TECHNOLOGY

CARBON UTILIZATION— A VITAL AND EFFECTIVE PATHWAY FOR DECARBONIZATION

Summary Report

CENTER FOR CLIMATE AND ENERGY SOLUTIONS

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EXECUTIVE SUMMARY

The capture and utilization of CO_2 and other carbon oxides emitted from power generation and industrial facilities has been technologically feasible for generations and has gained greater attention in recent years as a tool for reducing greenhouse gas emissions. Captured carbon can be stored in geologic formations, or used either to produce oil from depleted wells through the enhanced oil recovery (EOR) process (which sequesters the CO_2 underground), or in the creation of a variety of products. These measures generate revenue that can partially offset the costs associated with capture.

Because EOR is already widely practiced, it is not considered by this report. Instead, the focus is on non-EOR utilization of captured carbon, which offers the potential to significantly contribute to greenhouse gas emissions reduction. Pathways include the production of construction materials, fuels, plastics, chemicals, and algae-based products (e.g., fuels, animal feed, and fertilizers). Each of these sectors, along with their potential for market growth is explored herein.

Carbon capture and utilization (CCU) includes the use of all carbon oxides, including CO_2 and carbon monoxide (CO), that would displace the release of greenhouse gases into the atmosphere. The alternative term "CO_2U" applies to technologies that use only CO_2 specifically. Other broad terms for utilization include "carbon recycling" and "carbontech."

While non-EOR carbon utilization does not, at present, greatly contribute to greenhouse gas reduction it offers significant potential to do so in the coming decades, given advances in technology, wider commercialization, and supportive government policies. CCU may be an especially useful tool for decarbonizing certain industrial sectors and providing an option in locations where either social issues or land constraints do not allow for other types of carbon disposition. Also, the continued development of CCU technologies may help drive carbon capture innovation generally, making broader greenhouse gas reductions possible.

Numerous government agencies, non-governmental entities, and academic institutions have recently considered the potential development of carbon utilization and how government polices might encourage it. Rather than duplicate that body of research, this report seeks to provide an overview of options, growth and greenhouse gas reduction potential summarized by use category.

CARBON UTILIZATION PRODUCTS AND PROCESSES

As to particular sectors, construction materials that rely on CO_2 utilization today represent the most widespread of all non-EOR CCU sectors and are projected to continue growing as market preferences for low-carbon materials expand. However, prescriptive standards for products like concrete are a significant challenge to the wider acceptance of CO_2-based materials. Low-carbon aggregates (the gravel, sand, or crushed stone used with cement to form concrete) do not face the same hurdle to market entry, but they are not currently competitive purely on price, and so would require some form of policy support. Taken together, low-carbon construction materials (including aggregates) offer the greatest prospects for growth in both market value and greenhouse gas reduction potential.

Low-carbon fuels, chemicals, and plastics are diverse categories of products that are considered together here because their production processes have similarities. Conversion of CO_2 to fuels and chemicals often entails adding hydrogen to the carbon in CO_2. Developing catalytic, electrochemical, photolytic and other processes that can facilitate this type of reaction and generate products inexpensively is an important research priority. Advancing these processes to operate at commercial scale represents a significant technical challenge.

Another key challenge to carbon utilization for the production of fuels is the availability of low-cost, low-carbon hydrogen. Steam methane reforming (SMR), the process by which methane reacts with steam at a high temperature to produce hydrogen, is in use with carbon capture at a number of projects worldwide. Water electrolysis, where hydrogen is separated from water in an electrochemical cell, is far more expensive and requires low-carbon electricity but is an area of active research. An increase in market demand for hydrogen would likely be met in the short term by SMR in conjunction with carbon capture.

Algae-based carbon utilization offers significant near-term opportunities in some product categories (e.g., biofertilizers, aquaculture, livestock feed, and feed additives), while other product categories (e.g., fuels, bioplastics) require research and development (R&D) efforts to drive down costs, especially downstream processing costs. One significant advantage of algae-based carbon utilization is that high-purity CO_2 is not required to support algae growth, and some combustion waste products such as nitrogen oxides (NOx) and sulphur oxides (SOx) can actually serve as algal nutrients.

POLICY CONSIDERATIONS

All CCU sectors face challenges to commercialization in terms of either technology, cost, or market acceptance. These can be overcome with supportive government policies in four areas: financial enablers, R&D support, development of CO_2 transportation infrastructure, and market preferences such as procurement policies and "green labeling." Some broad policy approaches, such as those that encourage all applications of carbon capture (not only beneficial carbon utilization), may be necessary to generally help foster decarbonization. However, sector-specific challenges may also be addressed.

One broad-based policy currently in place is the "45Q" tax credit, enacted in 2018, which offers a tax preference for either qualified utilization of carbon oxides, or geologic storage (including in saline formations or through EOR). However, the U.S. Internal Revenue Service is not expected to publish the guidance necessary to implement the law until later in 2019, which has caused uncertainty for CCU developers who might expect to benefit from the tax credit. Given the delay in implementation, Congress may need to extend the law's deadline for commencing project construction and lower the eligibility threshold requirement if it expects small CCU developers to benefit.

Several policies currently before Congress would encourage the deployment of CCU. Legislation known as the USE IT Act, introduced in both houses of Congress, would facilitate coordinated development of CO_2 pipelines and provide CCU research prize funding. Similarly, CCU will advance sooner if relevant federal R&D is expanded both in terms of its funding level and its support for pilot-level work. Finally, facilitating the construction of adequate infrastructure for the movement of CO_2 is also important to sparking widespread CCU deployment.

As for sectoral issues, government procurement rules can act as market drivers, while federal R&D spending should be targeted to ensure successful pathways to commercialization, not only basic research. Low-carbon construction materials will benefit from incentives at all levels of government that encourage the use of components containing captured carbon. For fuels, renewable fuel standards, low-carbon fuel standards, and other incentives will grow the low-carbon fuel market, if they include fuels from carbon utilization.

This report focuses on policy actions that can foster growth in carbon utilization by 2030, in part because markets beyond that timeframe are difficult to predict, but mostly because deliberate near-term action is needed if CCU is to expand significantly. However, more general climate policies, such as carbon pricing or the inclusion of fossil-based carbon capture in clean energy standards, are also necessary to lay the foundation for a low-carbon economy that includes new demand for CCU-based products and processes.

I. INTRODUCTION AND CONTEXT

The scientific evidence for climate change is undeniable, and the consequences of climate change are already being felt through sea level rise and extreme weather events. The most recent estimates by the Intergovernmental Panel on Climate Change (IPCC, 2018) stated that impacts on health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5 degrees C and increase further with 2 C above pre-industrial levels. To avoid these impacts and give adaptation efforts a better chance of success, economies must transition to lower-carbon technologies.

One component of the suite of technologies necessary for deep decarbonization is carbon capture, utilization, and storage (CCUS). The IPCC has noted that without CCUS, the costs of addressing climate change will be significantly higher.[1] The most economical and immediate path forward for the development of carbon capture is closely tied to creating corridors of CO_2 transportation infrastructure that link sources of CO_2 to enhanced oil recovery (EOR) markets, and eventually other types of geologic storage.

Additionally, accelerating deployment of carbon utilization would provide a number of important pathways for decarbonization. For instance, while many sources of carbon emissions can be addressed through traditional carbon capture, certain industrial sectors are harder to decarbonize. One example would be aviation fuel emissions, which cannot be "captured" in real time by traditional means; using captured carbon to produce aviation fuel that has lower carbon content *before* it is combusted offers an effective pathway to reduce emissions in this sector.

Geography may represent another circumstance where carbon utilization may be useful. In certain jurisdictions, such as those where any type of carbon storage may be constrained by social license to operate issues or by land use restrictions, carbon utilization may be an important decarbonization option. In other locations, the small size and proximity of existing CO_2 sources may not justify building the infrastructure necessary to transport and store the CO_2. In those regions, creating an on-site market for carbon capture and use (CCU) may be a pathway for decarbonization.

This paper summarizes the current state of knowledge on CCU in an effort to highlight the potential for using carbon as part of the transition to a lower-carbon economy. To understand the technologies and the importance of policies to accelerate their availability, this report is built on a review of existing literature, a series of interviews and finally a workgroup of technical experts who provided significant insights and direction for this work. C2ES interviewed more than 20 developers and other leaders to better understand how policy could spark growth in beneficial carbon utilization. The questions used to guide those interviews can be found in **Appendix B.**

WHAT IS CARBON UTILIZATION?

The capture, utilization, and storage of carbon oxides has been technologically feasible for generations and has been in operation since the early 1970s. Currently, 19 "full-scale" projects are in operation worldwide. Of these, 14 use captured CO_2 for enhanced oil recovery (EOR) while five store CO_2 in saline aquifers.[2]

Carbon utilization (a term used in this report interchangeably with CCU) is a broad term used to describe the many different pathways where captured CO_2 —or in some cases carbon monoxide (CO)—can be used or "recycled" to produce economically valuable products or services.

EOR using CO_2 is the most widely practiced form of carbon utilization today. Approximately 17 million metric tons per year of anthropogenic CO_2 are currently used in the United States for EOR, along with much higher quantities of CO_2 from naturally-occurring, but depleting, sources. Future domestic CO_2 use applying current state-of-the-art CO_2-EOR techniques for economically recoverable oil is projected to be 10.7 gigatons (Gt). Projections based on the development of "next-generation" EOR techniques applicable to U.S. resources, such as those designated as the residual oil zone (ROZ), are more uncertain than for state-of-the-art techniques, but indicate the use of an additional 23.6 Gt of CO_2.[3]

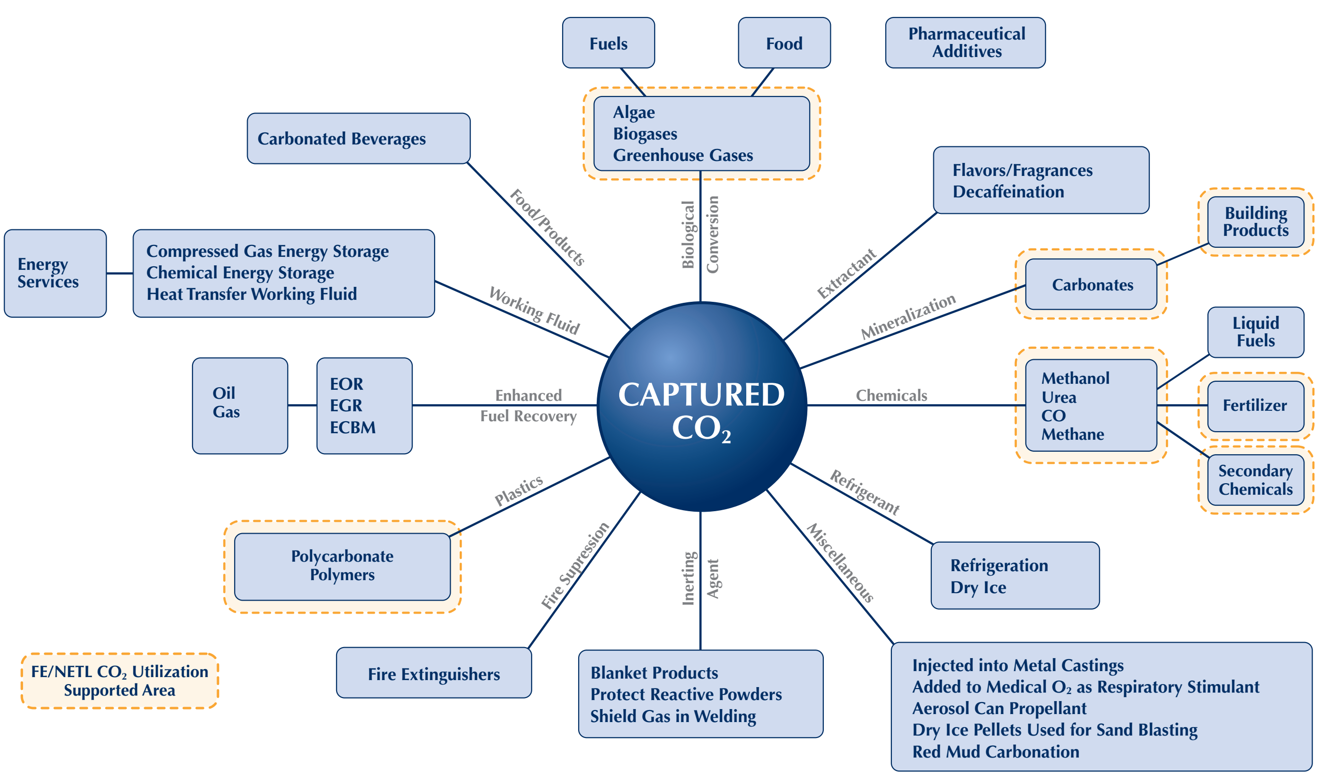
Because it is already widely practiced, CO_2-EOR is not further addressed in this report. Instead, non-EOR utilization approaches are the focus of material presented below.

The wide array of carbon utilization options is illustrated in **Figure 1**. Each carbon utilization pathway has specific characteristics in terms of technical maturity, market potential, economics, and CO_2 reduction impact. Given this diversity, implementing both broad-based policies and sector-specific ones together will have the greatest impact on CCU development.

Entities from across the spectrum of greenhouse gas emissions stakeholders are increasingly focused on new uses for recycled carbon and how policies can encourage them. Five prominent examples include:

- The U.S. Department of Energy commissioned the development of a report by the National Coal Council (NCC) entitled *CO_2 Building Blocks: Assessing CO_2 Utilization Options*[3]. The 2016 report's primary focus, "is to assess opportunities to advance commercial markets for CO_2 from coal-based power generation and the extent to which CO_2 markets for EOR and non-EOR utilization could incentivize deployment of carbon capture, utilization and storage (CCUS) technologies."
- China's Ministry of Science and Technology (MOST) published the results of its comprehensive scientific assessment of geologic and non-geologic CO_2 utilization technologies in the country, highlighting the following technologies as holding particular promise: (1) CO_2-EOR, with and without enhanced water recovery; (2) use of CO_2 from coal conversion technologies for use in enhanced coal-bed methane recovery; and (3) use of CO_2 from steel and cement production for mineralization of bulk solids and cultivation of microalgae that could

FIGURE 1: CO2 utilization pathways



Source: National Energy Technology Laboratory www.netl.doe.gov be used for fertilizer or as feedstock for fuels and other chemicals.[4]

- The European Commission published a report[5] in 2018 that concluded, among other things, that, 1) carbon utilization may play a role to reduce the role of fossil fuels in the economy and provide help reaching climate change mitigation targets, and 2) uptake of carbon utilization will depend on a favorable legislative and investment environment.
- The XPRIZE Foundation is holding a competition with $20 million in total prize money, funded by utility company NRG and Canada's Oil Sands Innovation Alliance (COSIA), in which teams from multiple countries are testing and demonstrating breakthrough technologies that will convert CO_2 emissions into valuable products like building materials, fuels and other items. Teams will be scored based on how much CO_2 they convert and the net value of their products.[6]
- In 2016, the Global CO_2 Initiative released *A Roadmap for the Global Implementation of Carbon Utilization Technologies*,[7] which estimated the potential market size and emissions reduction associated with the "Carbon Based Products Industry" (CBPI)—essentially non-geologic carbon utilization.

II. CARBON UTILIZATION'S MARKET AND EMISSIONS POTENTIAL

The Global CO_2 Initiative *Roadmap* (2016) provided a useful projection of how carbon utilization could grow in coming years if certain scenarios and assumptions are realized. To provide insight into what full potential might look like, the *Roadmap* lays the ground work for what might be considered high-end markers for the potential of carbon utilization moving forward. A significant conclusion summarized from the report was that, "Funding, incentives and prompt strategic action are necessary to move the CBPI [Carbon Based Products Industry] to its full potential... [at which] CBPI could reach or exceed US $800 billion by 2030."

As for emissions reduction, the *Roadmap* concluded that, "Critically, the CBPI has the potential to utilize seven billion metric tons of CO_2 per year by 2030—the equivalent of approximately 15 percent of current annual global CO_2 emissions."

The *Roadmap* divided utilization approaches into seven general categories, as illustrated in **Figure 2.**

The status of these technologies, and their associated opportunities for market growth and greenhouse gas reduction potential are presented together graphically in **Figure 3** and summarized in tabular form in **Appendix A**. The sizes of the "balloon" markers in **Figure 3** correspond to the relative emission reduction potential for each sector at different points in time. While current product volumes across all CCU sectors are small, they offer significant potential in the longer term.

FIGURE 2: General categories of utilization technologies

Construction Materials
- Cement and Concrete
- Asphalt
- Aggregate
- Timber/super hardwood

Fuel
- Synthetic (methanol, butanol, natural gas, syngas, etc)
- Micro-algae fuel
- Macro-algae fuel

New Materials
- Carbon Fiber
- Carbon nanotubes and fullerenes
- Graphene

Industrigas & Fluids
- Enhanced oil recovery
- Enhanced coal bed methane recovery
- Enhanced water recovery
- Semiconductor fabrication
- Power cycles

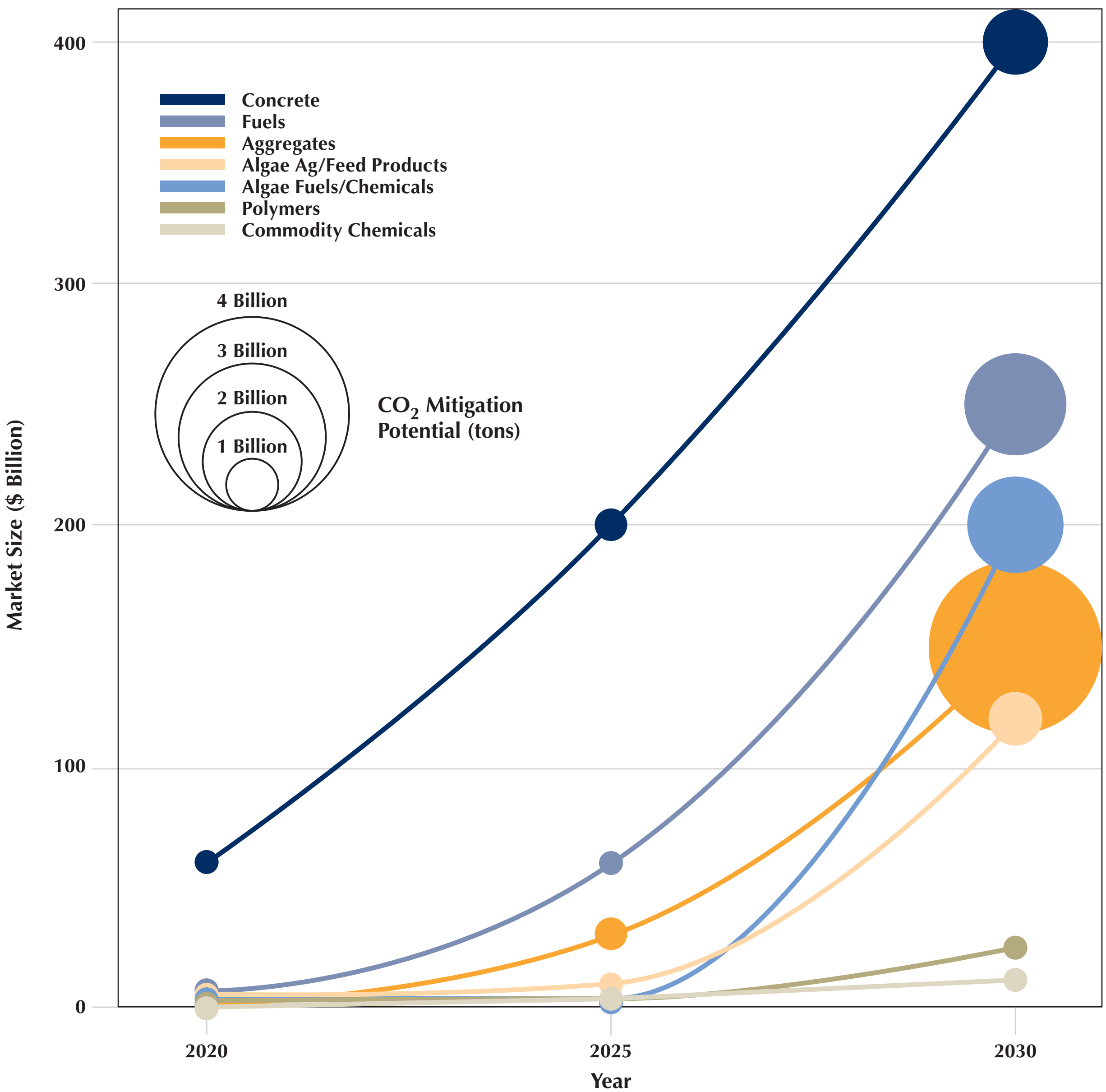
Plastics
- Polyurethane foams
- Polycarbonate (glass replacement)
- Acrylonitrile butadiene styrene
- Many more

Agriculture & Food
- Algae-based food or animal feed
- Microbial fertilizer
- Biochar, bio-pesticides, bio-cosmetics

Chemicals
- Preservatives (formic acid)
- Medicinal
- Antifreeze (ethylene glycol)
- Carbon black
- Many more

Source: A Roadmap for the Global Implementation of Carbon Utilization Technologies https://assets.ctfassets.net/xg0gv1arhdr3/5VPLtRFY3YAIasum6oYkaU/48b0f48e32d6f468d71cd80dbd451a3a/CBPI_Roadmap_Executive_Summary_Nov_2016_web.pdf

FIGURE 3: Market size and GHG mitigation potential of selected CCU sectors



Source: C2ES/Cogentiv Solutions analysis of market trends and potential greenhouse gas reduction capacity based on market projections from the Global CO_2 Initiative's Roadmap.

Figure 3 helps to visualize the notion that the respective market potential for each sector is different, and doesn't always correlate with its greenhouse gas reduction potential. For instance, the current market value of low-carbon concrete is greater than all other sectors, as is its level of greenhouse gas reduction. And while concrete promises to remain the largest CCU sector in terms of market value, the potential greenhouse gas reduction contributed by other sectors, including low-carbon fuels, algae-based fuels and products, and aggregates, may surpass that of concrete by 2030. This suggests that, given favorable policies, all CCU sectors have significant potential for market growth and emission reduction.

Table 1 shows the numeric values associated with the different sectors shown in **Figure 3**, which were compiled from a variety of sources, including reports focused specifically on carbon utilization opportunities,[8,9] energy related publications,[10] trade publications,[11] financial market analyses,[12] technical publications,[13] and United Nations organization reports.[14] To achieve these projections, policies and measures will be needed to support the growth of carbon utilization technologies and products across the various value chains. Without this support, it is uncertain whether this potential can be realized. Additional detail regarding various CCU technologies and policies is presented in the sections below.

TABLE 1: Market size and GHG mitigation potential of selected CCU sectors

MARKET SIZE: $ BILLION	2020	2025	2030
Concrete	60	200	400
Fuels	5	60	250
Aggregates	4	30	150
Algae Ag/Feed Products	3	10	120
Algae Fuels/Chemicals	2	4	200
Polymers	1	3	25
Commodity Chemicals	0	5	12

GHG MITIGATION: BILLIONS OF METRIC TONS OF CO_2	2020	2025	2030
Concrete	*	0.7	1.4
Fuels	*	*	2.1
Aggregates	*	0.7	3.6
Algae Ag/Feed Products	*	*	1.2
Algae Fuels/Chemicals	*	*	2
Polymers	*	*	*
Commodity Chemicals	*	*	*

* less than 0.5 billion tons CO_2

Source: C2ES/Cogentiv Solutions analysis of market trends and potential greenhouse gas reduction capacity based on market projections from the Global CO_2 Initiative's Roadmap.

III. CARBON UTILIZATION'S SECTORS AND TECHNOLOGIES

CONSTRUCTION MATERIALS

Construction materials represent a large, near-term opportunity for carbon utilization, principally through cement and aggregate (the gravel, sand, or crushed stone used with cement to form concrete). The current global market for concrete is around 30 billion tons and is estimated to grow to about 40 billion tons by 2030. Similarly, the global aggregates market is 25 billion to 35 billion tons, and is estimated to grow to about 50 billion tons by 2030. If carbon is used as an input and replacement for calcium carbonate, the Global CO_2 Initiative estimates the associated emissions reduction potential in the construction materials sector could be in the range of 1 billion to 10 billion tons by 2030 (see **Appendix A**).[15] Technologies to develop new structural materials from captured carbon, such as carbon fibers, are also in development.

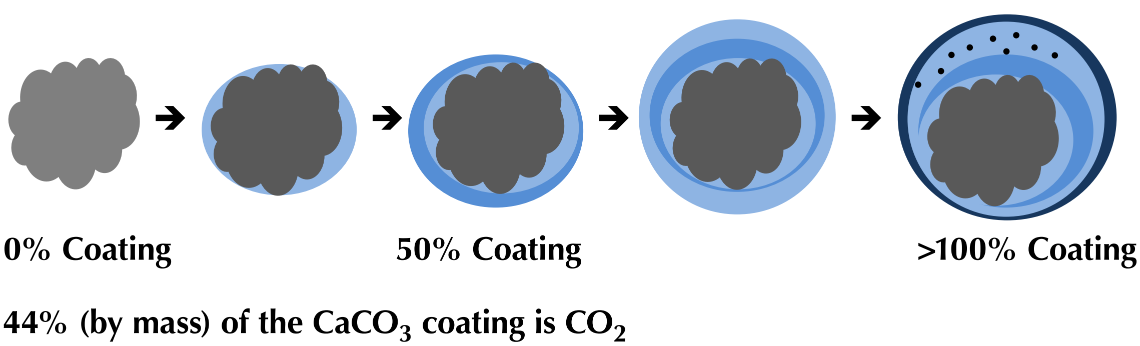
One of the most significant challenges of utilizing CO_2 is that it is a very low-energy molecule. For most applications, a form of energy (either thermal, chemical, or electrical) has to be added to convert CO_2 into a different molecule to form fuels and chemicals. In contrast, carbonates are even lower-energy than CO_2, which minimizes the energy needed to form them. When CO_2 is incorporated into the production of cement and aggregate (and thus concrete), forming carbonates, it is not necessary to add energy to overcome thermodynamic constraints. This is important because the energy required to make large volumes of material could be extremely expensive, rendering the materials non-cost-competitive and potentially less beneficial to greenhouse gas reduction efforts.[16]

One way that CO_2 can be incorporated into building materials involves formation of a carbonate coating on small solid materials, as illustrated in **Figure 4**. In order to form carbonate-based solids, the negatively charged carbonate ions must be balanced by positively charged ions. For cement and aggregate, those ions are most commonly either calcium or magnesium.

Unfortunately, ionic calcium and magnesium are not widely available in easily accessible forms. Possible sources include seawater, volcanic rocks, slags and other alkaline industrial wastes, though each of these is challenged by the need for proximity to a CO_2 source in order to be economic. Development of methods to produce reliable, sustainable, low-cost calcium and magnesium is an area of active research.

Another way that CO_2 can be used in construction materials is referred to as direct utilization or adding CO_2 to concrete during curing. This reduces the amount of cement required to produce equivalent-strength concrete, reducing emissions from cement production

FIGURE 4. Formation of aggregates using carbonate coatings and waste CO_2



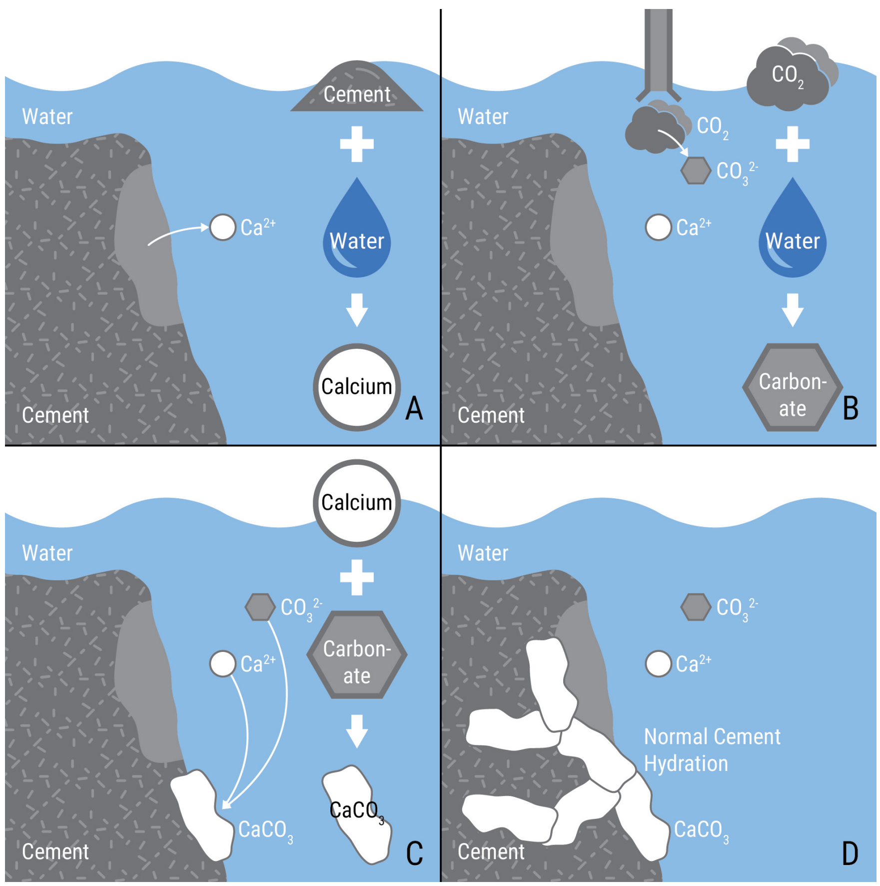
Source: Blue Planet http://www.blueplanet-ltd.com/

in addition to the CO_2 incorporated into the concrete. The company Carbon Cure has applied this approach to over 100 conventional, Portland Cement-based ready-mix concrete plants in the United State and Canada. CO_2 is injected into the concrete mix, and as the concrete cures, the CO_2 is permanently mineralized, as illustrated in **Figure 5**.[17]

Solidia Technologies uses a cement that contains more silica-rich materials than conventional Portland Cement. This unconventional cement binds with more CO_2 during curing and can be used to make low-carbon, high-strength, pre-cast materials. The technology has been demonstrated at pilot scale and is anticipated to be ready for commercialization soon. Current research and pilot projects associated with direct utilization focuses on increasing the amount of CO_2 absorbed while still maintaining concrete product standards.

The existence of prescriptive standards, such as those of ASTM International (formerly known as the American Society for Testing and Materials), represents a significant challenge for advancing the use of CO_2-based construction materials. ASTM standards, for example, narrowly define a variety of parameters/characteristics including setting times and compressive strength for Portland Cement-sand mixtures, and the specific amounts of ground limestone and inert extender that can be blended with cement, among many others. If CO_2-based construction materials do not match those

FIGURE 5: CO_2 utilization in the Carbon Cure process



NOTE: Process consists of a) water added to cement leading to dissolution; b) CO_2 introduced and enters solution; c) solid phase calcium carbonate ($CaCO_3$) formed; d) normal cement hydration with $CaCO_3$ acting as a nucleating agent

Source: Adapted from Monkman http://nas-sites.org/dels/files/2018/02/MonkmanNASEM-Webinar-CarbonCure_180118-export.pdf specific requirements, they may not be accepted for use, even when they exceed performance levels of traditional materials. Successful entrants to the market, such as Carbon Cure, have focused on making incremental changes to traditional concrete formulations to minimize the acceptance challenges.

The use of carbonate as aggregate does not face the same hurdles to market entry, but its cost is a significant barrier. Current gravel aggregate costs are typically near $50/ton depending on location, while technology developers say low-carbon aggregate might sell for $70 to $100/ton[18]. Thus, it is unlikely that CO_2-based aggregate could be widely competitive purely on price, and instead would require some form of policy support.

FUELS/CHEMICALS/PLASTICS

Fuels, chemicals and plastics represent a significant opportunity for utilization technologies. Their potential markets are diverse and varied, but they are considered together here because their carbon utilization production processes tend to have some commonalities.

The Global CO_2 Initiative *Roadmap* estimates the total market size potential for the three product categories to range from $1 billion to more than $250 billion per year. That corresponds to an emissions reduction potential of 100,000 to 2.1 billion metric tons per year (**Table 2** and **Appendix A**). Again, while these estimates may represent high-end market potentials, a key takeaway is that fuels may have a much larger market and a much larger emission reduction potential than chemicals and polymers. Industrial emissions containing CO and CO_2 already are being biologically converted to low-carbon fuels at commercial scale today, creating fuels with over 70-percent greenhouse gas reductions compared to their fossil counterparts.

As noted in the section describing construction materials, CO_2 is a very low-energy molecule. And while formation of carbonates for construction materials does not require input of large amounts of energy, the use of CO_2 for fuels, chemicals, or polymers does require significant energy inputs to convert CO_2 into products. An exception to this occurs in cases where CO is present in industrial waste gases.

At a basic level, conversion of CO_2 to fuels and chemicals entails adding hydrogen (either in molecular form or from other reaction partners) to the carbon in CO_2. The two primary pathways for doing this are direct hydrogenation of CO_2, and indirect production (**Figure 6**), which involves conversion of CO_2 to carbon monoxide (CO) followed by synthesis of specific products.

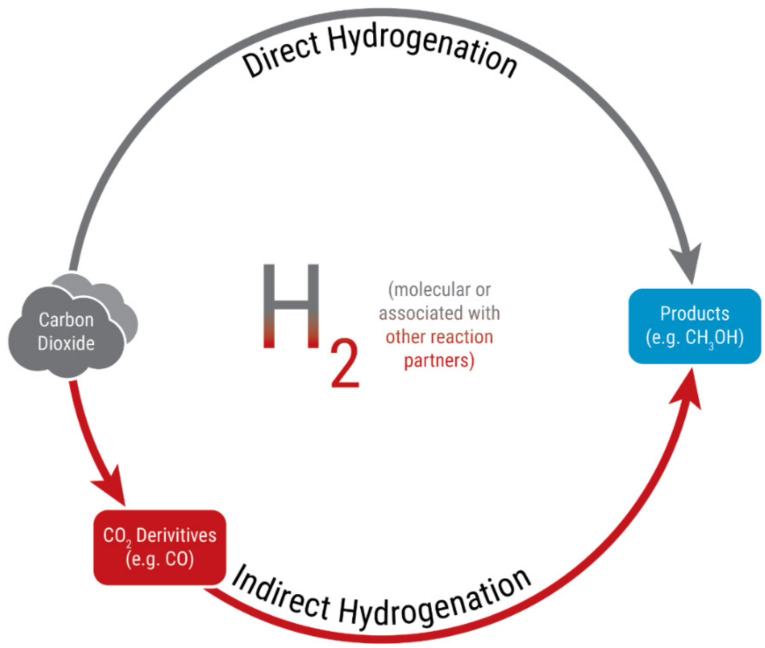
TABLE 2: Market Size Potential

Product	Current Potential Revenue ($ billion)	2030 Potential Revenue ($ billion)	Current Emissions Reduction Potential (million tons)	2030 Emissions Reduction Potential (million tons)
Fuels	1 – 5	10 – 250	10 – 30	700 – 2,100
Methanol	0.1 – 0.2	1 – 12	0.1 – 1	5 – 50
Polymers	0.1 – 0.6	2 – 25	0.02 – 0.05	0.1 – 2

Note: Methanol is used as a representative for commodity chemicals.

Source: Global CO_2 Initiative, A Roadmap for the Global Implementation of Carbon Utilization Technologies *https://assets.ctfassets.net/xg0gv1arhdr3/5VPLtRFY3YAIasum6oYkaU/48b0f48e32d6f468d71cd80dbd451a3a/CBPI_Roadmap_Executive_Summary_Nov_2016_web.pdf*

FIGURE 6. Primary pathways for production of fuels from CO_2



Source: Carbon Dioxide Utilization (CO_2U) ICEF Roadmap 2.0 https://www.icef-forum.org/platform/upload/CO2U_Roadmap_ICEF2017.pdf.
Note that some industrial sources contain CO and do not require an initial conversion step.

Mechanisms for accomplishing this fall into the following categories:

- **Thermocatalytic:** Energy is provided in the form of heat (and pressure) and the reaction is driven by a catalyst that activates CO_2 so that it can react with hydrogen.
- **Electrochemical:** Energy is provided in the form of electricity and reactions take place in an electrochemical cell.
- **Biochemical:** Living organisms or the unique products they generate (e.g. enzymes) convert CO_2 or CO to products.
- **Photochemical:** Solar energy provides the heat or electricity needed to drive catalytic conversion reactions.
- **Hybrid approaches:** The approaches noted above are combined (e.g. electrolysis coupled with thermocatalytic approaches, electrochemical reactions driven by microbes, etc.).[19]

In general, the two leading methods of hydrogen production are steam methane reforming (SMR) and electrolysis of water. Hydrogen production using SMR is currently much less expensive than water electrolysis. However, electrolytic production of hydrogen is an area of active research, and there is significant potential for reduced costs in the future. If demand for hydrogen to support CCU increases in the short term, it is likely that SMR coupled with carbon capture would be the lowest-cost option for meeting that short-term demand. Current examples of carbon capture technology paired with steam methane reforming include the Shell Quest project near Edmonton, Canada, an Air Products facility in Port Arthur, Texas, and the Tomakomai project in Hokkaido, Japan.

Direct Hydrogenation Pathway

Technology for direct hydrogenation—the process of adding hydrogen to CO_2 without first converting it to a different compound—exists and has been commercialized for production of methane, methanol and other chemicals. Methanol (CH_3OH) is an attractive product for CO_2 utilization because commercial processes exist to convert methanol to gasoline and other chemicals that are used in multiple industrial processes. Production of methanol from CO_2 has been tested at pilot scale, and a five million-liter-per-year CO_2-to-methanol plant is currently operating in Iceland (which enjoys the benefit of inexpensive hydroelectric power generation and geothermal heat that can be used for hydrogen production and process heating—see below).

However, costs associated with direct hydrogenation of CO_2 to methanol and other products are too high without some form of policy support to be competitive with the production of chemicals starting with fossil fuel-based feedstocks. The two components of the process needed for conversion—catalytically activated CO_2 and hydrogen—both have extremely high costs associated with them. Research to create better catalysts and more efficient separation processes is essential to drive down costs for the CO_2 activation step.

Availability of inexpensive, low-carbon hydrogen is another challenging piece of the puzzle. Many advocates for the utilization of CO_2 for fuels assume that availability of excess renewable energy will drive down the costs of electrochemical hydrogen production. Currently, electricity costs make electrochemical splitting of water to generate hydrogen uneconomic. The argument has been made that with excess renewable energy available at certain times on the grid, the cost of electricity for hydrogen production can be driven to nearly zero, making the process more economic.

However, that argument does not account for the intermittent nature of excess renewable electricity availability. If an electrochemical hydrogen production facility is only available for operation for a limited amount of time each day, the economics of the argument tend to fall apart due to the lower capacity factor and corresponding increase in capital costs per unit of production. The capital investment made for the facility would be based on continuous operation, which could not be delivered. One of the significant needs to help advance CO_2 utilization for fuels is a mechanism to deliver low-cost, low-carbon hydrogen that does not depend on the assumption of nearly-free electricity.

Direct electrochemical processes that convert CO_2 to fuels and chemicals have been demonstrated at laboratory-scale to generate a variety of products, including formic acid, methanol, methane, and ethylene. Challenges associated with direct electrochemical conversion processes include low selectivity in transferring charge (faradic efficiency); low current density that limits production rates; and poor stability of the electrodes. R&D is needed to develop improved electrode materials and structures and improved process designs for practical applications. One other promising area of active research is "hybrid" microbial electrolysis cells, in which microbial communities living in the electrochemical cell convert CO_2 to chemicals.

Indirect Production Pathway

The indirect fuels and chemicals production pathway involving conversion of CO_2 to CO prior to processing is similar to direct conversion but with a defined CO intermediate product. It is attractive because CO is much more chemically active than CO_2. The process of converting CO and hydrogen (i.e., syngas) into methanol and into hydrocarbons via Fischer-Tropsch (F-T) synthesis is very well-known, although it does require hydrogen.

The principal challenge for this approach is the CO_2-to-CO conversion step. Options include catalytically-driven processes such as reverse water gas shift (RWGS) to generate CO from CO_2, various forms of reforming, which use methane (or other light hydrocarbons) to convert CO_2 to CO, and electrochemical approaches such as polymer electrolyte membranes or solid oxide eclectrochemical cells. Fundamental advances such as catalysts that operate at lower temperatures and advanced gas separations techniques are required to commercialize these processes.

A near-term opportunity to advance CO_2 conversion technology that can potentially overcome the hydrogen cost/availability issue noted above is dry reforming of methane and CO_2 to produce methanol in natural gas producing regions. Natural gas producers in the Permian Basin, Bakken Formation, and the Marcellus/Utica Formation are under regulatory pressure to reduce flaring.

One mechanism to reduce flaring would be to produce methanol using the methane and CO_2 present in the natural gas. Traditional, low-pressure dry reforming is technically viable but is currently uneconomic for a variety of reasons, including issues surrounding coking. There are, however, technologies under development/commercialization that appear promising. An R&D initiative to support development of lower-cost technologies could provide an opportunity for a public/private partnership that advances CO_2 conversion technologies broadly, lowers CO_2 emissions associated with flaring, generates a saleable product, and addresses the methane regulatory issue for gas producers.

A good example of the importance of advancing this indirect conversion pathway is provided by technology developed by LanzaTech. The company has created a process through which engineered microbes convert CO into ethanol. This technology has been demonstrated at commercial scale using waste gas from steel production, which is high in CO content. The availability of CO was a critical component that allowed for the development of this successful utilization technology. Inexpensive, widespread availability of more chemically active CO generated from CO_2 could result in the advancement of multiple technologies to generate fuels and chemicals from CO_2.

Plastics are included in this section on fuels and chemicals because the building blocks of most polymers include the commodity chemicals discussed above. Processes that generate commodity chemicals from CO_2 will inherently produce polymers with lower life-cycle carbon emissions than those generated from petrochemicals.

Polymers can also play a significant role in carbon utilization through direct inclusion of CO_2 into the polymer matrix of various materials. For example, Covestro has developed a process that imbeds CO_2 within the polymer chain of polyols used in the manufacture of foams for products such as mattresses. Production using this approach started in 2016 near Cologne, Germany. The facility now produces approximately 5,000 tons/year of foams that incorporate CO_2. Research is being conducted to develop approaches that incorporate more CO_2 into their polymer blends.

ALGAE-BASED PRODUCTS

Algae-based carbon utilization holds near-term promise in some product categories (e.g., biofertilizers, aquaculture, livestock feed, and feed additives), while other product categories (e.g., fuels, bioplastics) will require additional R&D to drive down costs to be commercially viable.

Algae are extremely efficient photosynthetic organisms—sometimes referred to as CO_2 eating machines. In 2015, the IEA Clean Coal Centre noted several advantages to algae-based carbon utilization:[20]

- High-purity CO_2 is not required to support algal growth.
- Flue gas containing varying amounts of CO_2 can be fed directly to the microalgae, reducing or eliminating the need for CO_2 capture systems.
- Some combustion waste products such as nitrogen oxides (NOx) or sulphur oxides (SOx) can be used as nutrients for microalgae (microscopic algae).
- Microalgae could yield high-value commercial products. The sale of these high-value products could offset the capital and operating costs of the process.
- Algae can be grown in open raceway pond systems and closed photobioreactor systems, including flexible plastic film systems, tubular reactors, and flat panel systems.

The U.S. Department of Energy (DOE) has also noted that algae-based CO_2 conversion offers a number of economic and environmental benefits, including:[21]

- High potential yield per acre
- The ability to grow on land not suited for agriculture, as well as in brackish or waste water
- High absorption of CO_2 and relative ease of conversion into fuels and products.

One of the most attractive features of algae-based utilization is the wide range of potential products that can be generated, as noted in **Table 3**.

TABLE 3: Potential microalgae products and prices

PRODUCT	SUBSTITUTE	PRICE	UNIT
Biodiesel	Diesel	$2.27	USD/gal
Bio-ethanol	Gasoline	$3.96	USD/gal
Bio-methane (fuel)	Liquefied petroleum gas	$1.92	USD/gal
Bio-jet fuel	Jet fuel	$2.49	USD/gal
Electricity	Fossil energy	$0.13-$0.21	USD/kWh
Bio-methane (electricity)	Natural gas	$0.05-$0.06	USD/kWh
Biofertilizers	Synthetic fertilizers	$0.25-$0.63	USD/kg
Biostimulants	Growth promoters	$37.50-$312.50	USD/kg
Biopesticides	Synthetic pesticides	$5.00	USD/acre
Bioplastics	Fossil based plastics	$1.75	USD/kg
Food	Proteins, carbohydrates, oils	$50.00	USD/kg
Beta-carotene	Synthetic/natural	$275.00-$2750.00	USD/kg
Omega-3 polyunsaturated fatty acids	Fish	$50.00	USD/g
Aquaculture	Fishmeal/fish oil	$68.75-$625.00	USD/kg
Livestock Feed	Soybean meal	$300.00	USD/tonne
Feed additives	Botanicals, antibiotics	$20.00	USD/kg

Source: Adapted from http://bioenergykdf.net/billionton2016/overview

A potentially significant long-term product pathway associated with algal uptake of CO_2 is the production of fuels—which is similar in some respects to the fuels production pathways previously described. Fuels can be produced from algae through whole biomass conversion techniques such as hydrothermal liquefaction, through lipid extraction or through fermentation of carbohydrates. Some strains of algae, such as certain cyanobacteria, are capable of excreting fuel or fuel precursors, eliminating the need for extraction or conversion.

EPA analyses of algae-based fuel pathways under the federal Renewable Fuel Standard (RFS) program found greenhouse gas reductions of 69-85 percent on a full lifecycle basis versus petroleum-based alternatives. Algae-based renewable diesel is also approved by EPA under the RFS as a qualified advanced biofuel with lifecycle greenhouse gas emissions reductions of greater than 50 percent versus petroleum-based diesel.[22]

In addition, several very high-value algae-derived nutraceuticals (dietary supplements) such as astaxanthin and betacarotene, already have small but well-established and growing markets with values that can exceed $1 million per ton of product.[23]

Animal feed and feed ingredients are also significant markets for algae-based products—particularly aquafeeds for fish and shellfish. CO_2-based algae are effective substitutes for traditional wild fish sources of nutrients because they can serve as the base of the marine food chain that many fish meal species rely on. Bloomberg estimates the potential market size for fish feed is $9 billion and for livestock feed is $370 billion and expected to grow up to 40 percent in the next 20 years.[24]

IV. THE ROLE OF POLICY IN ACCELERATING CO_2 UTILIZATION

As described above, carbon utilization applications have enormous commercial and decarbonization potential. However, if carbon utilization is to approach the levels of market value and CO_2 removal outlined by the 2016 Roadmap study, specific policies are needed to help overcome the challenges noted above. These policy options fall into four general categories:

- **Financial enablers** include incentives like tax credits and subsidized project finance.
- **Research** includes more and better coordinated federal spending on all phases of research, development, demonstration, and deployment (RDD&D).
- **Infrastructure** includes development of CO_2 transportation infrastructure.
- **Market enablers** include industry standards, and procurement policies that provide preferential demand for products with recycled carbon.

Congress provided an important financial enabler with the 2018 passage of the FUTURE Act, which improved and extended the federal "45Q" tax credit for carbon storage and utilization. This was a landmark for both carbon management and climate policy since it made the tax credit available for non-EOR utilization for the first time. When implemented, the tax credit has the potential to encourage all of the carbon uses identified above. But because individual CCU sectors are dissimilar both in terms of their levels of development and their future capacity, policymakers must also consider policies designed to overcome sector-specific challenges.

In the pages that follow, a variety of policies and measures are outlined. The first section discusses cross-cutting mechanisms while the second focuses on specific sectoral challenges. **Appendix A** offers a summary comparison of specific policies along with an overview of the status, barriers and market potential of the individual carbon-use sectors.

BROAD POLICY APPROACHES TO ACCELERATING CARBON UTILIZATION

Financial Enablers

The enactment of 45Q in 2018 was a significant achievement for all carbon uses, but two of its requirements may prevent non-EOR CCU from qualifying for the tax credit.

First, because of the time involved in planning and developing a new project, developers may have difficulty reaching the law's "begin construction" cutoff date of Dec. 31, 2023. Even then, they may not be able to ramp up to the 25,000-ton threshold level of CO_2 usage necessary to qualify for the credit. If the tax credit is not claimed by a significant number of CCU developers, Congress should push back or eliminate the begin-construction deadline and lower the tax credit's eligibility threshold to as little as 1,000 tons.

In addition to the 45Q tax credit, making carbon capture projects (including CCU projects) eligible for existing forms of preferable treatment would improve their financial profile. For example, **private activity bonds** (PABs) are tax-exempt bonds that allow project developers to qualify for lower-cost financing for privately-run projects that provide a public benefit. Also, **master limited partnerships** (MLPs) allow entities organized as partnerships to be publicly traded (therefore combining the lower-tax treatment of a partnership with access to securities markets). Making carbon utilization projects eligible for these financing options like PABs and MLPs would make them more attractive to investors, with little direct cost to the U.S. Treasury.

Finally, **FEED (front end engineering design) studies** represent a critical early step in project development, and one whose cost is not insubstantial for a startup. DOE presently has a selection process to fund FEED studies for capture projects; it could do the same for utilization projects. Meanwhile, incumbent industries such as oil and gas companies and chemical manufacturers have substantial expertise incorporating new technologies into existing production. DOE could work with those industries to fund FEED studies to help determine how components of carbon utilization technologies could be incorporated into existing facilities, especially refineries and ammonia production facilities.

Research, Development, Demonstration, & Deployment (RDD&D)

Experts consulted for this report mentioned the importance reforming and enhancing federal R&D spending. The budget for U.S. Department of Energy's Fossil Energy (DOE-FE) CO_2 utilization program has been in the $10-12 million range in recent fiscal years, out of a total R&D budget of approximately $500 million per year. Suggestions included:

- **Increasing spending:** Doubling or even tripling the relatively small current budget for utilization R&D (without robbing other FE R&D programs) would have an outsize impact on the rate of development. In October 2018, the National Academy of Sciences (NAS) released an evaluation of research agendas for each CCU sector. While NAS did not endorse a specific level of federal R&D spending, current spending levels simply won't permit the realization of the research agendas evaluated. Expanded R&D investment also would be consistent with the goals of the multilateral Mission Innovation (MI) and would enable greater focus on the "priority research directions" identified by the MI Carbon Capture Challenge.
- **Applying federal R&D support to all phases of development and deployment:** Current DOE-FE research dollars are directed mainly toward the Lab/Bench and Small Pilot phases (Technology Readiness Levels (TRL) 3-6, on the 1-9 TRL scale. Providing funding for later stage pilots was seen as important. Additional funding would also allow for follow-through on current projects to the commercialization stage. Getting beyond the "valley of death" (between pilot and full commercialization) is a challenge for any new product, but especially for CO_2 utilization, where so many additional challenges are present.
- **Allowing the conversion of CO_2 capture pilot projects to CO_2 *utilization* pilots:** CO_2 capture pilot projects currently use a "catch and release" approach that simply vents the captured CO_2 into the atmosphere. Moreover, capture project developers do not have any incentive to continue capturing or providing disposition for the related CO_2 after their pilot projects are completed. Incentivizing the continued operation of pilots could provide the CO_2 needed for new utilization projects at an appropriate scale.

Federal R&D Legislation

The DOE-FE R&D program still operates under its 2005 authorization, thus many of its current research objectives were barely envisioned by Congress when it was last considered. Certainly, the concept of beneficial use of captured carbon oxides in commercial products was in its infancy at that time.

Separate bipartisan bills to rewrite the DOE-FE R&D authorization have been introduced in both houses of Congress in 2019. The House bill, known as the Fossil Energy Research and Development Act, would provide additional money and direction specifically to develop CCU technologies. It was introduced as H.R. 3607 by Reps. Marc Veasey (D-Texas) and David Schweikert (R-Ariz.) and includes House Science, Space and Technology Committee chair Eddie Bernice Johnson (D-Texas) as a cosponsor.

In the Senate, the EFFECT Act (Enhancing Fossil Fuel Energy Carbon Technology, S. 1201) was introduced in May 2019 by Energy and Natural Resources Committee Ranking Member Joe Manchin (D-W.Va.), with committee chair Lisa Murkowski (R-Alaska) as primary cosponsor. The bill would support development of fossil emissions technology through all levels of development, including traditional R&D, large-scale pilot projects, demonstration projects, and FEED studies. Both the House and Senate R&D reauthorization bills have been approved by their respective committees and, at this writing, await floor action.

Also, a key provision of the USE IT Act (Utilizing Significant Emissions with Innovative Technologies) would direct the U.S. EPA to initiate an R&D program for utilization of CO_2 generated by industrial processes. Identical bills have been introduced in both the Senate and House in the 116th Congress (S. 383 and H.R. 1186).

Federal R&D Coordination

Finally, while total federal spending on all CCU activities is relatively small, it is also spread between many federal agencies, including multiple DOE offices and the Pentagon. These offices separately manage CCU research, with little high-level coordination of various research priorities and outcomes. Creation of an Interagency CCU Task Force could elevate carbon utilization in the government's science agenda and help inform decisions about future Funding Opportunity Announcements (FOAs).

Along with DOE-FE, DOE's Bioenergy Technology Office (BETO) also receives carbon utilization research funding. Increasing funding for BETO's algae carbon utilization research alongside that for the DOE-FE R&D program would advance algae project development. Other federal agencies that receive funding for synthetic biology include DOE's Advanced Research Projects Agency-Energy (ARPA-E) and the Pentagon's Defense Advanced Research Projects Agency (DARPA). Better coordinating the goals of all of these programs would ensure alignment of research priorities.

CO_2 Transportation Infrastructure

Pipelines

A threshold issue for most carbon use applications is the siting and building of transportation infrastructure to move captured CO_2 to users. For example, capturing CO_2 from ethanol production plants is relatively inexpensive given that the process emits a high-purity stream. However, ethanol plants are often located far from where developers could use the CO_2 and the compression and transportation costs can be substantial. The USE IT bill includes language to spur federal, state, and non-governmental collaboration in the development of facilities and CO_2 pipelines needed to capture and transport CO_2 from source to market.

Another potential legislative vehicle for creating a national CO_2 pipeline network would be national infrastructure legislation, which has been discussed for years and may finally advance in the 116th Congress. If Congress moves forward on this front, inclusion of language authorizing CO_2 pipelines adequate to linking sources of CO_2 with both geologic storage and potential CO_2 utilization opportunities would be helpful. Also, the Carbon Capture Coalition has suggested authorizing the "supersizing" of new CO_2 pipelines to account for future demand for CO_2 transportation needs.[25] (Since most pipeline construction costs are fixed, increasing pipeline diameter to substantially expand capacity adds little to total project costs.) This would be helpful for handling the growth in CO_2 transportation demand that future utilization projects would create.

CO_2 Opportunity Zones

A continuing challenge is simply access to low-cost, high-purity CO_2 itself. Currently, most CO_2 for utilization applications is purchased in relatively small quantities and transported by truck. One approach to solving the access problem would be to locate utilization development near high-purity CO_2 sources. Co-location of CO_2 utilization facilities with major industrial sources of CO_2 could be mutually beneficial and would reduce or eliminate the cost of transportation infrastructure. (Power generation is not a good source of low-cost, high-purity CO_2, given the impurities in flue gas, compared with a "pure stream" that can be captured from ethanol production, for instance.)

To help with this, incentives such as tax preferences that encouraged locating multiple utilization CO_2 applications near large sources of high-purity CO_2 would be helpful. This may be best accomplished by state-level policies that take economic development into account; for instance, tax forgiveness for a particular period. Such designated "opportunity zones," where investment is focused on CCU applications (among other clean energy technologies), could generate a variety of economic benefits, including new investment and jobs.

Market Enablers

In the absence of an economy-wide price on carbon, federal and state governments can help create a market for beneficial utilization products in a number of ways. These include improved disclosure requirements (including green labeling), so products can be compared on an "apples to apples" basis, as well as updated industry standards that allow and encourage procurement of low-carbon technologies including the use of captured carbon.

To encourage low-carbon markets, consistent standards are needed for determining the carbon footprint of materials, especially the lifecycle emissions of those products. Many companies are interested in the carbon footprint of their operations, including their building and materials. Companies increasingly disclose these metrics to various sustainability platforms and standards. Climate reporting and disclosure has grown significantly in recent years, particularly in response to recommendations made by the Task Force on Climate-related Financial Disclosures (TCFD) in 2017.[26] Consistent metrics allowing an apples-to-apples comparison between regular and low-carbon materials would help increase demand for these materials.

Related to this, consumers have also demonstrated their interest in supporting companies and products with environmentally beneficial attributes and are accustomed to federal "green labeling" standards that can guide them on issues like energy efficiency. At the same time, the extent to which consumers are willing to pay a premium varies by product. Products like low-carbon cement, for example, may attract a premium price, while other low-carbon products like chemicals and polymers may only reach the consumer market indirectly through business-to-business transactions. Accurately measuring the carbon footprint for these products, however, can be useful as more large retailers are asking for this information from their supply chains.

Industry Standards

Updated and enhanced industry standards have the potential to promote the development and deployment of CCU technologies. For example, enhanced information about embodied carbon in infrastructure could play a role in encouraging the use of captured carbon. The University of Washington Carbon Leadership Forum is developing the open-source Embodied Carbon Construction Calculator (EC3) tool to help real-estate developers, architects, engineers, and the public better understand the carbon footprint of the built environment. Some Fortune 500 companies already have agreed to take a closer look at embodied carbon. For instance, Microsoft will be piloting the use of EC3 to develop its new campus in Redmond, Washington. Beyond pilot projects, there is an opportunity for tools like EC3 to be integrated into existing green building standards, such as the U.S. Green Building Council Leadership in Energy and Environmental Design (LEED) standard and various International Standards Organization standards.

Procurement Policies

Federal and state governments are large purchasers of building materials for infrastructure and of fuel for government fleets of vehicles. Some state programs already prioritize the use of building materials and fuels with environmental attributes. For example, the "Buy Clean California" program requires state agencies to consider the emissions performance of suppliers of materials for infrastructure projects. The program applies to steel, mineral wool (insulation), and flat glass. Concrete is exempt, however, which may reduce the impact of the program. For fuels, policies that would require the use of a certain percentage of fuel derived from captured carbon could expand upon existing procurement policies that are focused on ethanol and biodiesel.

Expanding these programs could create large markets for the re-use of captured carbon. Government agencies have the capacity to be "market makers" based on their own buying patterns. Thus, the establishment of federal, state, and local procurement standards requiring incrementally increasing use of low-carbon fuels, concrete and aggregate would both ensure a growing demand for these products and spur investment in their development.

SECTORAL POLICY ISSUES

While taking action on the above issues could provide a boost to all recycled carbon based products, it is important to consider sector-specific challenges as well.

Construction Materials

While the buildings sector has made significant progress reducing its carbon footprint through energy efficiency, the carbon footprint of the steel, concrete, and other materials used to construct the built environment should be a focus for policy. Utilization of CO_2 in the production of construction materials like cement and aggregate has relatively low technological barriers. However, these products must be commercially competitive in markets that are characterized as being both low-margin, and highly standardized by widely adopted technical specifications and building codes.

Despite the proven qualities of low-CO_2 building materials, those specifications and codes may or may not currently allow their use in many construction applications. This has led developers of low-carbon construction materials to focus initially on markets for pavers and other products that are covered by fewer performance standards than structural materials. The low-carbon construction materials market could grow rapidly in response to building codes that are performance-based and are updated to expressly encourage greater use of these materials while ensuring that they meet both quality and safety requirements.

While updating building codes often takes time, state governments could incentivize this activity by providing performance-based incentives for jurisdictions that have updated their building codes to encourage the use of captured carbon in building materials.

Fuels

The markets for low-carbon fuels of all types face similar challenges as they tend to be low-margin, highly standardized, and compete with conventional fuels whose retail prices do not reflect externalities related to climate change. Policies are needed to level the playing field for such fuels in order to realize their potential benefits in terms of energy security and economic growth.

Policies that allow either carbon sequestration or recycled carbon as compliance-eligible can help create more demand for these products. For example, the International Civil Aviation Organization decision to allow recycled carbon-based fuels to count as low-carbon fuels has spurred airline interest in these technologies.

Similarly, California's low-carbon fuel standard (LCFS) has gained attention for its focus on reducing the carbon intensity of transportation fuels. The state's LCFS was amended in 2018 to allow CCS to count toward this standard and again can only help increase demand for the technology. California could broaden its LCFS to include storage through mineralization in construction materials, which would pose no threat of subsurface leakage and therefore require no monitoring of groundwater. In addition, other states might consider changing what qualifies under existing rules to allow materials made using carbon sequestration or with recycled carbon.

Chemicals and Plastics

Unlike the markets for building materials and fuels, CCU-derived chemicals represent a higher-margin and lower-volume market. It's useful to think of the "ecosystem" of products that can be made from captured carbon in the same way that most people are aware that petroleum can be used to make chemicals and plastics, as well as fuels.

While some carbon utilization chemicals and plastics comply with existing ASTM standards, incentives or use requirements would help grow this market. In Europe, the organization CO_2 Value Europe has been engaging governments, businesses, and consumers around this goal.

Algae

Responsibility for federal algae policy is shared by three Cabinet-level departments and the EPA. Those four agencies (along with the National Science Foundation) coordinate through an interagency work group. DOE's recent annual research spending through BETO has been in the range of $30-32 million (although only a small portion is spent on carbon utilization research).

The public is likely more aware of the role that forests and land management play in mitigating climate change as carbon sinks, so consumer education is needed regarding algae-based products.

Also, a regulatory regime that ensures both quality and safety is necessary. As with other sectors, government procurement rules would be a market driver. Federal and state authorities, for instance, could require incrementally increasing use of algae-based products (e.g., soil supplements) for public lands management.

V. CONCLUSIONS AND RECOMMENDATIONS

The increased attention recently devoted to carbon utilization by both the private and public sectors suggests the potential these nascent processes may have to help drive decarbonization. However, because the levels of technology and commercial readiness differ so widely from sector to sector, no proposed single policy reform offers a "silver bullet," rather, a portfolio of policies is needed to address technology development, financing, and market preferences. Moreover, federal action alone is not sufficient. States and local governments may be in the best position to tailor policies that address their specific circumstances.

The principal recommendation of contributors to this report is straightforward: *The focus of policy toward carbon utilization should aim for growth by 2030*, ensuring that a significant amount of CO_2 is being sequestered by utilization processes in that timeframe. The year 2030 is a useful target because many state and local climate plan goals are tied to it, and because the report issued in October 2018 by the UN Intergovernmental Panel on Climate Change, pegged 2030 as the timeframe by which the planet may reach the threshold of 1.5 C above pre-industrial levels.

If carbon utilization sectors have not developed by then to the point where commercial forces are driving continued growth, the expected contribution of CCU to decarbonization may not be reached. If CCU development falls short of its potential, an important capacity for greenhouse gas reduction will remain unfulfilled.

Wide agreement exists among stakeholders and experts consulted in the preparation of this report regarding the policy pathways that will grow carbon utilization. At the federal level, it starts with immediate action on three initiatives—the USE IT Act, reauthorizing the Department of Energy's Fossil Energy (DOE-FE) research program, and infrastructure legislation—which would significantly strengthen the foundation upon which carbon utilization's future can be built.

However, these proposals are only first steps; an aggressive strategy to stimulate low-carbon market demand is needed if CCU is to meet its economic and environmental potential, especially if the goal is 2030. Actions including carbon intensity disclosure requirements, better lifecycle analysis, incentives for using carbon-based products, expanded low-carbon fuel standard and renewable fuel standard policies, and targeted procurement policies are all critical tools to scale up carbon utilization.

Policymakers should consider goals for carbon utilization development set out by reports including the National Academy of Sciences Report, 2018; University of Michigan CCUS Report, 2017; the National Coal Council *CO_2 Building Blocks* Report, 2016; and the CCU *Roadmap*, 2018. The understanding of these new processes and their development needs has increased in recent years, and together these reports form a basis for action.

In sum, the following actions are recommended as a path forward for CO_2 utilization policy.

IMMEDIATE ACTIONS (2019)

45Q Tax Credit

While Congress enacted the 45Q tax credit in February 2018, it cannot take effect until the IRS publishes the guidance for taxpayers to claim the credit. The actual value of the credit to advancing a particular project is unknown until that guidance is published. The IRS should act swiftly to put forth its guidance on the many issues needing clarification and definition. Of particular importance to the CCU developers will be the guidance on a required greenhouse gas lifecyle analysis (LCA).

Meanwhile, Congress should note that provisions of the new law already threaten to limit the policy's impact on encouraging CCU. As such, Congress should proactively address those issues, by lowering the threshold for credit eligibility and extending or eliminating statutorily imposed deadlines, including the begin construction date.

Other Federal Legislation. Congress has the opportunity to pass three pieces of legislation before the next election that would advance carbon utilization.

- First, the USE IT Act was expressly proposed by Congressional carbon capture supporters as a logical set of next steps after 45Q. For carbon utilization, USE IT promises to improve coordination of CO_2 transportation and to provide additional research support.
- Second, both the House and Senate committees of jurisdiction for the DOE-FE research and development (R&D) program have begun crafting reauthorization legislation that committee leaders hope to advance with bipartisan support. This is a critical opportunity for Congress to prioritize the development of CCU technologies, and to authorize the funding levels that would support an amibitious research agenda.
- Third, national infrastructure legislation, if and when it begins to move, should prioritize the construction of CO_2 transportation that will facilitate linking CO_2 sources with potential CCU development.

NEAR-TERM ACTIONS (2019–2022)

Research and Development

CCU R&D is at a critical stage, and continued progress in specific areas such as electrolytic hydrogen, as discussed above, may have significant impact by the end of the "near-term" period. Regardless of whether Congress is able to agree on a new FE R&D authorization, it has the authority to continue increasing spending levels through this period. (It should also continue increasing the Bioenergy Technology Office's research budget.)

As for research priorities, the needs described by the 2018 National Academy of Sciences Report are a good starting point for considering government R&D agenda for both the near- and longer-term. Establishing interagency coordination of federal CO_2 utilization policy at senior level would help to align priorities.

In addition, consideration should be given to:

- Authorizing the funding of more and larger pilots ($5 million–$10 million range)
- Ensuring follow-through funding through the commercialization stage to address the "valley of death" problem;
- Allowing for the conversion of carbon capture pilot projects to carbon *utilization* pilots (Some pilot projects that receive funding for CO_2 capture could be incentivized to continue operating to provide CO_2 for project developers).

Project Financing

Making carbon utilization projects eligible for private activity bonds and treatment as master limited partnerships would make financing projects more attractive. Congress could extend these options to carbon capture projects, including CCU, with little cost to the U.S. Treasury. Another small but significant action would be to allow for the subsidization of private industry front-end engineering design (FEED) studies.

Market Enablers

Pipelines, technology, and financing are "supply side" policies, but providing incentives on the demand side will help as well. They could include the following supportive actions:

- Establish incentives for businesses that adopt CCU technologies, such as construction materials, fuels, chemicals, and plastics, into their supply chains.
- Expand incentives for low-carbon fuels, such as by expanding Low Carbon Fuel Standards, Renewable Fuel Standards, and other mandates to include fuels made from captured carbon.
- Increase state and local procurement policies that encourage the use of captured carbon in materials for infrastructure development and fuels for government fleets.

While not a government policy issue, industry standard setters could encourage the use of captured carbon by reforming guidelines like the Leadership in Energy and Environmental Design (LEED) standard for buildings, and those set by the International Standards Organization (ISO) and ASTM (formerly known as the American Society for Testing and Materials) for commercial and industrial activities.

MID-TERM ACTIONS (2023–2030)

If government can accomplish the above policy reforms by 2023, the rest of the decade can be focused on implementation. A significant expansion of CO_2 transportation pipelines will take time but will be dependent upon the above-described actions at both the federal and state level.

As markets for CO_2 develop, economic approaches to linking sources with utilization may become clearer. State and local governments may consider establishing Carbon Opportunity Zones to create incentives for co-location of utilization with higher-purity CO_2 sources. Meanwhile, both technology advancements and experience—development of "n^{th} of a kind" practices—should lead to the deployment of larger pilots and commercial projects.

Another broad incentive would be for more states to adopt a Clean Energy Standard (CES) which would recognize abated fossil power generation as a form of clean energy alongside renewable energy. A CES provides a market incentive for electric utilities to capture CO_2, which in turn provides a supply for the CO_2 market.

Finally, the greatest potential variable for all carbon management projects is whether governments (state and/or federal) may impose a price on carbon, and how such rules would be implemented. Carbon pricing is beyond the scope of this paper, but it should be noted that forms of carbon pricing already play a role in some CO_2U markets (e.g., California's LCFS). Implementing carbon pricing would ensure that building materials, products, and fuels reflect the true environmental and climate costs of competing alternatives.

LONGER-TERM ACTIONS

This report deliberately avoids suggesting policy actions in a timeframe beyond 2030 because, as described above, the consensus of contributors that significant progress on all fronts must be evident by 2030, and policies and action should aim for growing CCU sectors during that timeframe. Policymakers at all levels of government must be prepared to implement a portfolio of interconnected policies if CCU is to contribute both to economic development and to greenhouse gas reduction.

APPENDIX A: SUMMARY OF STATUS, OPPORTUNITIES, CHALLENGES, AND POLICY CONSIDERATIONS FOR CARBON UTILIZATION APPROACHES

PRODUCT	CURRENT STATUS	OPPORTUNITIES	CHALLENGES	POLICY CONSIDERATIONS
Construction Materials	Cormmercial/Near Commercial	• Current market size = 55–65 billion metric tons • CO_2 use potential (by 2030) = 1–10 billion metric tons/year • Time frame = now (small scale); 5+ years broad commercial scale	• R&D needs: Decreased cost and increased availability of alkaline materials to provide needed Calcium and/or Magnesium • Low-margin, highly standardized markets that are difficult to penetrate with new products • Cost pressures	• Foster a regulatory environment that promotes a measured and fair process to ensure that products meet both quality and safety requirements • Establish government (fed/state/local) procurement requirements that require incrementally increasing use of low-carbon concrete and aggregate
Fuels	Wide range - near commercial to early stage R&D	• Current market size = 55 million barrels/day[27] • CO_2 use potential (by 2030) = 0.07–2.1 billion tonnes/year • Time frame = now (small scale); 5–20 years broad commercial scale	• R&D needs: catalyst development, low carbon, low cost hydrogen; electrochemical process development; photocatalytic processes; LCA development • Low-margin, highly standardized markets that are difficult to penetrate with new products • Cost pressures	• Expansion of policies such as the California low carbon fuel standard to additional states or perhaps nationally • Establish government (fed/state/local) procurement requirements that require incrementally increasing use of low-carbon fuels

PRODUCT	CURRENT STATUS	OPPORTUNITIES	CHALLENGES	POLICY CONSIDERATIONS
Chemicals/ Plastics	Wide range—near commercial to early stage R&D	• Current market size = 350 million metric tons[i] • CO_2 use potential (by 2030) = 50–100+ million metric tons/ year[i,ii] • Time frame = now (small scale); 5–20 years broad commercial scale	• R&D needs: catalyst development, low carbon, low cost hydrogen; electrochemical process development; photocatalytic processes; LCA development • For commodity chemicals—Low-margin, highly standardized markets that are difficult to penetrate with new products • Cost pressures	• Establish government (fed/ state/local) procurement requirements that require incrementally increasing use of low-carbon products (e.g., those made from low-carbon commodity chemicals) • Economy-wide incentives for use of low-C products
Algae (agriculture, aquaculture, nutraceutical, and consumer products)	Cormmercial/Near Commercial	• Current market size = $2.5 billion[28] • CO_2 use potential (by 2030) = 0.07–1 billion metric tons/ year[29,30,31] • Time frame = now (small scale); 5+ years broad commercial scale	• R&D needs: testing at scale • Established markets that are difficult to penetrate with new products • Cost pressures	• Foster a regulatory environment that promotes a measured and fair process to ensure that products meet both quality and safety requirements • Establish government (fed/ state/local) procurement requirements that require incrementally increasing use of algae-based products (e.g., soil supplements) for public lands management
Algae (refined products such as fuels/ chemicals)	Cormmercial/Near Commercial	• Current market size = $1.5 billion • CO_2 use potential (by 2030) = up to 2 billion metric tons/year • Time frame = now (small scale); 5+ years broad commercial scale	• R&D needs: testing at scale • Highly standardized markets that are difficult to penetrate with new products • Cost pressures	• Expansion of policies such as the California low carbon fuel standard to additional states or perhaps nationally • Establish government (fed/ state/local) procurement requirements that require incrementally increasing use of algae-based fuels for government vehicles

APPENDIX B: SURVEY QUESTIONS ON CARBON UTILIZATION POLICY

1. To what extent have you benefited from federal R&D funding, either directly or indirectly?
2. The lack of a **coherent government strategy on CO_2U research and development** *has been cited* as a barrier to the development of this industry. *Some advocates* recommend that the R&D budget for CO_2U technologies focus on geologic applications with potentially large volumes, such as enhanced oil recovery or enhanced coal bed methane. *Other experts* have suggested that a portion of the R&D budget for CO_2U technologies be reserved for long-shot technologies with high CO_2 abatement potential. How do you think the R&D budget for CO2U technologies should be prioritized?
3. **Increasing access to hydrogen and sources of carbon-free electricity** would facilitate development of CO_2U technologies. How could Federal and state governments incentivize: a) the production of hydrogen using excess renewable energy and b) the availability of carbon-free electricity for use in CO_2U applications?
4. **International ASTM standards** determine the specifications of building materials and other products. How could Federal or state policymakers help accelerate the updating of these standards to include products made from captured carbon?
5. **Procurement policies** can be used by national and state governments to create markets for advanced technologies. If Congress or state governments created procurement policies focused on increasing the use of materials made from captured carbon, what considerations should policymakers be aware of in designing the policies?
6. State and local governments are responsible for creating and updating **building codes**. In their financial support for state and local infrastructure, should the Federal government offer performance-based incentives for jurisdictions that have updated their building codes to prioritize using materials made from captured carbon?
7. In recent years, companies have responded to consumer demand by **"green labeling"** products with a smaller environmental footprint. How could the Federal government facilitate "green labeling" of fuels made from captured carbon?
8. While there are a variety of options to re-use captured carbon, some of them are geographically specific, such as algae which is more viable in coastal areas. How could the Federal government best **incentivize transportation of captured carbon** through pipelines or trucks to areas where it can be re-used?
9. Large sources of manmade CO_2, such as from power plants, are often subject to environmental regulations and **permits that do not allow for the diversion of CO_2 to CO_2U developers**. How could Congress help provide certainty for power plant operators who would be open to partnering with CO_2U developers to invest in CO_2U solutions and test them on-site?
10. Similarly, the useful life of large sources of manmade CO_2, such as from power plants, are often as long as 30-40 years while technology startups may not remain in business a similar duration and CO_2U investors may require a positive ROI within 10 years. How could the Federal government develop **public-private partnerships** to help bridge the gap?

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