CCUS: Utilizing CO2 to Reduce Emissions

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Converting carbon dioxide emissions into valuable products is an exciting concept for the chemical processing industries (CPI).

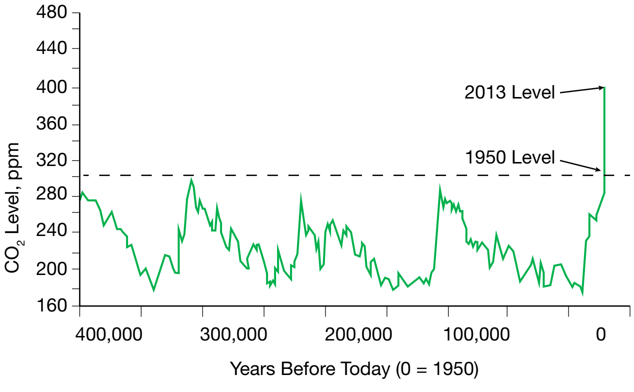
Carbon capture, utilization, and storage (CCUS) technologies may play a critical role in dealing with global carbon dioxide emissions in the 21st century. Whether in leading, supporting, temporary, or other roles, these technologies could be crucial in reducing and removing carbon emissions from the large sources of concentrated CO_2: fossil-fuel electric power stations; steel, concrete, cement, and other heavy manufacturing facilities; and natural resource refineries. However, high capital and operating costs, technology risks, and concerns that CCUS could delay a transition away from fossil fuels must be addressed before these technologies can be fully developed, deployed, and accepted.

This article explores the basic approaches to dealing with carbon dioxide emissions, barriers to the adoption of existing CCUS technologies, and CCUS technologies under development today. It describes the NRG COSIA Carbon XPRIZE, a $20-million global competition to catalyze breakthroughs in technologies that convert post-combustion CO_2 emissions into valuable products, and the capacity for such incentive prize competitions to create a lasting and meaningful impact on reducing greenhouse gas (GHG) emissions.

Global carbon budget

Anthropogenic CO_2 emissions are generally discussed within the larger context of energy and climate change. The coupling of science and engineering problems with the social and political discourse around energy, climate, and the environment presents challenges. But it also introduces opportunities to shine a spotlight on technologies at the heart of CO_2 production, conversion, and mitigation; on the creative minds developing solutions; and on the impact that breakthroughs in these areas can have inside and outside of the engineering and science communities.

The concentration of CO_2 in the atmosphere has increased from around 280 ppm before the start of the industrial revolution in the 18th century to over 400 ppm today, as shown in Figure 1 *(1)*. This rapid increase in



▲ **Figure 1.** Atmospheric CO_2 concentrations have dramatically increased since 1950. Source: National Aeronautics and Space Administration (NASA).

CO_2 concentration has been accompanied by significant increases in the concentrations of nitrous oxide (N_2O) and methane (CH_4). The Intergovernmental Panel on Climate Change (IPCC) has reported that, given the stability and lifetime of CO_2 in the atmosphere and oceans, emission rates of anthropogenic CO_2 will need to be significantly reduced to stabilize overall CO_2 concentrations. More recently, some researchers have concluded that stabilizing CO_2 concentrations may not be enough, and that "negative carbon" techniques — *i.e.*, approaches that actively remove CO_2 from the air and oceans — may be necessary.

The sources of anthropogenic CO_2 are well-documented elsewhere, so they are only summarized here. Energy use is responsible for the largest share — roughly 70% of global anthropogenic GHG emissions. Ninety percent of the GHG emissions attributable to energy use are CO_2. In 2014, total global CO_2 emissions were estimated to be 36 gigatons (Gt) per year *(2, 3)*.

The production of electricity and heat are the leading sources of anthropogenic CO_2 (42%), followed by emissions associated with transportation (combustion of liquid fuels), and industry (primarily manufacturing and refining), as shown in Figure 2. Despite rapid developments in renewables (including improvements in technology performance, cost, manufacturing, and deployment), global generation of electricity and heat is still dominated by fossil fuels, particularly coal. Furthermore, the balance between fossil and non-fossil sources of energy worldwide has shifted only slightly over the past generation, from roughly 86% fossil and 14% non-fossil in 1971 to 82% fossil and 18% non-fossil in 2012 *(4)*.

The future may not necessarily mirror the past, and history does not preclude an exponential transformation in global energy systems over the next generation. Still, inertial factors in energy systems — such as the decades-long lifespan of coal-fired power plants and other physical assets, and the structure and duration of fuel- and power-purchasing contracts — will continue to present major challenges to achieving such a transformation in the coming 30 or 40 years *(4)*.

Reducing CO2 emissions

Identifying the most efficient path to reducing atmospheric CO_2 is the subject of much research and debate. Most solutions being considered fall into one of three categories:

- eliminating CO_2 emissions at their source by replacing CO_2-intensive processes with alternatives (*e.g.*, replacing fossil-fuel-based electricity generation with a low-carbon-based alternative)
- mitigating CO_2 emissions from existing facilities and processes using carbon capture, conversion, utilization, and/or sequestration
- actively removing carbon from the biosphere.

Each general approach has its merits and drawbacks. Specific technologies in each category are discussed later in the article.

Carbon capture and sequestration

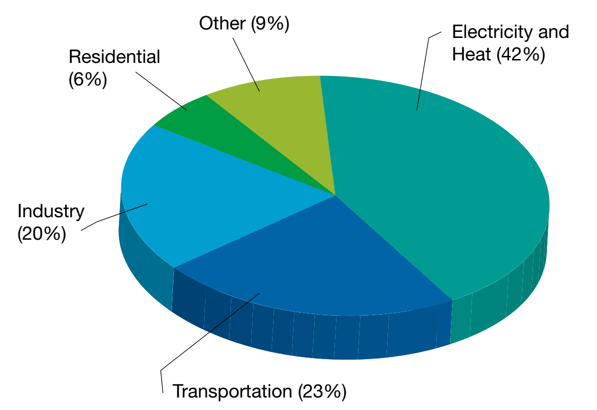
Carbon capture and sequestration (CCS) is the process by which CO_2 is captured and stored away from the atmosphere and oceans for a very long time. There are four basic elements to a CCS process:

1. capture the CO_2, *e.g.*, by separating the CO_2 from the fluegas of a power plant (Figure 3)
2. compress the gas for transport to a sequestration site
3. transport the compressed gas
4. store the compressed gas.

Capture. Capturing CO_2 from fluegas is the most energy-intensive and expensive step of a typical CCS process. Separating low-energy and stable CO_2 molecules from a stream of mostly nitrogen is difficult. A small portion (< 2%) of large point sources produce concentrated streams containing up to 95% CO_2, and for those capture is more efficient and cost-effective. But the overwhelming majority of large point sources emit CO_2 at concentrations of 15% or less *(5)*.

Several technologies exist for capturing CO_2 from fluegas *(6)*. The most common approaches are (Figure 4):

- *absorption*. In these systems, fluegas containing CO_2 flows through an absorber, where it contacts a solvent that selectively absorbs the CO_2. The CO_2-rich solvent is regenerated and the CO_2 is removed, generally by heating or reducing pressure. The CO_2 can then be collected, purified, and compressed and the regenerated solvent recycled. The most common solvent in use today is an aqueous solution of monoethanoamine (MEA) *(6)*. The major costs associated with this method are for the energy required to move fluegas through



▲ **Figure 2.** The production of electricity and heat is the leading source of CO_2 emissions.

the contactor and to heat the solvent for regeneration.

• *membrane separation*. Many groups are developing polymer membranes for CO_2 separation. These efforts are driven in large part by the high energy consumption and operating costs of traditional MEA systems *(7)*.

• *pre-combustion capture*. Pre-combustion capture of CO_2 typically refers to the removal of CO_2 from synthesis gas produced at an integrated gasification combined-cycle (IGCC) power plant before the gas is combusted to generate power. In IGCC power plants, coal is first gasified into a synthesis gas (a mixture of mainly hydrogen and carbon monoxide), which undergoes a water-gas shift reaction to convert CO and water to H_2 and CO_2. The gas is then cleaned and CO_2 is separated from the hydrogen. Oxy-combustion is similar to pre-combustion capture except the coal is burned in the presence of oxygen and some fluegas, rather than in air; the nitrogen-free, oxygen-rich environment dramatically increases the concentration of CO_2 in the exiting fluegas.

• *physical capture by advanced materials*. New materials that rely on physical, electrochemical, ionization, and other approaches to separate CO_2 from dilute gas streams are under development. These materials rely on physical pores for adsorption, functionalized sites, cages and traps, or other mechanisms *(8)*.

Air capture. Air capture, also referred to as direct air capture or atmospheric capture, is a process of directly separating CO_2 from the atmosphere, typically at or near the earth's surface (troposphere). Air capture may use methods similar to solvent absorption, and it faces similar challenges with respect to energy costs for moving air and regenerating solvents. The high costs are exacerbated in air capture systems because the concentration of CO_2 is lower in air (0.04 vol%) than it is in fluegas (5–15 vol%).

The advantages of air capture, however, may outweigh its drawbacks. For instance, air capture is, in principle, easily scalable, since individual systems can be deployed anywhere, and do not need to be located near sources of CO_2 emissions. In addition, air capture systems directly remove CO_2 from the environment, no matter its source and no matter when it was produced. When combined with an appropriate sequestration method, air capture is a pure form of negative carbon emissions that could, in theory, be used to remove past and present carbon emissions *(9)*.

Sequestration. In this context, sequestration is the process of fixing carbon from CO_2 in a form that keeps it out of the atmosphere and oceans. The relevant time scale for sequestration to have an impact on the dynamics of the global carbon budget and climate is on the order of decades and centuries, as set by the average residence time of CO_2 in the atmosphere and oceans. The three most common approaches to large-scale (gigaton-scale) storage options are *(5, 10)*:

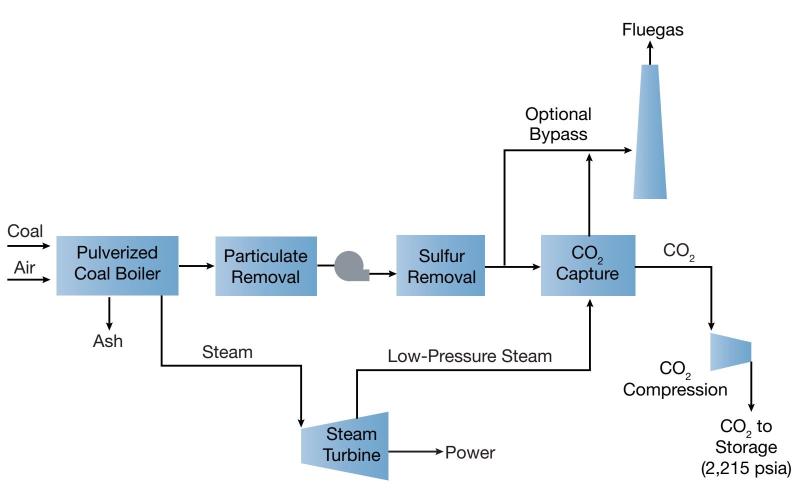
• *geologic storage*, in which CO_2 is injected and trapped within geological formations at subsurface depths of 800 m or greater, where the temperature and pressure are sufficient to transform gaseous CO_2 into supercritical CO_2 that can be held within porous rock

• *ocean storage*, in which CO_2 is injected into deep ocean waters, where it can disperse quickly or deposit on the ocean floor to form CO_2 lakes

• *enhanced oil recovery (EOR)* is a special form of geologic sequestration in which CO_2 is injected into an oil and gas field to both store CO_2 and stimulate the production of hydrocarbons. The produced oil and gas are considered revenue-generating streams that can offset the cost of capture and sequestration.

The use of EOR to mitigate global CO_2 emissions raises interesting questions about the life cycle analysis of carbon emissions and carbon accounting, since the produced oil and gas create additional CO_2 emissions. The critical question from a carbon standpoint is to what extent can carbon emissions from fuels produced using traditional CCS and EOR be offset by carbon sequestered in the extraction of the hydrocarbon feedstock of those fuels.

EOR is the leading use of industrial CO_2 in North America. Because of the value of CO_2 to these oil and gas producing operations, EOR sets the market price for CO_2, which impacts the economics of all other CO_2-mitigation activities, including carbon conversion.



▲ **Figure 3.** Carbon capture involves four basic steps, the first of which is capturing and separating the CO_2, for example, from the fluegas of a coal-fired power plant. Source: National Energy Technology Laboratory.

Carbon utilization

Using carbon dioxide as a feedstock to produce higher-value chemicals is not a new concept. Carbon dioxide has been used to produce methanol and urea since World War II. Production of those two chemicals currently consumes 120 million m.t. of CO_2 annually *(11)*. The CO_2 used in these processes generally comes from the production of ammonia from natural gas, often via a shift reaction to convert CO to CO_2.

CO_2 conversion could be a promising tool to reduce GHG emissions. Breakthroughs in CO_2-conversion chemistries could increase this potential dramatically. And, the demonstration of one breakthrough could give credibility to other technologies, setting off a chain reaction of sorts for investment in and deployment of CO_2 utilization.

Conventional wisdom has been that CO_2 conversion is too expensive and energy-intensive to thrive in markets dominated by fossil-based hydrocarbon feedstocks. But emerging technologies and government policies, as well as a new business climate, may shift such viewpoints.

For example, new catalysts, materials, and process designs are improving the overall efficiency of converting CO_2 into high-value chemicals *(12, 13)*. In addition, the generation of electricity from low-carbon resources, especially renewables, is becoming more common. Low-carbon electricity generation could be combined with higher-efficiency processes to reduce the emissions generated by CO_2-conversion processes *(14)*. Growing government and business investment in decarbonization and the prospect of carbon pricing are creating new market opportunities for low-carbon technologies, including CO_2-conversion processes *(15)*.

Approaches for converting CO_2 into higher-value products fall into one of four broad categories:

- *mineralization*, which converts CO_2 into an even more stable form of carbon, typically a carbonate; these solid minerals may then be incorporated into downstream products, such as building materials (*e.g.*, concrete)
- *chemical conversion*, in which CO_2 reacts in the presence of a catalyst to form higher-energy molecules, such as conventional liquid fuels (*e.g.*, methanol, butanol, gasoline, and diesel) or other industrially valuable chemicals (*e.g.*, ethane and formic acid); this includes gas- and liquid-phase approaches in general, as well as artificial photosynthesis, in which primary solar energy is used in photochemical or thermophotochemical reactions to split water and/or CO_2

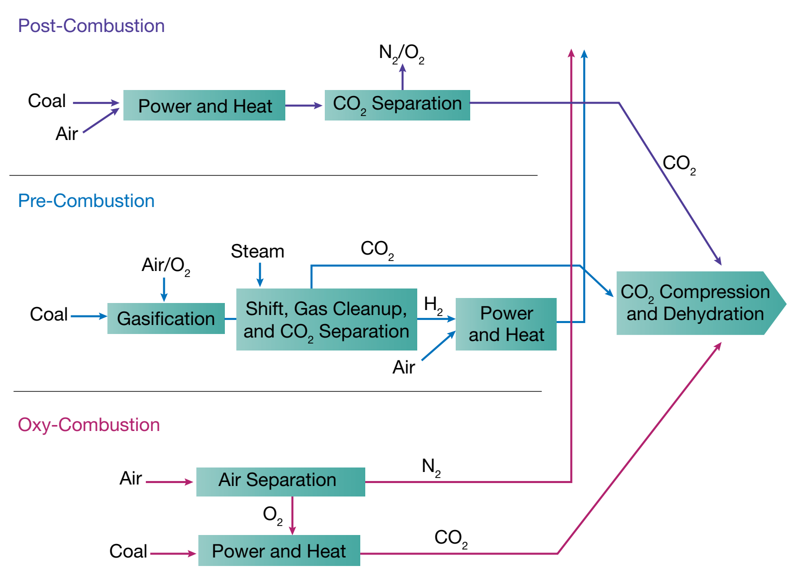
CO_2 conversion could be a promising tool to reduce GHG emissions.

- *electrochemical conversion*, which is similar to chemical conversion except that reactions are driven at least in part by electric energy; one particularly important area of research is the use of electrochemical cells that mimic photosynthesis
- *biological conversion*, which involves photosynthetic and other metabolic processes inherent to plants, algae, and bacteria to produce higher-value chemicals; examples include the direct chemical synthesis in bacteria or algae that have been engineered by synthetic biology, biofuels produced from hydrocarbons contained in dried algae grown in ponds or bioreactors, and ethanol produced through distillation of sugars extracted from plants (*e.g.*, switchgrass).

Closing the carbon loop

The CCUS concepts described in this article are aimed mainly at mitigating existing CO_2 emissions, and to ultimately reducing anthropogenic carbon emissions in the future. However, one other application of CCUS drives much active research and development in the field today: closed-carbon-loop recycling for energy storage and liquid fuels.

The concept is simple: Carbon dioxide emissions from the combustion of a liquid fuel (*e.g.*, butanol) are captured and converted back into a useable liquid fuel. If energy for the capture and conversion is provided from largely



▲ **Figure 4.** Carbon-capture technologies for power plants fall into three categories: post-combustion, pre-combustion, and oxy-combustion.

low-carbon sources of electricity and heat (*e.g.*, renewables such as wind, solar, and hydroelectric power), then the cycle can approach a closed carbon loop. Liquid fuels produced this way, in effect, serve as an energy-storage mechanism for low-carbon electricity, and themselves can be considered a low-carbon liquid fuel.

CCUS: Challenges and opportunities

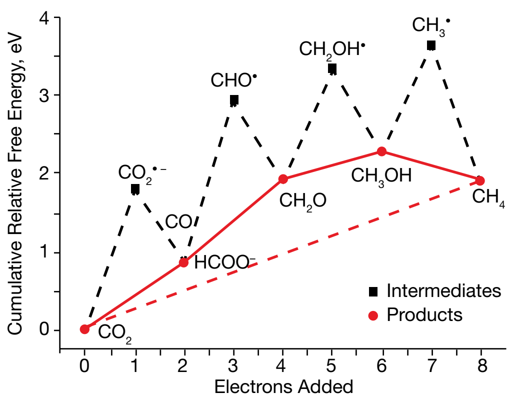
In theory, CCUS is an attractive and potentially viable way to significantly reduce anthropogenic carbon emissions. In practice, many technological, political, and economic hurdles to development and scaling of these technologies must be overcome. Carbon capture and sequestration, often the poster child of CCUS, has historically faced several major hurdles, mainly economic and political.

Who should pay? First consider capital costs.

Shell's Quest project near Fort Saskatchewan, Alberta, Canada, will capture and sequester 1 million m.t./yr of CO_2. The plant, which came online in late 2015, cost on the order of C$1.35 billion (US$1 billion) — much of it public money *(16, 17)*.

Proponents argue that this type of public expenditure is necessary because CCS is the only technology that has the potential to reduce global CO_2 emissions from existing facilities on a large scale. Industry groups designing and building these facilities argue that public investment is warranted, since ultimately the public will benefit from reduced emissions.

On the other hand, detractors of CCS argue that such investments are better allocated elsewhere, such as to developing or deploying alternative technologies that are either inherently less carbon intensive or on other mitigation or adaptation projects altogether. Some view public CCS investment as nothing more than another subsidy of a fossil-fuel industry at a time when non-fossil sources should be favored.



▲ **Figure 5.** Converting CO_2 into most chemical products involves an energy penalty. Depending on the pathways (dashed lines) and intermediate carbon-containing molecules produced along the way (black), the energy penalty can be modest or severe. The black dashed lines depict possible pathways from CO_2 as the starting point to a handful of common CO_2-derived products. The thermodynamic best-case pathway (red dashed line) goes directly from CO_2 to methane (CH_4). Source: Dmitry Polyansky, Brookhaven National Laboratory.

Enter carbon conversion. Carbon dioxide conversion and utilization exists in the same context as CCS. However, CCUS is not as well-known as CCS (and projects generally do not exist at the scales found in the CCS world), and therefore has not suffered the same economic and political pushback. Still, the value and potential of carbon conversion and utilization technologies is the subject of debate — not just in the CCS community, but also in the energy and chemical processing communities.

The debate centers around three main issues:

• *thermodynamics*. The first point of debate relates to the basic thermodynamics and energetics of the proposed CO_2-conversion chemistries (Figure 5). Carbon dioxide, a byproduct of combustion, is a low-energy molecule. Converting CO_2 into a molecule of higher energy (*e.g.*, a liquid fuel) necessarily involves a net energy input. Such a process is not ruled out by thermodynamics, but the energetics make it difficult to develop a cost-efficient and CO_2-neutral process at industrial scale.

It is worth pointing out, however, that a lower-energy form of carbon than CO_2 — carbonates — is found throughout earth's crust in the form of limestone ($CaCO_3$). Conversion of CO_2 into carbonates could require less energy input — enabling cost-efficient industrial processes for converting CO_2 into higher-value chemicals.

• *economics and carbon budget*. The second point of debate concerns the perceived trade-off between producing high-value products from CO_2 and reducing global CO_2 emissions in a meaningful way. Consider the economics of manufacturing and commodity markets. Low-volume products typically are sold at higher unit prices, while high-volume bulk products are sold at lower unit prices. Several optimal production volumes within the volume-price spectrum will make business sense. The most-profitable scenario for CO_2-conversion processes may be the one with the highest-value products produced in low volumes and with the lowest operating costs. The scenario that maximizes reductions in GHG emissions, on the other hand, could involve producing lower-value products in vast quantities. Hence there is a perceived trade-off between profitability and CO_2 reduction.

• *mitigating CO_2 on a global scale*. A third critique of carbon conversion and utilization technologies is that they could not consume a large enough fraction of the total CO_2 emissions to make a difference *(18)*.

One study analyzed the GHG emissions from the production of the top 50 commodity chemicals produced globally and concluded that CO_2 conversion can be, at best, a niche solution *(19)*. However, this type of analysis overlooks two crucial factors: avoided emissions, *i.e.*, CO_2 emissions not produced in the standard manufacture of a chemical when that chemical is instead manufactured from CO_2; and nontraditional or new chemical markets that could utilize CO_2-derived products under the right economic conditions.

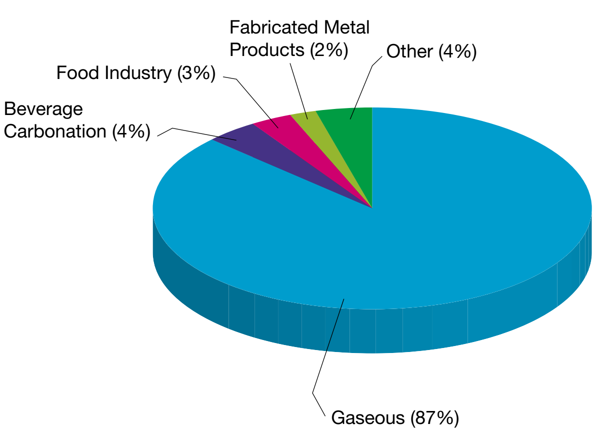
Another analysis estimated that maximum deployment of currently known CO_2 conversion processes would consume 300 million m.t. of CO_2 and in doing so would reduce CO_2 emissions by 5% indirectly through avoided emissions *(11)*. For comparison, approximately 220 million m.t. of industrial CO_2 was consumed in 2015 for industrial markets. The leading applications for CO_2 are EOR, beverage carbonation, and the food industry (Figure 6).

Proponents of CO_2 conversion and utilization point to the additional benefits of minimizing the world's reliance on fossil-based hydrocarbons as energy and chemical feedstocks, and the use of CO_2-derived fuels as an energy-storage mechanism.

In the midst of these challenges is an opportunity to catalyze technology innovation and collaboration. One strong point of consensus among many in the CCUS community is that gaps persist between plant operators, synthesis chemists, catalysis experts, sequestration experts, and others. Each community has its own nuanced view of the problem and the solution, but none has yet developed a cost-effective breakthrough.

That is precisely the dilemma that XPRIZE hopes to address through the NRG COSIA Carbon XPRIZE Competition. The prize model and competition format explicitly invite creative minds from any discipline to form teams to develop new carbon conversion and utilization systems. XPRIZE has established an ambitious target that can only be achieved by the careful integration of several technologies into a single efficient process. The hope is that individuals and groups with a wide variety of experience and backgrounds will collaborate by combining technology subsystems (*e.g.*, in broad terms, CO_2 capture, CO_2 purification, catalysis, conversion) to optimize the overall process.

By explicitly allowing participants to use a wide range of biological, chemical, and other process technologies, XPRIZE hopes to encourage a broader conversation that challenges conventional wisdom and invites new ideas and new approaches, even those not traditionally associated with energy or climate. In challenging teams to develop integrated solutions, we also support the partnerships on technology, business planning, financing, and process optimization that will help competitors to thrive and benefit from participation in the competition.



▲ **Figure 6.** Most industrial CO_2 is consumed in gaseous form (87%), with the rest consumed in liquid or solid form. Enhanced oil recovery (EOR) is the single largest end-use application of industrial CO_2, and accounts for the majority of the gaseous demand.

Technology horizon for CCUS

The XPRIZE competition is ramping up at a crucial time. The international climate change agreement announced in Paris has set high expectations for GHG

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emission reductions, yet many of the technological, regulatory, business, political, and social hurdles to reducing CO_2 emissions persist. XPRIZE's vision is that, if given the right venue and public support, many of the CCUS technologies and communities of practice mentioned in this article may be poised to achieve radical breakthroughs in the path toward decarbonization.

As this article goes to print, XPRIZE is accepting registrations and submissions from teams around the world. Although this competition will take place within the context of the current CCUS landscape (see sidebar), it is designed to draw new ideas, perspectives, and technology and process innovations. The most exciting part is that it is almost impossible to predict what teams and innovations will emerge during the competition. We look forward to seeing breakthroughs and innovations in several technology areas, and we hope the competition will be a springboard to breaking barriers and filling in the existing technology gaps.

Capture and conversion integration. Carbon capture technology has traditionally been the domain of the CCS community, while carbon conversion is part of the catalysis, synthesis chemistry, and materials science communities. Integrating these groups is necessary to create the inputs (CO_2 stream) and outputs (products) that will enable economic opportunity and have a real impact on global emissions and material synthesis. Greater collaboration between these communities and their various stakeholders may result in increased performance and tangible technology benefits on both sides. For example, innovations in the capture and separation of CO_2 from dilute and/or concentrated sources would be a tremendous boon to all stakeholders, whether they focus on sequestration, air cap-

XPRIZE and Incentive-Based Innovation

XPRIZE creates and manages the world's largest global, high-profile incentivized prize competitions that stimulate investment in research and development worth far more than the prize itself in order to solve the world's Grand Challenges. The organization motivates and inspires brilliant innovators from all disciplines to leverage their intellectual and financial capital for the benefit of humanity. Active prizes include the $5-million IBM AI XPRIZE, the $7-million Shell Ocean Discovery XPRIZE, the $20-million NRG COSIA Carbon XPRIZE, the $30-million Google Lunar XPRIZE, the $10-million Qualcomm Tricorder XPRIZE, the $15-million Global Learning XPRIZE, and the $7-million Barbara Bush Foundation Adult Literacy XPRIZE.

Incentive prize competitions are powerful tools for inspiring and showcasing breakthroughs and for engaging a broad community of stakeholders around a common goal. The success of prizes at supporting science and technology communities has attracted growing attention from government agencies, independent charities, and science-oriented foundations. The incentive prize model, in which only the successful demonstration of a performance target is rewarded, is becoming more popular. Recently announced XPRIZE competitions present opportunities for the chemistry, chemical engineering, and materials science communities in particular.

The NRG COSIA Carbon XPRIZE is a four-and-a-half-year global competition open to any team that can demonstrate the conversion of post-combustion CO_2 into valuable products. The winning team will demonstrate conversion of the largest quantity of CO_2 into one or more products with the highest net value. Judges will take into account production costs and the market volumes and prices of the product(s) produced. Finalists will demonstrate their CO_2 conversion technologies using actual emissions from an operating power station, either at the Integrated Test Center (ITC) tied to the Dry Fork Station, a 385-MW coal-fired power station in Gillette, WY, or at a natural-gas-fired power station in Western Canada.

The NRG COSIA Carbon XPRIZE aims to not only support technology game-changers, but also to catalyze the post-prize markets and investments. This support includes celebrating all teams — including those that fail — and providing lessons for the entire community.

It is designed to be a catalyst of exponential change and growth in a field that is experiencing growth in the number, size, and nature of funding opportunities globally. Some notable examples include the Virgin Earth Challenge, a prize competition for direct air capture; the upcoming €1.5-million European Union (EU) Horizon 2020 prize for CO_2 conversion; the Climate Change and Emissions Management Corp. (CCEMC) Grand Challenge program supported by the Province of Alberta, Canada; program funding of approximately US$110 million since 2009 from the German Ministry of Education and Research, and similar program funding totaling roughly US$110 million from the U.S. Dept. of Energy; and anticipated program funding of 30 billion Yuan (US$4.7 billion) from China devoted to CO_2 conversion and utilization in heavy industry.

Such increasing funding sends a signal that there is value in rapidly developing and commercializing new CCUS technologies. The Carbon XPRIZE is designed to accelerate this momentum by inspiring not only new technologies, but new ways of framing and approaching the carbon, energy, and climate challenges. Demonstrating positive technology solutions to what is often viewed as a hopeless or intractable problem can be a way to reinvigorate the conversation. In particular, it will be crucial to shift the media, business, and public narrative away from despondency and withdrawal to one of positive opportunity and action. If we can do that, we will have achieved something truly great.

ture, conversion, or another CO_2 mitigation approach.

Innovation in catalysis. Novel or improved catalysts will likely play a significant role in changing the thermodynamics of the conversion of CO_2 molecules into other products. The vetting of a wide array of novel and conventional catalytic approaches from competitors will be extremely exciting and meaningful for the broader catalysis community.

Energy and process efficiency. Scaling up CO_2-mitigation technologies will require teams to use real-world process engineering to move rapidly through demonstration of integrated solutions. Teams that can demonstrate energy efficiency and operating efficiency, specifically minimal use of reagents and other material inputs, will do well in the XPRIZE competition, and beyond.

Novel conversion products. Existing markets for products derived from CO_2 are limited. In addition to the demand for the products currently produced from CO_2, there is demand for novel products, including advanced materials, polymers, ceramics, liquid fuels, and cements. While these processes are at various stages of development, most remain in the laboratory phase. With rapid advances in the production processes and basic technology at the heart of these products, it is possible to see the rapid growth of new markets for CO_2. Exciting breakthroughs in carbon conversion are likely to drive demand for CCUS.

Collaboration across nontraditional disciplines. The open format of the competition provides a level playing field for a wide range of technologies and approaches to compete and to be judged according to the same simple criteria. Naturally, some technologies will fall outside the scope of the competition, either explicitly (*e.g.*, CO_2 utilization such as EOR or liquid CO_2 for cooling) or because they fail to meet a basic performance threshold. Nevertheless, we expect and encourage collaboration and sharing among teams not normally associated with CCUS, which might include chemical, biological, agricultural, polymer, or other material or application specialists. CEP

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