Turner, "Quality Guidelines for Energy System Studies – Capital Cost Scaling Methodology: Revision 4a Report," National Energy Technology Laboratory, DOE/NETL 2022/3340, Pittsburgh, PA, October 14, 2022.
- T. Schmitt, S. Leptinsky, M. Turner, A. Zoelle, M. Woods, T. Shultz and R. James, "Cost And Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 4A," National Energy Technology Laboratory, DOE/NETL 2023/4320, Pittsburgh, PA, October 14, 2022.
- J. Valentine and A. Zoelle, "Direct Air Capture Case Studies: Solvent System," National Energy Technology Laboratory, DOE/NETL 2021/2864, August 31, 2022.

Conference Proceedings and Events

- E. Grol, " NETL Crosscutting Program Research Guidance – Condensers and Wastewater Treatment Projects," paper presented at the 2019 Annual Project Review Meeting for Crosscutting, Rare Earth Elements, Gasification and Transformative Power, Pittsburgh, PA, April 9–11, 2019.
- S. C. Uysal, D. Straub and J. Black, "Impact on Cycle Efficiency of Small CHP Plants from Increasing Firing Temperature Enabled by AM of Turbine Blades – GT2021-58718," presentation at the ASME 2021 Turbo Expo, Virtual, June 7–11, 2021.
- S. Pidaparti, "Impact of Plant Siting on Performance and Economics of Indirect Supercritical CO_2 Coal Fired Power Plants – GT2021-58867," presentation at the ASME 2021 Turbo Expo, Virtual, June 7–11, 2021.
- T. J. Skone, "U.S. DOE/NETL LCA of LNG: Overview & Key (LCA) Challenges," presentation at the LNGnet Special Working Group 2 Meeting, Virtual, July 1, 2021.
- T. J. Skone and S. Rai, "NETL's Upstream Natural Gas LCA Modeling," presentation to the European Commission, Virtual, January 20, 2022.
- Z. Wu, H. Zhai, E. J. Grol, C. M. Able and N. S. Siefert, "A Technical-Economic Assessment of Brackish Water Treatment for Fossil Power

// RECENT PUBLICATIONS cont'd

Plant Cooling with Reduced Environmental Impact," presentation at the 18th Annual Rocky Mountain Section of the American Water Works Association (RMSAWWA)/Rocky Mountain Water Environment Association (RMWEA) Student Conference, Albuquerque, NM, May 16, 2022.

- S. E. Zitney, D. Bhattacharyya, F. V. Lima and Y. Tian, "Science-informed Virtual Digital Twin for an Integrated Energy System with Carbon Capture: Research, Training, and Education," presentation at the 2022 Advanced Manufacturing and Processing Conference, Bethesda, MD, June 1–3, 2022.
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// REFERENCE SECTION

Models / Tools / Databases

Carbon Capture Simulation Initiative (CCSI) Toolset

FECM/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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CCSI[2] webpage

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