Optimizing Carbon Capture, Utilization and Storage to Meet Ambitious Sustainability Goals

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Executive Summary

The race to a zero carbon future is on. Global oil and gas, petrochemical and chemical companies alike have announced ambitious and broad carbon mitigation, plastics re-use and water conservation targets. At the same time, continued investor, financial market and societal pressure on leading energy, chemicals, mining, steel, cement and power corporations has increased the urgency for achieving net zero carbon emissions. Proposed SEC disclosure rules on climate change risk for publicly listed US companies, strict European Green Deal requirements for emissions reduction, and demands from the investment community and environmental lobbyists for auditable reporting, have further propelled carbon mitigation into the spotlight.

As chemical and energy producers develop and evolve their strategies to meet global carbon mitigation targets (typically a 45% reduction in carbon levels by 2030 and net zero carbon by 2050[1]), many are finding it challenging to identify the right solutions that deliver the level of promised carbon reduction by established deadlines. Carbon capture and storage (CCS) and carbon capture and utilization (CCU) are key pathways being developed today to help companies realistically reach these goals.

To align with industry plans and meet expectations set by the mitigation pathways identified by the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA) and others, the following factors will need to be prioritized and achieved for CCS and CCU (including direct air capture) to be viable, energy efficient alternatives:

- **Continuous innovation and development of technologies** to improve efficiency
- **Economics that scales efficiently** to drive wider adoption of the technology
- **Accelerated pace of implementation**
- **Complete confidence in subsurface storage and sequestration**

Digital technologies will be crucial enablers in each of these four areas. Examples of recent innovations that are delivering results today include systems-level risk modeling technology that ranks the most practical and economically feasible options for carbon reduction, capture, storage and re-use. AspenTech® process simulation software already has a strong track record of helping companies reduce emissions. This same software is even more crucial in CCUS, enabling organizations to improve carbon capture and storage. Approaching the pursuit of effective solutions below ground, industry leaders are using subsurface geophysical and geological modeling software to quickly determine the best reservoir targets for reliable, long-term carbon storage. Digital grid management software is another effective solution, optimizing the use of distributed energy sources.

Separately, these digital solution areas impact CCS and CCU projects; combined in a more holistic, collaborative approach, the possibilities are even greater. The powerful combination of breakthroughs in process simulation, subsurface geophysical and geological modeling, AI-powered hybrid modeling, process optimization software and digital grid management can deliver results at scale—both economically and at an accelerated pace to meet the requirements of industrial carbon mitigation.

Industry leaders like **Saudi Aramco, Kinder Morgan, Shell CANSOLV, Fluor** and others are already using these digital technology solutions to drive innovation and economics of CCUS projects.

Carbon Engineering

Carbon Engineering, Ltd.

A leading innovator in direct air capture (DAC), Carbon Engineering Ltd. has been using AspenTech's Concurrent Engineering solution throughout its innovation and scale-up of DAC process, and for development of its Air to Fuels™ CO_2 utilization process, which combines hydrogen with CO_2. Carbon Engineering's processes are modeled in Aspen Plus, which has helped it optimize the design from a technical feasibility and performance perspective. Carbon Engineering is working in partnership with Occidental Petroleum Corporation (Oxy), as reported in Oxy's most recent Investor Presentation, to implement 70 DAC facilities based on these designs by 2035.

Carbon Capture: Challenges and Opportunities

Carbon capture and storage has gained momentum as a top sustainability investment area, along with energy efficiency and hydrogen economy, according to two surveys recently conducted by AspenTech. The June 2021 survey of over 300 global companies across multiple industries found that 36% of respondents expect to invest in carbon capture, utilization and storage approaches (CCUS) over the next five years. The February 2022 survey—canvassing upstream, refining, chemicals and mining companies—revealed that carbon capture had increased to 47% among respondents when they were asked to name primary sustainability investment areas within the next three to five years. The results are in line with the IPCC 2022 view that point source carbon capture (i.e., from industrial emissions) and DAC are two of the main technology pathways to carbon dioxide removal (CDR).

With oil and gas, petrochemical, power generation and other companies committing substantial resources to carbon capture and storage technology—and the growing opportunity for captured and sequestered carbon as a fungible substance—a new "carbon management" industry niche is quickly taking hold. The term "carbon management" was first used in October 2021 by Vicki Hollub, president and CEO of upstream oil and gas company, **Occidental Petroleum Corporation** (Oxy), when she said her company was becoming a "carbon management company."

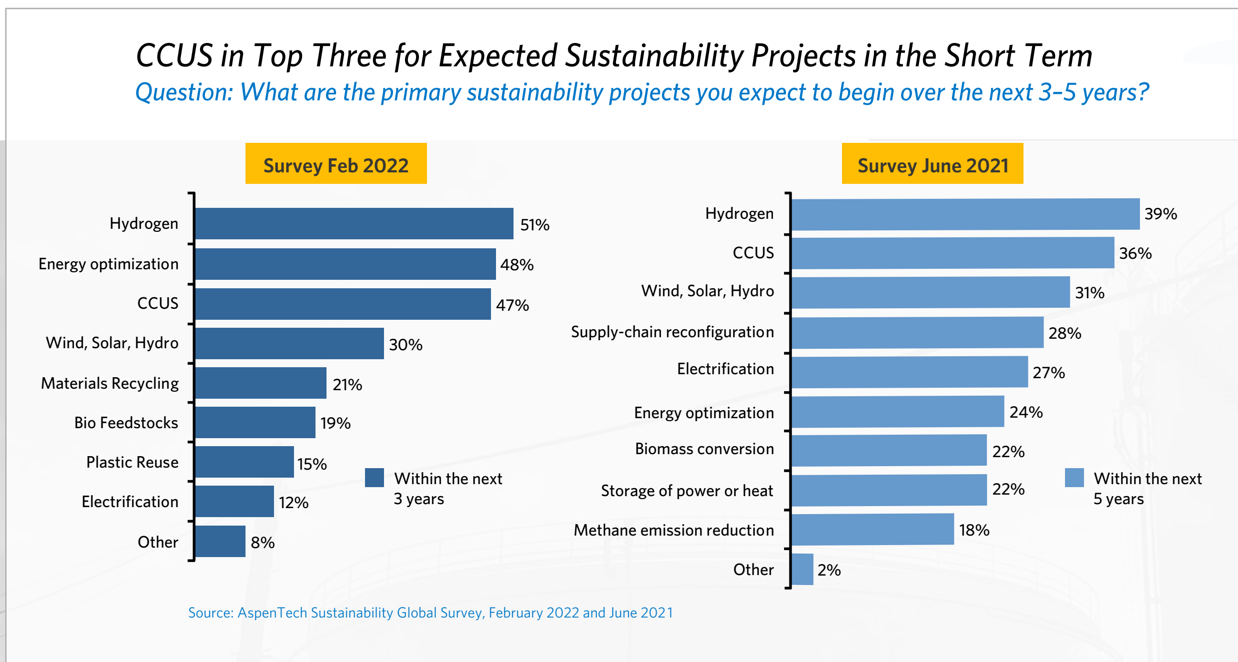
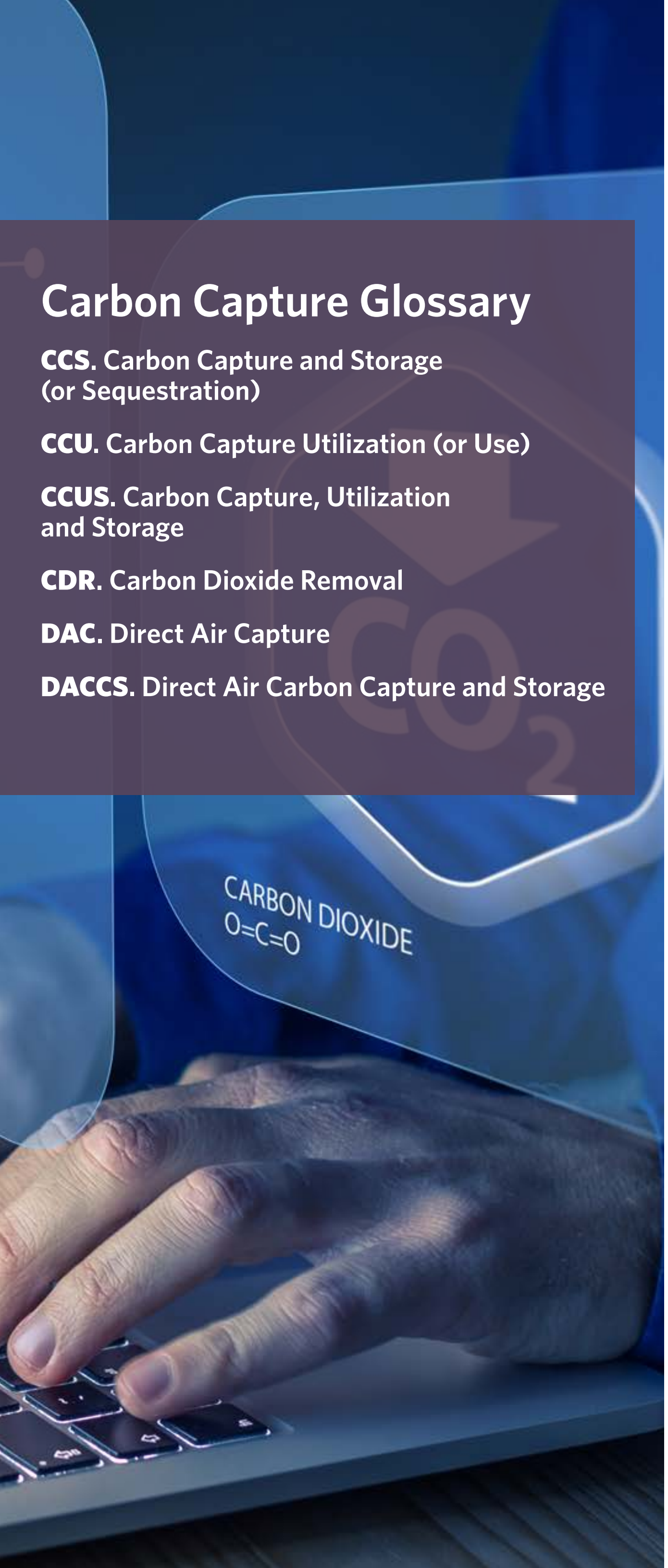


Figure 1. CCUS ranks in the top three sustainability investment areas over the next three to five years.



Carbon Capture Glossary

CCS. Carbon Capture and Storage (or Sequestration)

CCU. Carbon Capture Utilization (or Use)

CCUS. Carbon Capture, Utilization and Storage

CDR. Carbon Dioxide Removal

DAC. Direct Air Capture

DACCS. Direct Air Carbon Capture and Storage

Oxy sees carbon sequestration as a future profit center and has publicly announced an intention to construct and operate three carbon sequestration hubs by 2025 with 70 DACCS facilities by 2035 using the proprietary **Carbon Engineering** technologies for DAC and CO_2 to clean fuels[4]. The Iceland Orca DAC project, which has experimented with crowd-source funding on social media and attracted Microsoft investment, is another example of this developing trend.

The IPCC recently issued its report, "Climate Change 2022: Mitigation of Climate Change," and as could be expected, carbon capture is mentioned frequently in the report. The following graphic shows the IPCC's projected impact timeline for global carbon mitigation strategies (Figure 2).

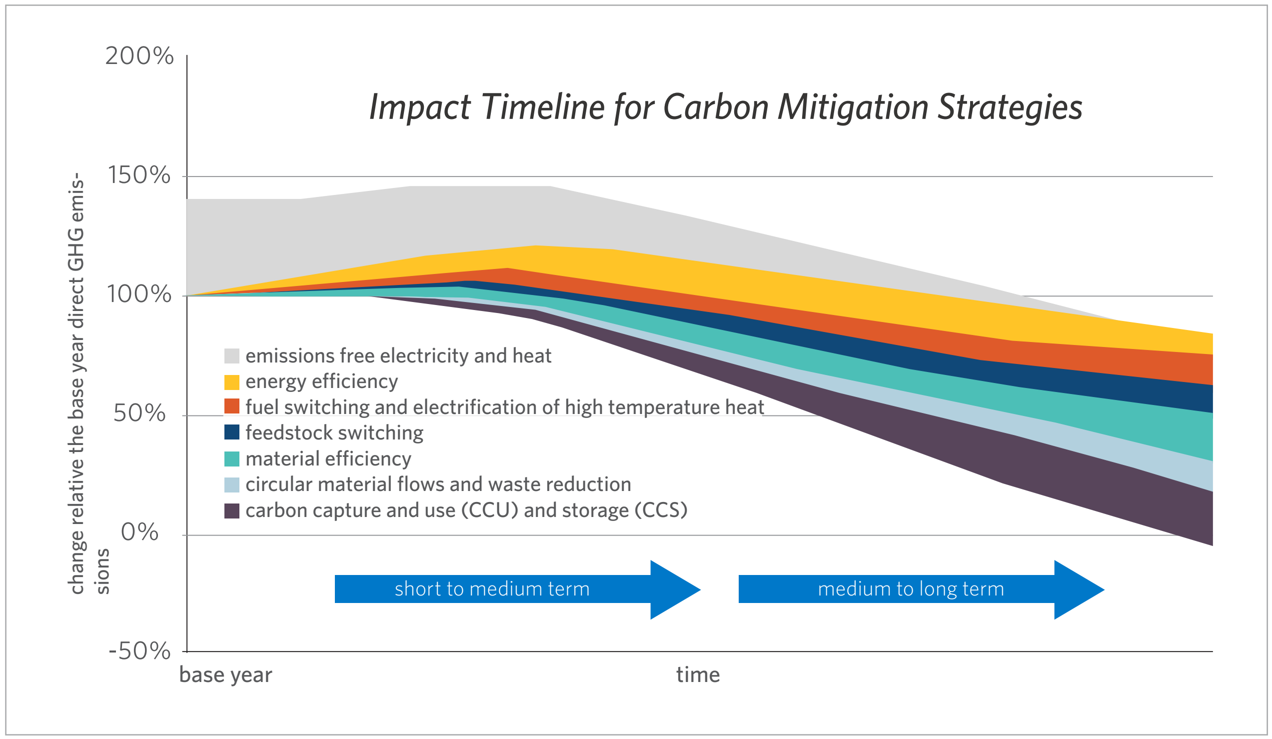


Figure 2. Impact timeline for global carbon mitigation strategies, with CCU and CCS in purple. (Source: IPCC Report, 2022)

To meet the carbon mitigation impact timing shown in Figure 2, carbon capture technology must continue to advance and the pace of projects must be accelerated.

As the chart below illustrates, the number of carbon capture projects in the pipeline for 2030 are significantly below where they need to be to reach net zero (Figure 3). Closing the gap will require a dramatic change, resulting in rapid design, development and implementation of carbon capture solutions.

The data in Figures 2 and 3 clearly indicate that breakthrough innovation in carbon capture and adoption of digitalization need to advance at a much quicker pace. Digital technology is a critical enabler to improve carbon capture economics and accelerate commercialization.

As revealed in the AspenTech February 2022 survey, proving economic viability is one of the biggest obstacles to executing sustainability projects (Figure 4).

Becoming More Economically Viable

CCS and CCU can be looked at end-to-end (from the energy source that powers the carbon capture through to carbon utilization in chemicals or sequestering in geological formations or via chemical reaction approaches) and in terms of risk. The techno-economic picture is complicated. This is where digital end-to-end optimization and risk analysis come to the forefront.

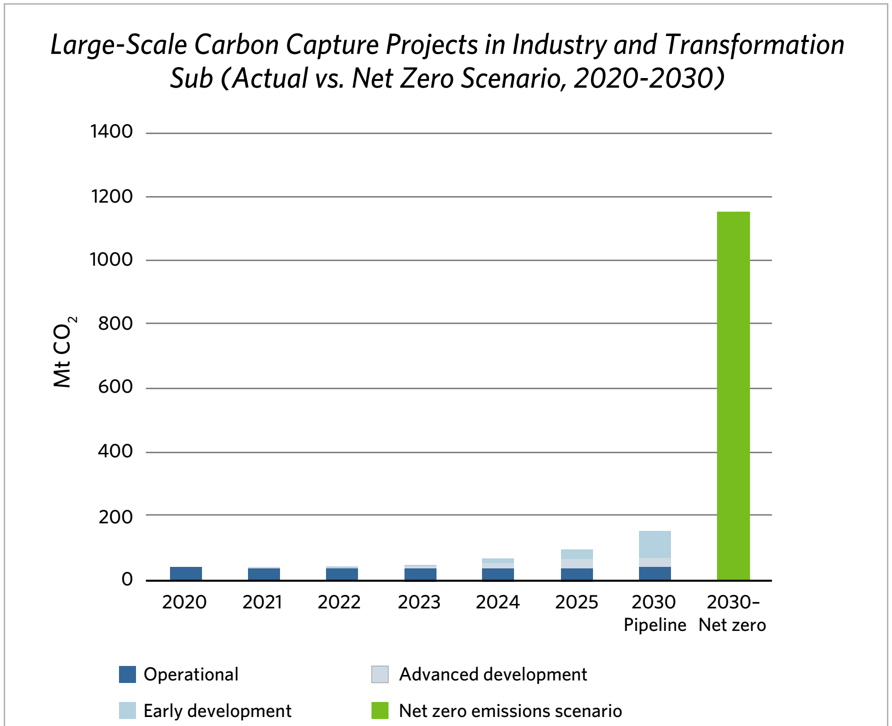


Figure 3. Actual carbon capture projects currently in pipeline for 2030 vs number to achieve net zero. (Source: IEA)

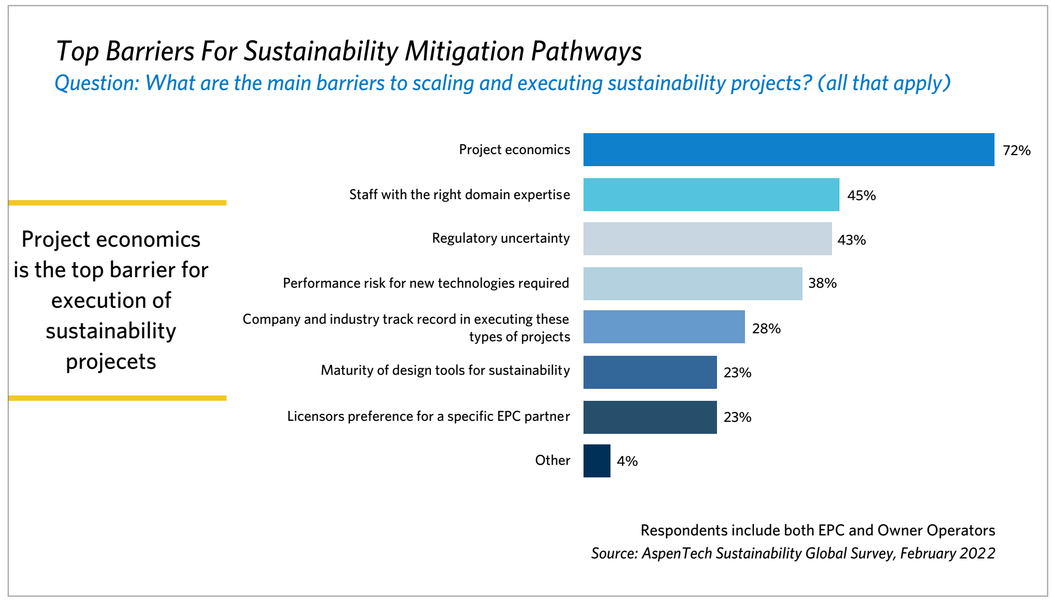


Figure 4. Top barriers to scaling and executing sustainability projects. (Source: AspenTech Sustainability Survey, February 2022)

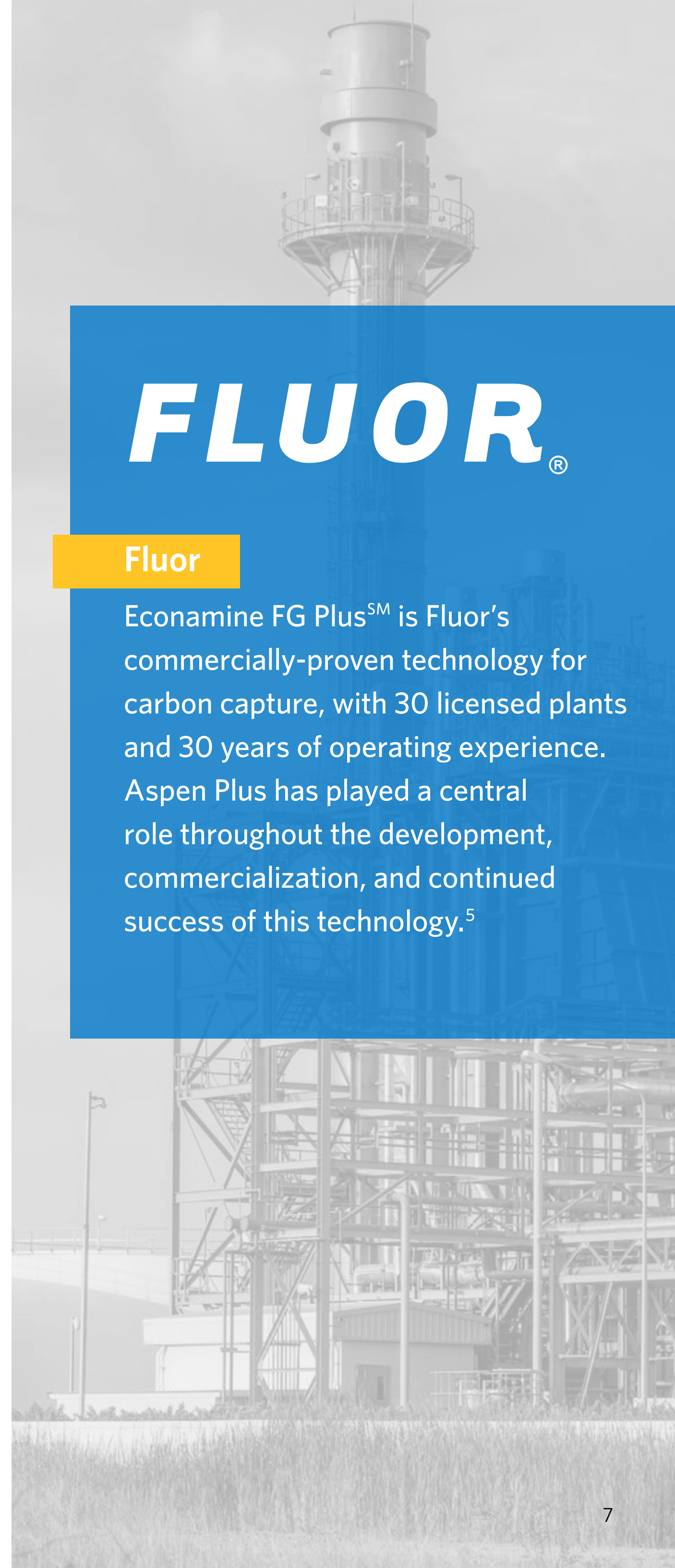
One thing that's changed dramatically in the past several years is the basic economic calculus of carbon capture. With the process of removing carbon from emissions valued at roughly $75 per ton of CO_2 captured and stored (as set by recently imposed carbon taxes, higher in some jurisdictions), carbon capture projects are immediately attractive. Carbon offset prices are higher for DAC projects and have the potential to go even higher with more secure sequestration of carbon for a longer period. Entities such as Microsoft and Stripe pay offsets in the range of $100-$200 USD/metric ton of CO_2 , further improving the economic feasibility of such projects.

Achieving End-to-End Optimization Through Digital Technology

Certainly, digitalization will play a central role in ensuring the rapid scaling and adoption of CCS and CCU. Two technology areas in particular: process modeling and optimization and subsurface characterization and modeling present organizations with a unique opportunity to rapidly screen projects, look at multiple options and design the most effective, economic solutions to address carbon mitigation requirements.

Identifying the Best Carbon Removal Approach

At the earliest stages of a CCS or CCU initiative, the project's leaders typically evaluate long-term impacts, risks and overall economics, assessing the entire lifecycle of capturing carbon, generating and storing power to run the capture facility, transporting carbon, injecting and sequestering carbon in geological formations, or converting carbon to usable products. Today's process modeling and system-level risk modeling capabilities enable these efforts, looking at the flows, capacities, efficiencies, technology risks and external stochastic factors that will affect the system.



FLUOR®

Fluor

Econamine FG Plus℠ is Fluor's commercially-proven technology for carbon capture, with 30 licensed plants and 30 years of operating experience. Aspen Plus has played a central role throughout the development, commercialization, and continued success of this technology.[5]

Many renewable energy sources being considered for carbon capture are intermittent or seasonal. Power and hydrogen storage facilities are critical aspects enabling successful operation of CCUS systems. A system-level risk modeler, such as Aspen Fidelis™, helps evaluate these storage requirements while also considering how to minimize capital cost and maximize the desired carbon removal result.

Additionally, the carbon value chain is generating new business models with companies who are taking point source carbon from emitters as a service. As carbon capture and storage gains steam, look for leading companies to optimize both areas (capture and storage) together:

- **Feasibility.** Geophysical interpretation and reservoir modeling help to effectively analyze all extant data and rapidly screen candidate subsurface reservoirs and aquifers for suitability and capacity.
- **Funding.** Simulation and economic modeling tools rapidly optimize designs and technology selections to match the processing system with the target storage.
- **Implementation.** Subsurface characterization and well engineering helps with injection well planning and drilling. Process and subsurface modeling can be optimized together, employing reduced order modeling and AI, to achieve the most secure and effective execution plan.
- **Storage.** Geophysical interpretation, reservoir modeling and simulations will form the basis for converting monitor data into auditable visibility and decision support, helping to secure storage of the injected CO_2 in the target reservoir.

CarbonCapture™

CarbonCapture, Inc.

CarbonCapture is the brainchild of founder Bill Gross, a technology entrepreneur and founder of Idealab, a start-up incubator with a long track-record of creating successful companies—including 45 IPOs and acquisitions. CarbonCapture is looking at solar power and carbon capture as an integrated system, using AspenTech industrial AI and rigorous modeling software to innovate and optimize. Idealab is innovating several areas at once, including the use of AI technology to optimize solar array performance and improve capture processes to maximize capture using zeolites. Idealab believes that advanced digital technology is the key to achieving breakthroughs in carbon capture scale and economics.

Let's take a closer look at some of the specific and proven carbon mitigations methods available to companies, and how digital innovations have accelerated results, making once far-reaching reduction goals seem more attainable.

Point Source Carbon Capture

Digital technologies are already being used heavily in carbon capture to optimize the design and operation of the capture systems. **Technology Center Mongstad (TCM)**, one of the largest testing and innovation centers for carbon capture, has built an integrated data collection and modeling platform to understand key details of how the capture system is performing at the solvent level (see Figure 8 on page 12). Insights provided can include solvent degradation and reclamation, emission abatement options, including control of process temperatures and selection of where in the emissions stream to remove carbon. TCM is now examining the use of the same models as operator training for carbon capture systems. A virtual digital twin training application like this is crucial given the scale and speed of carbon capture systems envisioned in the world economy.

Substantial work is ongoing to improve efficiency of both carbon stripping and solvent and catalyst regeneration in these carbon capture processes. Process modeling solutions, such as Aspen Plus® and Aspen HYSYS®, are used widely to rapidly screen and evaluate ideas for innovation (Figure 5). Features like rate-based modeling provide the highest accuracy to understanding how these systems perform and can be improved. Combined with early-stage cost estimation, today's modeling solutions can evaluate the tradeoffs between different chemical and physical solvents and adsorbents, membrane approaches and column geometries. Deep understanding of solvent chemistry, thermodynamic limits and mass-transfer limits in installable industrial equipment within the software helps companies develop and deploy better solvent systems to reduce carbon capture energy consumption and capital costs.

Continual innovation has also chipped away at the "green penalty" for carbon capture. Process arrangements have become more efficient. New solvents have been invented. Better ways of extending the life of solvents have been developed. With this momentum, companies like **Shell CANSOLV** and **Delta CleanTech** have been leveraging new capabilities in software to drive forward solvent and adsorbent innovation.

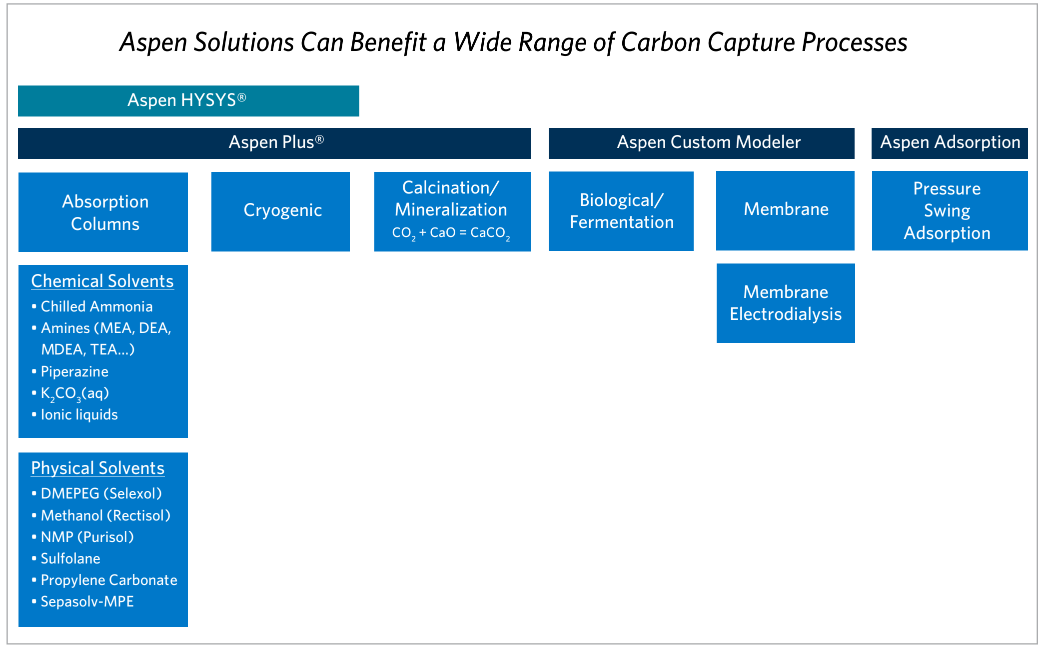


Figure 5. The typical carbon capture processes that can be modeled with digital software solutions. (Source: AspenTech)

Another promising approach is using high-efficiency solid adsorbents. Software solutions like Aspen Adsorption™ are effectively used by carbon capture innovator **Svante**, which is using nano-scale solid adsorbents to capture carbon from difficult processes such as cement, steel and aluminum. Through digital models and optioneering, they have been able to rapidly test materials and processes for optimum results (see Figure 6 on next page).

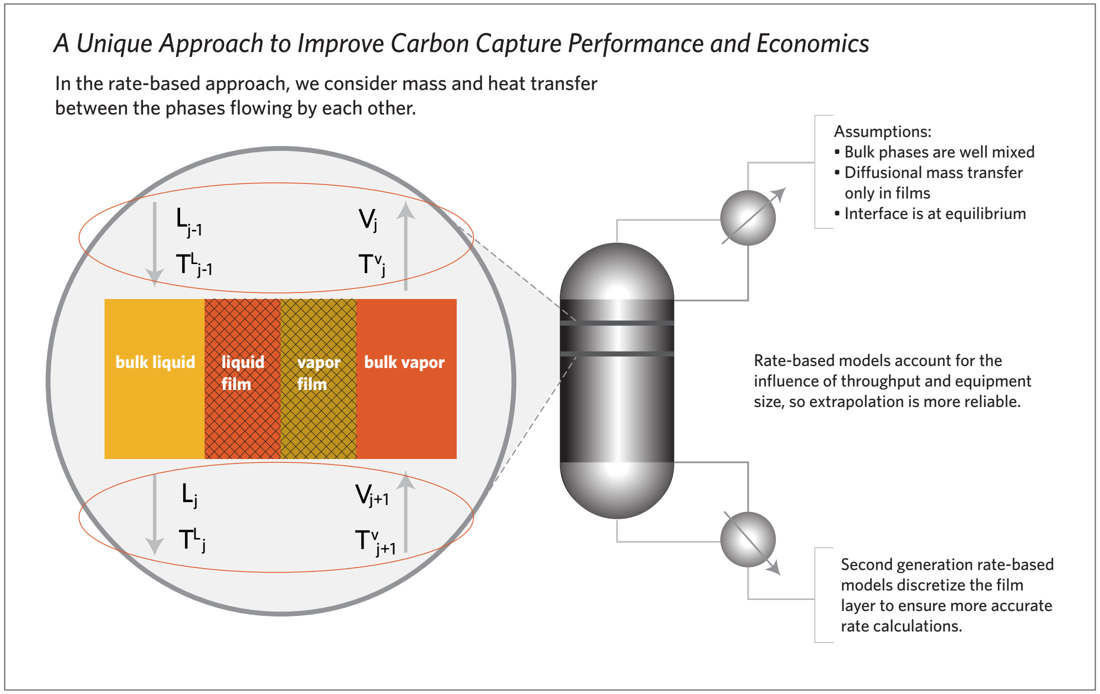


Figure 6. Rate-based distillation modeling to improve carbon capture performance and economics. (Source: AspenTech)

Direct Air Capture (DAC)

Point source carbon capture is necessary to achieve commitments while the world transitions to carbon-free energy sources. However, DAC technology is emerging as a long-term solution to remove the current elevated level of CO_2 that has accumulated in the atmosphere. DAC helps companies deal with emissions that are hard to abate from industries like steel, cement and agriculture, which tend to lag in the area of decarbonization.

There have already been significant breakthroughs in DAC. Energy consumption is the biggest economic challenge. A recognized innovator in DAC, Bill Gross, CEO of **Heliogen** and founder of **CarbonCapture Inc.**, combined breakthrough efficiencies in solar with new DAC concepts—leveraging process modeling software—to tie solar technology more closely with DAC, improving the overall economics.

Because direct air capture removes CO_2 from air at much lower concentrations, these processes require more effective removal agents, such as zeolites, and liquid and solid solvents. Concurrent engineering modeling software is helping innovators like Bill Gross evaluate thousands of process alternations, and then simulate scale-up to understand tradeoffs between capital and operating costs.

Transport of CO_2 to Target Reservoirs

To achieve carbon capture and storage on a large scale, three rarely co-located elements will be essential: sources of renewable energy to power capture, carbon capture plants and target geological reservoirs. Since storage may not be co-located, transportation of captured CO_2 by pipeline or ship from point sources and capture plants to target reservoirs will need to be developed on a large scale. A recent study by Princeton's High Meadow Environmental Institute, "Net Zero America," projects that by 2050, 930 million tons of CO_2 will need to be moved by 21,000 km of trunk pipelines and 85,000 km of gathering pipe networks. The total volume of CO_2 they project needing to be moved is 1.3 times the current level of US oil production (Figure 7).

What the Princeton study and Figure 7 project, is a transition from individual projects that connect a specific CO_2 capture site with a specific CO_2 storage site to a network with multiple sources feeding multiple sinks. Only then will there be a carbon market with competition and the real costs and benefits will be accounted for elastically. There are already several CCS clusters and hubs[2] in different phases of development. In addition to land-based pipeline networks, sea-based collection and

Carbon Transport Infrastructure Needed by 2050

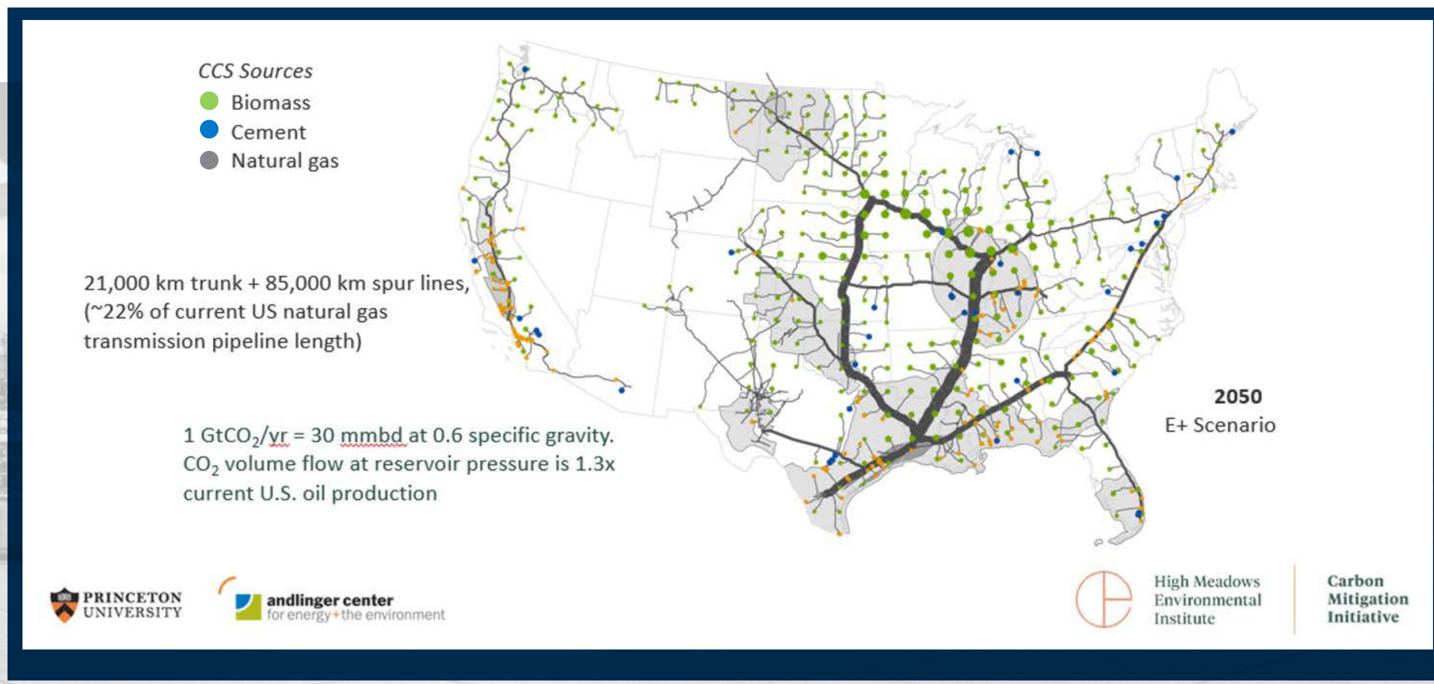


Figure 7. Required CO_2 transport infrastructure. (Source: High Meadows Environmental Institute, Princeton)

transport by vessels is also being developed by companies like **Carbon Collectors** in Northern Europe, that is using the digital tools mentioned here to accelerate its time-to-market.

The design of the transportation will benefit from systems-level modeling using the various digital tools previously mentioned. Technology will be strategic in matching locations and capacities of target reservoirs with locations of carbon capture plants and optimization of transportation networks to minimize required infrastructure and drive down total costs.

Subsurface Storage and Enhanced Oil Recovery

Another significant concern is where to store or utilize the carbon once it's captured. A big part of the lifecycle cost of CO_2 capture and storage will be designing, drilling and injecting the CO_2 into target geological formations. Successfully screening to select the optimal subsurface reservoirs to store the CO_2, designing optimal drilling and injecting of CO_2, and monitoring it for the long term will heavily rely on subsurface engineering software. For instance, a leading integrated energy company is using Aspen Subsurface Science & Engineering technology to re-purpose existing exploration data to rapidly re-characterize and screen depleted oil and gas reservoirs for the suitability and capacity to sequester CO_2. They now have the insights to analyze reservoir capacities, geologic suitability as a long-term storage location, usability of existing wells and strategies for drilling new injection wells.

The earliest carbon capture projects that achieved positive economic benefits were those where CO_2 was injected into producing reservoirs for enhanced oil recovery (EOR). Such projects have been executed effectively by several companies. **Kinder Morgan** leverages software innovations to create an integrated workflow to optimize well placement, optimize production, achieve higher production yields and keep the CO_2 in place in the reservoir.

KINDER MORGAN INC.

Kinder Morgan

The largest transporter of CO_2 in North America and a player in CO_2 EOR, Kinder Morgan has been using AspenTech's Subsurface Science and Engineering (SSE) integrated suite of geoscience software to efficiently validate future drilling locations and optimize field performance, reducing planning costs significantly, managing CO_2 injection and maximizing EOR yield.

Process Modeling Optimizes Carbon Capture Solvent Reclamation

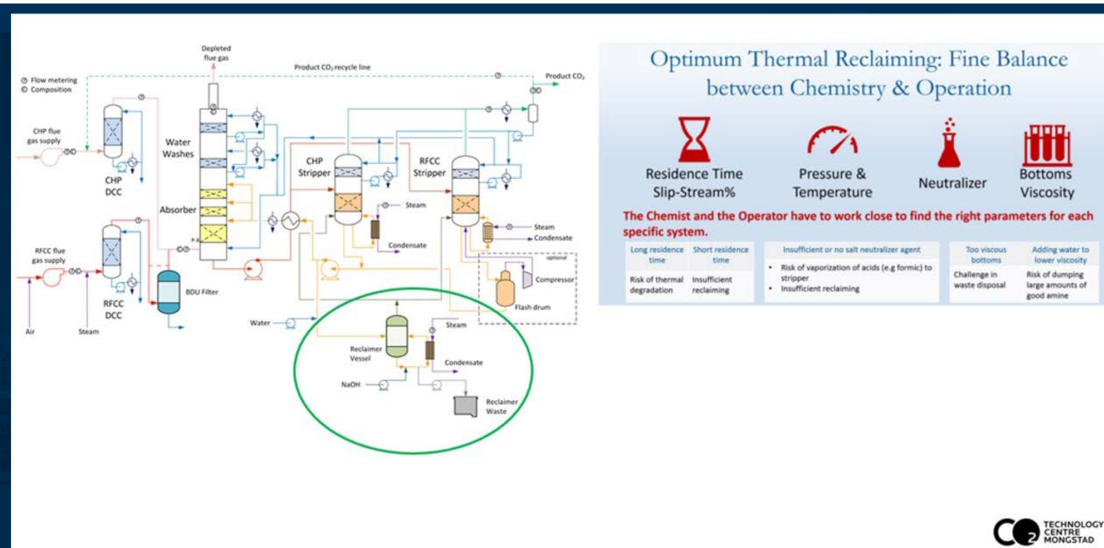
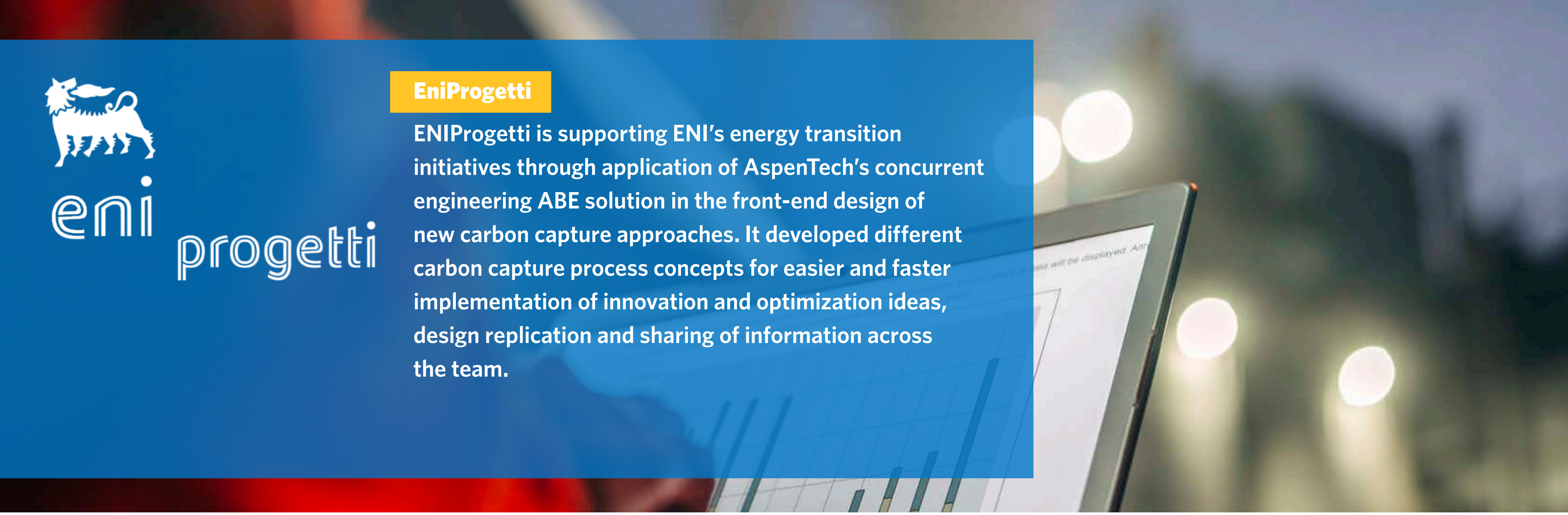


Figure 8. Solvent recovery to improve carbon capture approaches. (Source: Technology Centre Mongstad presentation, OPTIMIZE 2021 Global Conference)

When CO_2 is going to be stored in the subsurface for the long-term—either in saline aquifers (where CO_2 can be dissolved) or depleted oil and gas reservoirs—the efficiency of doing so becomes critical, since well drilling and retrofitting becomes a costly project component. Detailed characterization of the target formations is important, as is understanding of the disposition of existing wells and optimal placement and drilling strategies for new wells.

Long-Term Monitoring of Sequestered Carbon

In the long run, during operation of the carbon management system and at the post-closure stage, digital technology is crucial to enable reliable, transparent and auditable records of the performance of the carbon storage asset. Time lapse (4D) seismic monitoring allows the imaging of the growth of the CO_2 plume in the reservoir and helps demonstrate both containment and conformance. Direct measurements within and around the storage complex are also important. Wellhead and downhole well measurements (e.g., pressure, temperature, fluid saturation) allow the avoidance of fracturing activity and can provide early warning of unexpected pressure or fluid flow out of the target injection interval.



EniProgetti

ENIProgetti is supporting ENI's energy transition initiatives through application of AspenTech's concurrent engineering ABE solution in the front-end design of new carbon capture approaches. It developed different carbon capture process concepts for easier and faster implementation of innovation and optimization ideas, design replication and sharing of information across the team.

In addition, microseismic monitoring has proven valuable in understanding the relationship between injection rates, pressure distribution within and beyond onshore storage reservoirs, and rock strain. Today's subsurface engineering software provides the tools to analyze and interpret monitoring measurements and integrate it, through 3D model calibration, to update the performance prediction.

CO_2 Utilization as a Component of Materials, Chemicals and Fuels

Companies that are not storing or utilizing carbon directly via EOR are looking at alternatives to convert captured CO_2 into valuable products. **Saudi Aramco** has validated a new process to recycle CO_2 into concrete without affecting the product quality while innovating to improve economics for industrial-scale application. **Carbon Engineering** developed a process that uses CO_2 and green hydrogen to obtain fuels with low lifecycle carbon intensity. **SABIC** is focused on broad utilization of CO_2 as a feedstock for chemicals and polymers production, which includes methanol, acrylic acid, MEG, aromatics and special grades of polymers.

Digitalization is crucial to accelerate the development of new technologies and to optimize process designs to drive commercialization and scaling. Process simulation software, with integrated economic, energy and emission analysis, offers strong capabilities for conceptual design and techno-economic evaluation, helping to make these new processes feasible, cost-effective, less energy intensive and with low carbon footprint. Concurrent engineering technology also provides a platform to optimize the multiple disciplines involved in a project as new plants and facilities are planned.

Next Steps

Digital technology provides a key lever for rapidly improving economics, scale and speed of implementation of carbon capture, direct air carbon capture, carbon storage and utilization and carbon storage monitoring. Aspen Performance Engineering technology helps in the design and execution of process technologies and projects. Aspen Production Optimization technology provides the operations planning, control and optimization of carbon capture plants. AspenTech's Subsurface Science & Engineering (SSE) technology is strategic in selecting, characterizing and monitoring carbon sequestration geologic formations. And finally, Aspen AIOT Hub™ provides the data assembly and decision support infrastructure to transparently report on and audit carbon storage. Beyond these tools, AspenTech has an aggressive innovation program to further develop digital technologies that support CO_2 abatement and removal through CCUS, in design, operation, optimization and maintenance.

Regardless of where companies are in the journey to carbon capture and net zero carbon, it is important to partner with technology leaders that have the innovation and expertise to help you achieve critical sustainability goals while driving operational excellence. AspenTech welcomes the opportunity to leverage our 40 years of innovation and experience to partner with you on upcoming projects.

Citations:

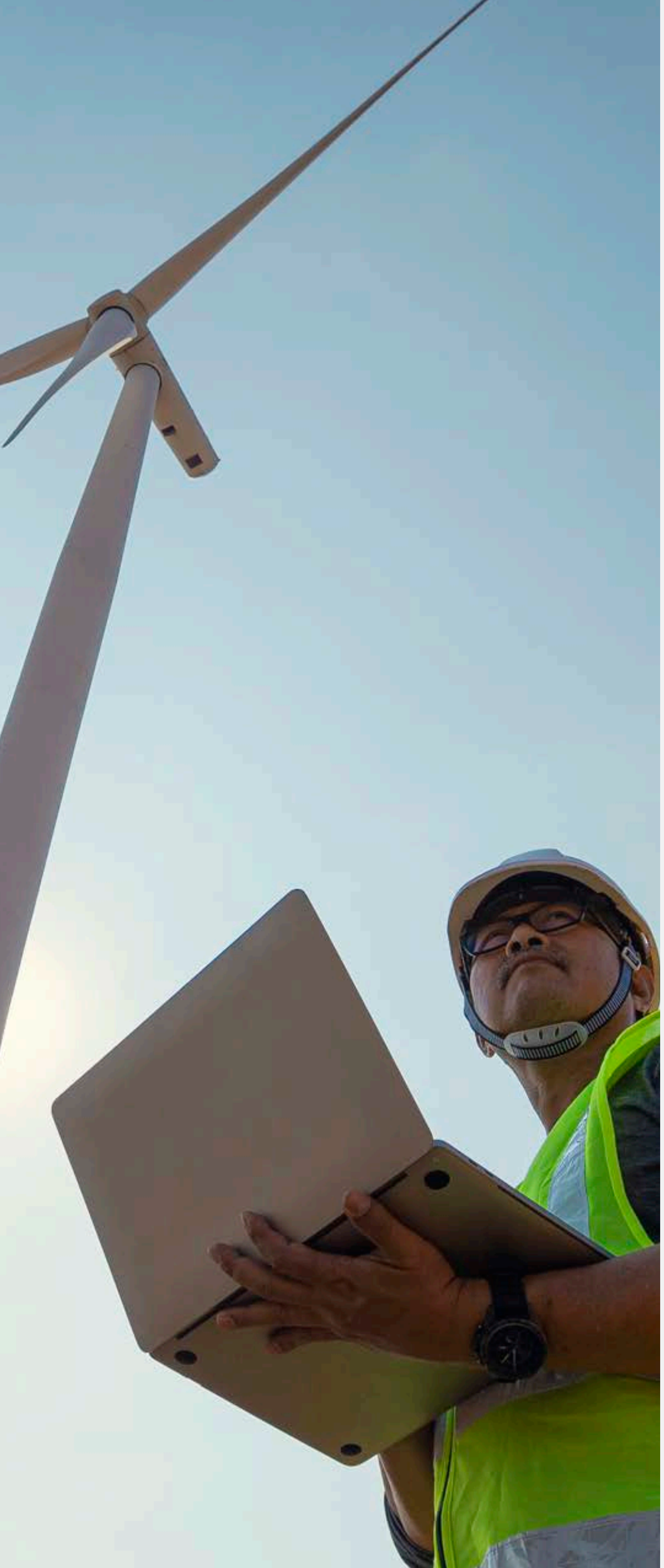
[1] Global Warming of 1.5°C," (Geneva: Intergovernmental Panel on Climate Change, 2022), https://www.ipcc.ch/sr15/

[2] https://www.globalccsinstitute.com/wp-content/uploads/2019/08/Understanding-Industrial-CCS-hubs-and-clusters.pdf

[3] Matthew Campbell, Technology Centre Mongstad presentation at OPTIMIZE 21 Global Conference

[4] Oxy Investor Presentation, April 2022

[5] Paul Matthias, Fluor, Hydrocarbon Processing, October 2021, AspenTech 2008 Global Conference



Your Partner for Optimizing CCUS and Accelerating Sustainability Initiatives

The following AspenTech digital software solutions are already playing a valuable role in CCUS activities around the globe.

Performance Engineering

- **Aspen Plus and Aspen HYSYS** | Leading chemical process simulator featuring rate-based distillation for carbon capture processes and physical property databanks covering most CO_2 solvents and adsorbents. Special sub models to handle membrane and other novel approaches.
- **Aspen Adsorption** | Dedicated process simulator that handles adsorption processes.
- **Aspen Economics** | Cost estimating software integrated with process simulation to evaluate capital and operating costs at feasibility stage through construction.
- **Aspen Fidelis** | Systemwide modeling system that evaluates system risks, uncertainties and performance to optimize production, mitigate carbon and reduce costs.

Subsurface Science and Engineering

- **EarthStudy 360** | Delivers a complete set of data to seismic depth imaging and processing experts to achieve accurate subsurface velocity models, structural attributes, medium properties and reservoir characteristics.
- **SeisEarth** | Comprehensive seismic interpretation and visualization system that allows interpreters to identify quality prospects, clearly delineate reservoirs and characterize reservoir properties.
- **Geolog** | The industry standard in formation evaluation and petrophysical analysis of borehole data.
- **RMS/SKUA-GOCAD** | Geological modeling solutions to integrate information coming from multiple sources in a 3D model and capture and propagate uncertainties on data and interpretations across the workflow.
- **Tempest** | Modeling reservoirs in 3D to understand formations, fluid reservoirs and 3D flow dynamics. Reservoir engineering and simulation tools to understand 3D flow dynamics, calibrate reservoir models to observed data and predict storage performance.
- **Sysdrill** | Well planning and drilling software, for accurate planning and safe drilling, on time and on budget.
- **METTE** | Efficient flow assurance and production optimization solution that enables flexible injection performance calculations, fast network simulation and optimal field flow.

Production Optimization

- **Aspen DMC3** | Adaptive process control software providing a sophisticated level of model-based control that manages the performance of process units to linear or non-linear control setpoints. It will be instrumental in managing the carbon capture stripping and solvent reclamation column systems.

About Aspen Technology

Aspen Technology, Inc. (NASDAQ: AZPN) is a global software leader helping industries at the forefront of the world's dual challenge meet the increasing demand for resources from a rapidly growing population in a profitable and sustainable manner. AspenTech solutions address complex environments where it is critical to optimize the asset design, operation and maintenance lifecycle. Through our unique combination of deep domain expertise and innovation, customers in capital-intensive industries can run their assets safer, greener, longer and faster to improve their operational excellence.

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