Business & Technology Surveillance

# Carbon Capture: Which Post-Combustion Technology Could Meet a Co-op's Needs

By Alice Clamp

APRIL 2021

NRECA
America's Electric Cooperatives

Business & Technology Surveillance

# Carbon Capture: Which Post-Combustion Technology Could Meet a Co-op's Needs

By Alice Clamp

## APRIL 2021


**SUBJECT MATTER EXPERT ON THIS TOPIC**

**Dan Walsh**
Senior Director, Power Supply and Generation: **Daniel.Walsh@nreca.coop**

**Will Morris Ph.D.**
Consultant to NRECA, President and Technical Director of Carbon Management Strategies LLC
Contracted Program Director, Wyoming Integrated Test Center: **Will.Morris-contractor@nreca.coop**


This article is a product of the **Generation, Environment, and Carbon Work Group**.

## ARTICLE SNAPSHOT


### WHAT HAS CHANGED?

The number of projects based on various carbon capture (CC) technologies is growing significantly. Many of these technologies are being applied to fossil fuel-fired power plants. In addition, industrial sector sources, such as cement and steel manufacturing, are the subject of demonstrations for the first time.

### WHAT IS THE IMPACT ON CO-OPS?

For cooperatives, assessing these technologies—given the number and varying types of projects—can be a challenge. Moreover, co-ops may have industrial customers that might require the addition of power-intensive carbon capture technologies.

Because no two generating plants are exactly the same, co-ops need to learn about the robustness of CC technologies, as well as how to handle challenges associated with these technologies. Cross-cutting areas of interest may include particulate-laden gas, high oxygen concentrations, high flue gas temperatures, or other process considerations that require innovation for deployments in other industries. Being aware of CC deployments across industries will help co-ops assess potential strengths and weaknesses associated with various technologies.

### WHAT DO CO-OPS NEED TO KNOW?

An overview of carbon capture technologies—both current and emerging—and the projects based on them can help co-ops decide which technologies to learn more about and which may be best suited for their particular needs.



NRECA
America's Electric Cooperatives

## Introduction

Interest in technologies associated with carbon capture has been growing rapidly in both the public and private sectors in recent years, as government and industry grapple with how to move cost effectively to a low-carbon future.

As more and more carbon capture technologies are developed, the question arises: *Which show the most promise – and for which applications?*

Through its National Energy Technology Laboratory (NETL), the U.S. Department of Energy (DOE) is supporting the testing of a wide range of these technologies. DOE has divided its carbon capture program into three main areas:

- Post-combustion capture
- Pre-combustion capture
- Oxy-fuel combustion

This article — the first of two — focuses on **post-combustion capture** (PCC), which is the capture of carbon dioxide from a fossil-fueled plant's post-combustion flue gas before it is released into the air. This is the technology class most likely to be retrofitted at the nation's existing fossil fuel-fired power plants. For this reason, PCC technologies are also the primary focus of DOE's carbon capture program.

The focus near-term should be on post-combustion capture for co-ops looking to maintain the operation of existing assets.

**Pre-combustion capture** has been historically associated with gasification, a process that produces syngas — a mixture consisting primarily of carbon monoxide, hydrogen, carbon dioxide, natural gas and water vapor — from coal and water, air and/or oxygen. However, both the level of interest and funding have declined over the past decade. DOE is currently funding approximately 10 active projects.

**Oxy-fuel combustion**, which was examined as a retrofit possibility approximately 10 years ago, has evolved to show its true advantages with new builds, such as NET Power — which operates an oxy-combustion, zero emissions 50-MW natural gas power plant — and pressurized oxy-combustion technologies being developed by the University of Wyoming, Southwest Research Institute, and Washington University. However, this is a new concept that has not been demonstrated at commercial scale.

Thus, for co-ops looking to maintain the operation of existing assets in a carbon constrained world, the focus in the near-term should be post-combustion capture. The second article will discuss uses and storage of captured carbon dioxide.

### COSTS

At present, there is no reliable cost data for the various carbon capture technologies, because none has been deployed on a widespread commercial scale. Techno-economic analyses conducted by project sponsors will provide more information on cost. Moreover, the cost of a given technology will be influenced by plant-specific circumstances. DOE has set a goal of $40 per metric ton of captured $CO_2$ by 2030, with a range of $35 to $45 per metric ton. See **Appendix A** for a discussion of oxy-fuel discussion.

## Post-Combustion Basics: Technology Types

Fundamentally, $CO_2$ capture is simply a gas separation process. There are four primary mechanisms that can be used to separate gases in the context of $CO_2$ capture: absorption, adsorption, diffusion, and phase change.

Each of these mechanisms has potential advantages and disadvantages for given applications, so it is important to consider these factors when examining the applicability of $CO_2$ capture technologies for a given generating unit. For this reason, no single technology is "best." Rather, there will be multiple technical solutions, and it will be up to the engineering team to determine the most suitable technology for the generating unit in the context of the overall generation assets, local site conditions, permitting constraints, and environmental considerations.

### ABSORPTION

For many, absorption is the most familiar mechanism for achieving carbon capture. It involves dissolving a gas in a liquid solvent at a given temperature and pressure. The gas can then be liberated by a change in temperature and/or pressure. The most common absorption mechanism involves dissolving $CO_2$ in an amine-based solvent. This type of carbon capture system has been used in the natural gas processing industry for approximately a century.

Currently, there are two commercial-scale demonstrations of the technology: Sask Power's Boundary Dam Unit 3 and Mitsubishi Heavy Industries' system at the Petra Nova project at NRG's Parish Station outside Houston, Texas (see Figure 1).

Both systems use a proprietary amine-based solvent that strips the $CO_2$ from the flue gas. This carbon dioxide-rich solvent is then pumped through a heat exchanger to cool the $CO_2$-lean solvent and preheat the $CO_2$-rich solvent before it enters the stripper or regenerator. Then, steam is used to heat and boil the solvent, which releases a high-purity $CO_2$ product.

Both projects use this produced $CO_2$ for enhanced oil recovery (EOR) operations when market conditions are favorable. "Having been in the control room at Petra Nova, I was struck by the fact that the system did not seem out of place at a power plant," said Dr. William (Will) Morris, consultant to NRECA. He has a PhD in chemical engineering and has been involved with carbon capture technologies for the past 15 years.

**FIGURE 1: Commercial Demonstration of Absorption Technology at Petra Nova Project** (Source: NRECA)

"While there is often a perception of solvent capture systems as complex chemical plants, I think with proper training, operation of these systems is well within the capabilities of power plant operators," he added. "However, I do understand the reticence associated with the cost."

Because the solvent systems are the most mature, they are also the only systems that are currently operating at existing coal-fired power plants at commercial demonstration scale. But these systems are not without tradeoffs, just like any other technology.

- Absorption Advantages:
  - Has the potential to capture 95%+ of $CO_2$.
  - Is the most mature technology.
  - Could be commercially procured today.
  - Greatest number of available vendors.
  - Excellent $CO_2$ product for EOR, storage, or utilization.

  While there are many considerations and tradeoffs with using absorption and solvent-based systems, there are some very distinct process advantages that extend beyond process maturity. Perhaps the most potentially significant advantage is that solvent systems may be able to exceed 90% capture rates, and solvent systems readily produce EOR-specification $CO_2$ product gases requiring no additional treatment. This aspect of their operation lends itself to very deep decarbonization, should it be required. In addition, it can have a pipeline-ready $CO_2$ product for both deep saline storage and EOR opportunities for revenue recovery.

- Absorption Disadvantages:
  - Potentially increases water demand significantly.
  - Solvent degradation issues and potentially hazardous waste.
  - Perceived as a chemical plant rather than emissions control (in reality not a lot more challenging than wet scrubber —Flue Gas Desulfurization (FGD)).
  - Requires integration with plant's steam system for optimum efficiency.
  - Parasitic loads and costs.

Sorbents have unique advantages including very narrow temperature swings to reduce energy penalty and high absorption capacities.

### Steam System

Solvent-based systems that are at the point of being commercially available, or at least in large pilot planning, all use steam to regenerate the solvent. This means that either the current steam cycle of the host site has to be modified, as in the case of the Boundary Dam project, or separate cogeneration or similar steam source must be procured in order to provide steam for the capture system, as was the case for Petra Nova.

### Capture System Integration

Depending on the potential to trigger New Source Review (NSR), disruption of turbine warranty or various other factors, a plant and its management may determine that integration of the capture system with the plant's steam cycle is not worth the benefits of optimizing overall cost or efficiency. For this reason, selecting the technology as well as a potential vendor requires a careful analysis of external factors, from permitting to warranty to maintenance planning, to determine the most beneficial technology and plant integration.

### Water Use

In addition to the integration constraints, the current generation of absorption systems using amine-based solvent technology also requires significant water usage. The water use comes in multiple operations. The first is that water will be needed to cool the incoming flue gas to an appropriate absorption temperature, which is typically around 104°F/40°C. This creates a very significant cooling load for the plant, which may or may not have additional cooling water available.

### Sulfur Dioxide Scrubber

In addition, the capture system will also require the use of a polishing $SO_2$ scrubber to reduce $SO_2$ concentrations to approximately 1 ppmv (parts per million by volume) in order to reduce the amount of heat-stable salt formation to an acceptable operational level. Otherwise, the solvent will be poisoned by the $SO_2$-forming heat-stable salts that cannot be broken down in the regenerator, leading to a loss of system performance and increased maintenance costs. In addition to its existing desulfurization unit, an operating plant will also require a polishing scrubber downstream from the scrubbers.

### Makeup Water

Also, during the solvent regeneration process, some water will be boiled off and recovered. This water dilutes the amine-based solvent to achieve acceptable viscosity and corrosion characteristics. Thus, additional water of high purity must be reintroduced as makeup water for the system.

## ADSORPTION

Adsorption uses a solid adsorbent to chemically or physically bind a gas particle to its surface. Most often referred to as solid sorbents, these materials use *chemisorption* or *physisorption* to bind with the target gas species. The gas can be released by changing temperature and/or pressure.

In chemisorption, the gas chemically bonds to the surface of the adsorbent material. Many sorbents use amine chemistry similar to the solvent systems to chemically bond $CO_2$ to the surface of the sorbent in an adsorber reactor. In physisorption, the target gas and the sorbent do not chemically bind, but rather stick together using Van der Waals forces.

The benefit of chemisorption is that sorption can often be more selective. That is, the ratio of $CO_2$ or the target gas to other components in the flue gas is higher. This provides a $CO_2$ product of higher concentration or purity. The advantage of physisorption is that the heat of reaction, or energy required to release the $CO_2$ in the regeneration reactor, is typically lower, leading to a reduced energy penalty of the capture system.

- Adsorption Advantages:
  - Potential for exciting novel materials such as metal organic frameworks (MOFs) with high $CO_2$ adsorption capacity.
  - Potential for reduced water usage.
  - Potential for reduced hazardous waste.

  Sorbents have some unique advantages, including the ability of MOFs to provide very narrow temperature swings between adsorption and regeneration to reduce the energy penalty. It also has very high adsorption capacities, making these materials of interest.

< PREVIOUS VIEW >

As an example, The Long Group from University of California Berkeley (under Dr. Jeffrey Long) and its Mosaic Materials spin-out company (as the licensee of the technology) have managed to produce sorbents that have up to several multiples greater adsorption of $CO_2$ than historic solvents, such as monoethylamine (MEA). "Some of the sorbents that I have had the opportunity to work with over the years are truly amazing materials," said Dr. Morris. "With time, I think there is a potential to develop novel processes that can take advantage of these very compelling material properties. However, I think the process design may need to be just as innovative in order to maximize the potential of solid sorbents for large-scale $CO_2$ capture," he said.

### Major Challenges

The challenge with using such high-performance materials is the ability to effectively build a functional process around the material at a suitable scale for power generation applications. While some sorbents may have issues with high humidity gases and, therefore, not be suitable for $CO_2$ capture applications from fossil fuel-fired generation plants, there are three fundamental challenges with using any sorbent in a post-combustion capture application. The challenges are pressure drop, heat transfer, and mass transfer.

The challenge with using high-performance materals is the ability to effectively build a functional process around the material at a suitable scale for power generation applications.

#### *Pressure Drop*

Pressure drop results from sorbent media being packaged in fixed or packed beds, fluidized beds, or even moving beds. Flue gas has to be driven through or past the sorbent media in order for the sorbent to strip the $CO_2$ from the flue gas. This creates pressure drop and increases the fan requirements to provide sufficient flue gas pressure to move the flue gas through the reactor vessels. This can be especially severe in fluidized bed applications where sufficient gas velocity is necessary to fluidize the sorbent particles.

#### *Heat Transfer*

The next issue is heat transfer. When the $CO_2$ reacts with the sorbent material, the reaction is exothermic and heat is released. In order to maintain continued $CO_2$ adsorption, that heat must be removed from the reactor. Unfortunately, packed beds have difficult heat transfer characteristics, because they are based largely on conductive rather than convective heat transfer. Conductive heat tends to be faster, but this comes at the expense of increased pressure drop.

#### *Mass Transfer*

The final issue is mass transfer. As the $CO_2$ migrates past sorbent, less $CO_2$ is available for adsorption by subsequent sorbent. Flow must be very even across the sorbent media, or else channeling or other phenomena will occur, which reduces overall effectiveness of the sorbent. Fundamentally, heat and mass transfer are both similar transport phenomena governed by very similar equations. They must be optimized for the scale of the system being constructed, which will require a significant level of study for each application.

- Adsorption Disadvantages:
  - Significant scaling issues around sorbent contactors to manage heat and mass transfer have yet to be completely resolved.
  - Product purity is typically not equivalent to amine solvents.
  - Temperature swing process will still need steam cycle integration with host plant.
  - Parasitic losses and costs.

### Steam Source

Many sorbents are used in a temperature swing process similar to solvent systems. This requires a source of steam, which must either be derived from the host plant or provided by a separate steam generating source, such as a cogeneration unit like that used in the Petra Nova project. Providing steam from the host site may not always be feasible, even though it provides the best opportunity for process integration and enhanced efficiency.

### Cooling Water

In addition to steam, temperature swing processes, like amine solvent processes, will require substantial amounts of cooling water. If the sorbent is a supported amine-based sorbent, then the sorbent will require a polishing $SO_2$ scrubber to prevent the formation of heat stable salts, just as with solvent systems.

Solid adsorbents suggest significant promise and exciting features, but further research is needed.

Membranes are most economical and efficient on higher concentration $CO_2$ flue gas sources and at capture rates of 70% or higher.

### Vacuum Swing

Adsorption systems can also be operated as a vacuum swing adsorption, where the gas is introduced at a higher pressure than ambient and then the sorbent is regenerated by being placed under vacuum. This reduces or eliminates steam consumption, but requires significant electrical loads to operate large booster fans and vacuum pumps.

### Temperature/Pressure Swing

There is also a possibility of hybrid adsorption systems that will use a combination of temperature and pressure swing. An example is the sorbent capture system being designed by Kawasaki Heavy Industries (KHI), which will operate at a very narrow temperature swing with the potential of using waste heat at 140° F/ 60° C or lower to regenerate the sorbent. KHI will commence construction of a 100 kWe-scale unit at the **Wyoming Integrated Test Center** in late 2021, to test the long-term performance of the sorbent in this process arrangement.

### Sensible Heat

Sensible heat is easily exchanged in solvents that may be pumped through a cross heat exchanger. Transferring sensible heat of sorbent materials is much more difficult, as it will be dominated by conduction rather than convection, which means that heat integration and reduction of energy penalties will be more challenging.

In summary, solid adsorbents suggest significant promise and exciting features, but further research is necessary to allow the materials to function in a well-optimized process.

## DIFFUSION

Diffusion uses a difference in partial pressure of gas to force the targeted species through a porous media, such as a membrane. By using a combination of pressure increase on flue gas and vacuum on the permeate side of a membrane, $CO_2$ can diffuse through a membrane while the bulk of the flue gas is sent to the stack.

Manufacturing membranes is a very complicated process to ensure consistent porosity across large sheets of membrane material. Significant art exists among membrane manufacturers to provide the necessary materials for gas separation systems. While the manufacture and production of a membrane requires a high degree of skill, one of the advantages of membranes is that they are very simple devices from an operational perspective.

Membrane separation or capture systems require a booster fan and a vacuum pump, which are standard rotating equipment. However, the separation occurs across the non-reacting membrane material that is packaged in modules that do not have to be moved between reaction vessels. Membrane-based systems do not consist of any moving parts aside from blowers and vacuum pumps, a fact that can provide a degree of comfort to power plant operators accustomed to similar pieces of equipment.

"I like the elegant simplicity of these systems, and am very interested to see how future membranes can improve overall system performance," said Dr. Morris. "The systems are relatively easy to retrofit, which is a definite advantage in the technology space," he noted.

However, the driving force across the membrane is the difference in partial pressure of $CO_2$. This means that the $CO_2$ product must be at a lower partial pressure than the $CO_2$ in the flue gas. As a result, membranes are most economical and efficient on higher concentration $CO_2$ flue gas sources, such as coal, and at capture rates of 70% or lower.

### Membrane Advantages and Disadvantages

- Advantages:
  - Can be retrofitted into plants without disturbing steam cycle.
  - Use membranes and rotating equipment, such as blowers and pumps, which are familiar to plant operators.
  - Potential to produce water as well as $CO_2$ product.
- Disadvantages:
  - Current membranes do not produce EOR quality $CO_2$ product without further purification, but potential exists for new membranes to do so.
  - Most cost effective for partial capture (~60-70%) of $CO_2$, which may not be suitable for all applications. However, new membranes may improve performance.

- With current membrane technology, costs for capture rates of 90% are significantly higher than those for capture rates of 70%, due to greater blower and vacuum pump requirements.
- Parasitic loads and costs.

### Capture Rates

Higher rates of capture are possible, but not necessarily the most economical. As membrane materials improve by improving both permeability and selectivity, the performance at higher capture rates is likely to improve. An example of this is a membrane developed at the Ohio State University to be used in a project with the Gas Technology Institute at the Wyoming Integrated Test Center.

### Purification

To meet purity specifications for EOR, current membrane diffusion systems also require an additional purification step for $CO_2$ after being initially concentrated by the membrane. This purification step requires additional energy input, as well as capital cost. However, much of the equipment associated with these types of processes is already commercialized.

### System Requirements

These systems only require electrical power and do not require steam, which makes retrofit to existing plants substantially easier than temperature swing processes that require disruption of the existing steam cycle or a separate steam generating facility.

### Amount of Water

Finally, some membranes permeate significant amounts of water, leading to a process that has the potential to be net water neutral under certain design constraints.

## PHASE CHANGE

A final method of separating gases is to condense or freeze a particular species, so that it may be easily removed from the gas stream. The idea is to cause the phase of a particular species, in this case $CO_2$, to phase-change separately from the bulk flue gas constituents.

In flue gas, $CO_2$ has a much higher freezing point than nitrogen and oxygen. For this reason, the gas can be cooled to the point where $CO_2$ solidifies, creating the opportunity to separate solid from liquid. This is much more straightforward than separating individual gas species from a mixed gas stream.

While this sounds very energy-intensive, much of the heat can be recovered, and the primary irrecoverable heat loss is the latent heat of $CO_2$ itself. As a result, this approach to $CO_2$ capture can be economical.

Sustainable Energy Solutions pioneered this type of $CO_2$ capture. To date, the system has been transported to various industrial sources, such as a coal-fired power plant as well as a cement plant. The operating rate was 1 metric ton of $CO_2$ captured per day.

One of the biggest challenges for the phase change method is that it is so novel and innovative that some key pieces of equipment will have to be custom built.

"At first, I was highly skeptical of the process and the energy penalty associated with this approach," said Dr. Morris. But, he added, this is fundamentally a refrigeration cycle and can integrate substantial heat recovery to deliver a surprisingly efficient process. One of the biggest challenges is that the concept was so novel and innovative that some key pieces of equipment will have to be custom built. "If some of these equipment issues are resolved and appropriately scaled, this has the potential to be a very exciting approach to carbon capture," said Dr. Morris.

The technology has the advantage of being able to integrate $SO_2$, $NO_x$ and mercury control to reduce overall emissions and control costs as well. However, the technology has yet to be scaled to a pilot stage, so it will likely not be available until further in the future than the other options.

- Advantages:
  - Potentially easier retrofit.
  - No chemicals.
  - Possibility of integrating NOX and $SO_2$ (multi-pollutant) control.
- Disadvantages:
  - Low current technology readiness level (TRI).
  - Equipment challenges.
  - The least studied separation method to date.
  - Parasitic loads and costs.

< PREVIOUS VIEW >

## DOE Funding Activities

Much of the DOE funded testing takes place at DOE's National Carbon Capture Center (NCCC) in Alabama, which provides technology developers with a state-of-the-art independent test facility. New technologies move from laboratory to bench scale and through small pilot testing at the facility. The aim is to accelerate the commercialization of the most promising advanced carbon capture technologies.

The NCCC has the flexibility for multiple and simultaneous slipstream testing of bench- and pilot-scale advanced carbon capture technologies from diverse fuel sources at commercially relevant process conditions. The technology testing at the NCCC, which includes modeling and simulation, enables evaluation of the efficiency, environmental performance, and economic viability of fossil fuel power generation processes with $CO_2$ capture.

In May 2020, DOE's NETL issued its ***Compendium of Carbon Capture Technology***, which provides summaries of the agency's R&D program in two areas: post-combustion and pre-combustion capture.

In the post-combustion area, DOE has listed completed and active projects focused on solvents, sorbents and membranes.

### POST-COMBUSTION PROJECTS

The DOE 2020 Compendium lists 21 completed post-combustion projects, all using solvent technology, and 27 active projects using various technologies. Summaries of some of these projects are given below.

#### Completed Projects Using Solvent Technologies

**Among the completed projects** is GE Global Research's large pilot-scale—10 MWe—project using a novel aminosilicone-based solvent to minimize and quantify the risks associated with technical success, cost and schedule. A 100-kg solvent sample was tested on the bench scale, meeting purity and performance specifications. The information from this Phase I project can be used to inform the experimental design, budget and schedule for a Phase II pilot test project.

The techno-economic analysis indicated a $CO_2$ removal cost using the steam stripper for desorption as $42 per metric ton of carbon dioxide (entitlement) and $48/t$CO_2$ (with degradation, at ~15 %/year solvent makeup). The $CO_2$ removal cost using the continuous stirred tank reactor desorber was higher, with the cost dominated by the solvent makeup costs. Due to a schedule slip in the testing at the NCCC because of a predecessor project, GE decided not to submit a Phase II application.

Details of the project are available in DOE's 2020 Compendium.

Another project is a three-phase large pilot test of an advanced amine-based post-combustion technology developed by Linde/BASF. The University of Illinois evaluated the design, construction and operation of a 10-MWe post-combustion capture system at a coal-fired power plant. Phase I of this project, completed in 2014, consisted of a feasibility study that outlined preliminary engineering designs, conducted preliminary analysis of the National Environmental Policy Act (NEPA) and selected a host site for Phases II and III—the CWLP coal-fired plant in Springfield, Illinois. These phases are discussed in the next section, which covers active projects.

#### Active Projects Using Solvent Technologies

Phase II of the Lide/BASF project, consisting of a detailed front-end engineering design (FEED) study, NEPA permitting and documentation, and cost-share commitments, is underway. Phase III, which will support construction and operation of the large-scale pilot facility, has not yet been funded.

Among other **active solvent projects** is ION Clean Energy, Inc.'s engineering-scale demonstration of its low-cost ICF-31 solvent with enhanced stability technology. The solvent will be tested on a flue gas slipstream at Los Medanos Energy Center, a commercially dispatched natural gas combined cycle power plant in Pittsburgh, Calif.

The project team will design, build and operate an engineering-scale pilot system that will capture 10 metric tons of carbon dioxide per day.

The project has been awarded nearly $17 million in funding, with DOE providing $13 million. Non-DOE funding accounts for nearly $7 million.

**Active solvent projects** also include those by SRI International and Research Triangle Institute.

- **SRI International** is developing a novel water-lean mixed salt-based transformational solvent to provide a step-change reduction in the cost and energy penalties of post-combustion carbon dioxide capture. The project team conducted VLE (vapor liquid equilibrium) measurements of various $CO_2$ loading levels and compositions for the regenerator side and is conducting lab-scale absorber tests to investigate reaction kinetics and $CO_2$ absorption capacity.

  According to DOE's Compendium, SRI completed the refurbishment of the existing absorber bench-scale unit and has performed parametric testing in the unit with simulated flue gas to determine the rate of $CO_2$ absorption in the mixed salt process (A-MSP) solutions as a function of temperature, gas flow rate, solution composition, $CO_2$ loading, and liquid/gas ratio. Oxidative and thermal degradation studies, integrated absorption/desorption testing, further development of the process flowsheet model, and a TEA [techno-economic analyses] will be completed in the next budget period.

- **Research Triangle Institute (RTI)** will develop a comprehensive solvent emission mitigation tool set for reducing the solvent and aerosol emissions from carbon dioxide capture systems using water-lean solvents (WLSs). Due to their low energy requirement for solvent regeneration, lower regeneration temperature, low corrosivity and low vapor pressure, WLS systems are rapidly being developed for $CO_2$ capture. RTI's tool set is specifically designed for WLS systems, implementing an advanced organic solvent wash system in conjunction with water wash, acid wash, and other commercially available, state-of-the-art emission reduction technologies.

  According to DOE's Compendium, under development are various components of the prototype emissions control system for using water-lean solvents for $CO_2$ capture. Solvent degradation testing systems were constructed to determine the oxidative degradation and chemical pathways for the formation of nitrosamines (NA) and amine component thermal degradation products. Various solid adsorbents were tested for their amine absorption capacity and ability to regenerate to identify potential sorbent candidates to be used for the amine recovery unit.

  RTI has developed a Principle Component Analysis (PCA) framework for an empirical model to predict aerosol-based emissions using RTI's bench-scale gas absorbent system. This model correlates the process parameters of a water-lean solvent $CO_2$ capture system that is based on bench-scale absorption testing system (BsGAS) testing of a water-lean solvent.

### Active Projects Using Sorbent Technologies

The Compendium lists 13 completed solvent technology project and 12 active projects.

**The most recently completed** sorbent technology project, according to the compendium, is a novel solid sorbent.

SRI International tested its process for post-combustion $CO_2$ capture on the bench-scale using its novel carbon sorbent. The technology is based on the sorbent developed in a previously funded DOE project. This novel sorbent, manufactured by ATMI, Inc., is composed of carbon microbeads. These microbeads show excellent $CO_2$ capacity and selectivity, fast adsorption/desorption kinetics, and good resistance to agglomeration and attrition, allowing for reductions in both capital and operating expenses. Reduced steam regeneration requirements in the process can reduce the parasitic power load.

SRI International operated a bench-scale test unit for post-combustion carbon dioxide capture to demonstrate its process using a novel low-cost, low-energy and high-capacity carbon sorbent in a single column integrating both the absorber and desorber. SRI also designed a 0.5-MWe pilot-scale test unit.

Details of the project are available in DOE's 2020 Compendium.

Among the 12 **active sorbent projects** is TDA Research, Inc.'s amine-functionalized resin sorbent for use in coal-fired power plants. TDA has developed a low-cost, high-capacity carbon dioxide adsorbent to demonstrate its technical and economic viability through sorbent evaluation and optimization, development of sorbent production techniques, and bench-scale testing of the process.

TDA developed a low-cost, high-capacity carbon dioxide ($CO_2$) adsorbent to demonstrate its technical and economic viability through sorbent evaluation and optimization, development of sorbent production techniques, and bench-scale testing of the process, using actual flue gas.

The company is designing, building, and operating a slipstream 0.5-MWe pilot-scale process for carbon capture using its low-cost alkalized alumina sorbent to conduct parametric and long-term steady-state testing. The aim is to demonstrate the effectiveness of the technology to reduce the cost of $CO_2$ capture and to develop scale-up conditions for the process.

Details of the project are available in DOE's 2020 Compendium.

According to DOE's Compendium, TDA Research, Inc. has designed and built the 0.5-MWe-scale pilot plant test unit and produced the sorbent needed for testing. The skid has been installed at the NCCC, to be followed by 1.5 months of parametric testing and 2 months of steady-state testing using a flue gas slipstream.

### Active Projects Using Membrane Technologies

The Compendium lists three completed membrane projects and 11 active projects.

**Among the completed projects** is Membrane Technology & Research, Inc.'s (MTR) low-pressure membrane contactors.

MTR is developing a new type of membrane contactor (or mega-module) to decrease capture costs, energy use and system footprint through bench-scale testing of a module with a membrane area that is 100 $m^2$, five times larger than that of current modules used for carbon dioxide capture.

Details of the project are available in DOE's 2020 Compendium.

According to DOE's Compendium, a 500-$m^2$ sweep membrane module skid was designed and fabricated for field testing. A pressure vessel with five 100-$m^2$ membrane modules can be run individually or as a group. The skid was designed for integration into the existing MTR 20-tpd $CO_2$ capture pilot test unit for testing at NCCC in Wilsonville, Ala.

A detailed performance and economic analysis of the MTR membrane $CO_2$ capture process with low-pressure sweep modules was performed. The methodology used by MTR to evaluate the membrane process is consistent with Case 10 of the 2010 DOE report. Econamine was used to capture 90% of the flue gas $CO_2$. The "all membrane" case demonstrates savings over the Econamine $CO_2$ capture process, but the cost is still higher than the DOE target of $40/metric ton.

**Another active membrane project** is a Gas Technology Institute (GTI) project to test a new hybrid carbon capture membrane. The membrane, developed by Ohio State University, consists of three layers and will improve two desirable membrane features: selectivity and permeability. Small pilot-scale testing at the Wyoming Integrated Test Center is expected to begin in late 2022 or 2023, after GTI has built, permitted, installed and commissioned the system.

The goal of testing—which will be conducted for a minimum of 2 months—is to demonstrate that the membrane process meets DOE's performance goal for carbon-capture technologies: a 90% capture rate with 95% purity at a cost of no more than $40 per metric ton of capture.

To test a new hybrid member process, the Gas Technology Institute has received total project funding of $16 million. DOE awarded GTI $13 million, with non-federal funding providing an additional $3.2 million.

Details of the project are available in DOE's 2020 Compendium. In addition, NRECA issued an Advisory on the project, which is published on **cooperative.com**.

### Recent Awards

In addition to ION Clean Energy's solvent project and GTI's membrane project, DOE has awarded funding to two other post-combustion carbon capture projects.

- **Chevron USA project**

  Chevron USA. Inc. plans to design, build, commission, and test an engineering-scale carbon capture plant using Svante's VeloxoTherm™ transformational post-combustion carbon capture technology. The plant will operate under realistic conditions at a California oil field for at least 2 months of continuous steady-state testing. The test will allow project participants to gather data for further process scale-up of carbon capture technology.

  **Total funding:** $16.272 million. DOE Funding: $13 million. An additional $3.272 million has been provided by non-federal sources.

- **Electric Power Research Institute (EPRI)**

  EPRI plans to demonstrate the performance of a water-lean solvent for post-combustion removal of carbon dioxide from coal- and natural gas-derived flue gas. The project team will develop a cost-effective method for synthesizing sufficient quantities of solvent to perform a 0.5 MWe-scale test at the National Carbon Capture Center. Modifications will then be made to run test campaigns with the solvent for coal and natural gas sources. In addition, the team will perform techno-economic analyses and an environmental health and safety risk assessment of a full-scale deployment of the solvent at power plants.

  **Total funding:** $5.125 million. DOE has awarded $4.129 million to the project, with an additional $1.032 million from non-federal sources.

DOE has also awarded approximately $6 million in funding for four projects focused on industrial sources of carbon dioxide. See **Appendix B** for a discussion of these sources.

In addition, DOE awarded $13.5 million for direct air capture research. See **Appendix C** for a discussion of this technology.

### RETROFIT STUDY

DOE's NETL issued a report in 2019 based on its study of the costs associated with the integration of carbon capture systems in coal-fired power plants. According to the report, *Economic Impact Assessment of CCUS Retrofit of the Comanche Generating Station,* the study evaluated the potential opportunities for retrofitting existing coal-fired power plants with carbon capture technologies. The study found that retrofits could reduce carbon dioxide emissions by 37% (100 million metric tons) more than the 2019 integrated resource plan baseline portfolio.

## Conclusion

This article will provide cooperatives with information on the types of post-combustion carbon capture technologies and their advantages and disadvantages. This information can help co-ops determine which technologies would be most appropriate for their individual circumstances.

In addition, co-ops can use DOE's 2020 Compendium to track those projects that employ post-combustion technologies of interest. ■

## APPENDIX A: OXYFUEL COMBUSTION: PROS AND CONS

The fundamental premise of oxyfuel combustion is that gas separation takes place with air rather than with flue gas. Nitrogen and oxygen are separated in a cryogenic air separation unit, which provides high-concentration oxygen to the combustor. The result is a flue gas stream that is primarily composed of $CO_2$ and water, which can be easily separated. Thus, the primary gas separation process is at the front end of the system rather than the back end.

Furthermore, air separation units have been in use as long as the industrial gas business has provided nitrogen and oxygen, so that piece of the process is very well understood. However, oxyfuel combustion can also allow process engineers various degrees of freedom and the ability to design novel power cycles, such as the Allam-Fetvedt cycle used by Net Power. "I have to admit that my Ph.D. research area 10-15 years ago was in oxyfuel combustion, so I may be biased," said Dr. Morris. "But I like oxyfuel combustion for the opportunity to rethink the way a power plant operates from the most fundamental level," he added. "There are so many degrees of freedom to increase efficiency and truly create a near zero emissions power plant with the dispatchability and frequency control associated with fossil generation. Of course, I am not excited about the prospect of trying to obtain a permit for a new fossil plant these days," he said.

Due to the clean sheet design opportunities with oxyfuel combustion, many components associated with the technology may not be readily available or will have to be fundamentally redesigned. Also, the difficulty in obtaining new permits and defending litigation for fossil generation assets is also a very significant hurdle to commercialization of these technologies.

## APPENDIX B: CARBON CAPTURE IN THE INDUSTRIAL SECTOR

One area of growing interest for CC technology is in the difficult-to-decarbonize industrial sector. While transportation may have the option of electric vehicles, and the power industry has options in addition to CC such as renewables, energy storage and nuclear energy, a suitable alternative to cement, steel, aluminum and other industries that produce the raw materials that make industrialized life possible has not been identified.

As a result, these industries will essentially have to deploy CC in order to effectively decarbonize. DOE funding awards also have gone to projects that entail the design of carbon capture technologies for use at cement and other industrial production facilities.

Therefore, these industries are the ones to watch for successful carbon capture technologies. Furthermore, each application in the industrial sector will have unique circumstances, such as high particulate gases, high gas temperature, or other process constraints that will provide additional information to electric generation units that are examining the robustness as well as applicability of CC technologies to their unique conditions.

In 2020, DOE awarded approximately $7.5 million in funding for several industrial carbon capture projects: a blast furnace producing steel, two cement production plants, a commercial steam reforming hydrogen plant, and an ethanol plant.

## APPENDIX C: DIRECT AIR CAPTURE

Direct air capture (DAC) has generated significant interest and media coverage recently. It relies on mechanical systems to capture carbon dioxide directly from the atmosphere and compress it to be injected into geological storage or used to make long-lasting products, such as cement.

At present, the process is very energy intensive. Moreover, its application is likely to be decades in the future, when the last percentage points of carbon dioxide reduction must be obtained.

The energy required to separate $CO_2$ from air at 425 ppmv is 270% higher than the energy required to capture $CO_2$ at 12% by volume from a coal-fired power plant based on the second law of thermodynamics and the fundamental calculation of the entropy of mixing of gases. Therefore, DAC will not be practical until the power and other industries are also deeply decarbonized.

Because of its high energy requirements, DAC will be very expensive, and therefore, will be used only to reach the last percentage points of decarbonization to achieve net neutral carbon goals.

At present, there is no reliable cost data for the various carbon capture technologies because none has been deployed on a widespread commercial scale. As technology techno-economic analyses become available, co-ops will have a better sense of cost. DOE has set a goal of $40 per metric ton of captured $CO_2$ by 2030, with a projected range of $35 to $45 per metric ton for post combustion capture technologies.

## ABOUT THE AUTHOR

**Alice Clamp** is a technology writer for the Virginia-based National Rural Electric Cooperative Association. With more than two decades of experience in the energy field, she has researched and written articles on renewable energy, nuclear energy, fossil fuels, grid reliability, environmental issues, energy efficiency, demand response, and emerging technologies.

## QUESTIONS OR COMMENTS


- Daniel Walsh, Senior Director, Power Supply and Generation
  **Daniel.Walsh@nreca.coop**
- Will Morris Ph.D., Consultant to NRECA, President and Technical Director of Carbon Management Strategies LLC, Contracted Program Director Wyoming Integrated Test Center
  **Will.Morris-contractor@nreca.coop**

- To find more resources on business and technology issues for cooperatives, visit our **website**.

## GENERATION, ENVIRONMENT, AND CARBON WORK GROUP

The Business and Technologies Strategies—Generation, Environment, and Carbon Work Group is focused on identifying the opportunities and challenges associated with electricity generation. *Surveillance* research relevant to this work group looks at the various aspects of electricity generation technology, including market status, related policies and regulations, and business models to assist cooperatives in making operational and investment decisions. For more information about technology and business resources available to members through the Generation, Environment, and Carbon Work Group, please visit **www.cooperative.com**, and for the current work by the Business and Technology Strategies department of NRECA, please see our **Portfolio.**