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MANAGING CARBON IN THE MIDWEST

Summary Report from Workshop on June 14, 2022

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Carbon management has a critical role in helping the United States address the climate crisis and achieve net-zero emissions by 2050. To catalyze innovation and private sector investment, the government is launching programs such as DOE's Carbon Negative Shot (DOE 2019) and a set of Clean Direct Air Capture Hubs, among other major activities. With a deep history in manufacturing, transportation, and fossil energy, the Midwest region is uniquely positioned to contribute to these programs.

This workshop, hosted by Argonne National Laboratory on June 14, 2022, convened key industrial, academic, and government stakeholders with bases in and near Illinois to share information on capabilities in carbon capture, utilization, and storage (CCUS). Participants identified priority technology gaps and synergies in capabilities that can serve as a foundation for collaboration in response to national CCUS opportunities.

With a broad and deep R&D portfolio contributing to decarbonization across the economy — in transportation, industry, and the electrical grid, as well as in agriculture, buildings, and homes — Argonne was pleased to convene Managing Carbon in the Midwest. This unique forum helped clarify the science and technology needed to unlock the potential of carbon management in a clean energy economy and forged regional partnerships to effect meaningful solutions.

U.S. Department of Energy Priorities in Carbon Management Technology

Our domestic energy and economy currently depend on energy sources with greenhouse gas (GHG) emission implications. Fossil fuels are deeply embedded in power generation, transportation, and industrial processes now and in the near future. Transitioning to low/zero-carbon energy sources is essential, but the pace of this transition coupled with the acceleration of climate change necessitates capturing carbon from both point sources as well as directly from the air. This will require either utilizing captured carbon as a replacement for current products and services that release GHGs or storing it indefinitely.

The Office of Fossil Energy and Carbon Management's (FECM) core mission is to address the climate crisis, with the goal of achieving net-zero GHG emissions by mid-century. FECM envisions enabling the demonstration and deployment of technologies for carbon management and mitigating challenges of fossil fuel use via three strategic directions:

- Advancing justice, labor, and engagement
- Advancing carbon management approaches toward deep decarbonization
- Advancing technologies that lead to sustainable energy resources

To achieve these strategic directions, FECM defines priorities in limiting carbon from emissions, removing carbon from the atmosphere, and mitigating unintentional emissions. FECM envisions that the United States will deploy commercial-scale point source capture (PSC) technologies with long-duration carbon storage to the power and industrial sectors in the near term. Regarding direct air capture (DAC), FECM will invest in advancing a portfolio of CO_2 removal approaches that will enable gigaton-scale removal by 2050. For the future of carbon storage and transport, FECM will make investments in RD&D, large-scale transport and storage facilities, and regional hubs to support the rapid deployment of carbon storage. FECM is also focused on minimizing the environmental impacts associated with extracting fossil energy sources consumed in the United States, with a focus on mitigation of methane emissions. These investments support DOE's Carbon Negative Shot goal of $100/net metric ton of CO2e (DOE 2019). Verification will include rigorously evaluating practices and technologies to analyze life cycle impacts with a deep commitment to environmental justice (see following section).

It is critical to couple DAC to zero-carbon energy. Energy, water, and land needs for CO_2 removal will compete with other uses, and these resources will need to be stewarded and prioritized for ethical pathways toward deep decarbonization. One approach will be development of carbon management hubs centered around shared transportation and geological storage infrastructure, as demonstrated in Figure 1 below.

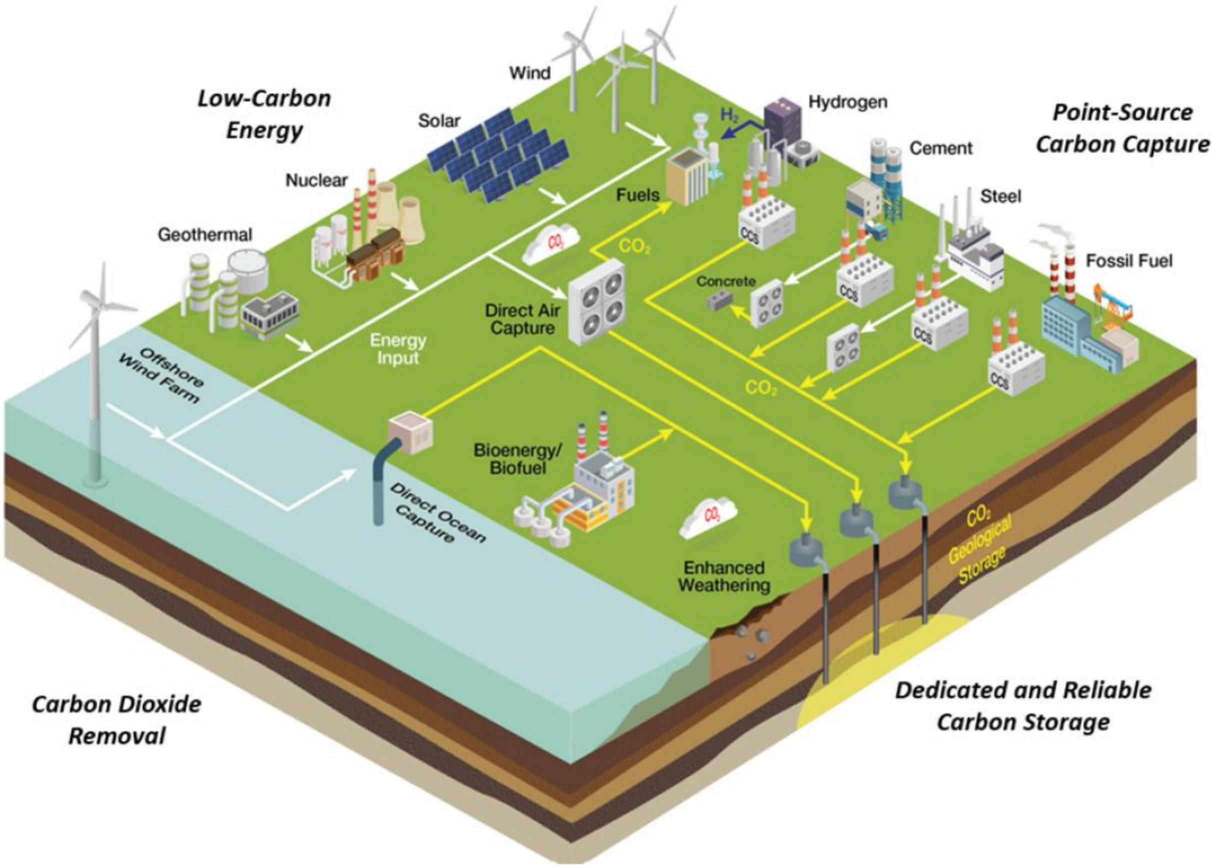

Figure 1: A depiction of a carbon management hub that will help to centralize decarbonization resources (FECM 2022).

Complementing the efforts of FECM, the Bioenergy Technologies Office (BETO) is establishing research strategies and technology pathways for converting gaseous feedstocks such as carbon dioxide into biofuels or bioproducts with advanced conversion technologies using low/non-carbon power. BETO's CO_2 utilization portfolio focuses on leveraging low-cost electricity of low carbon intensity with a strategy to investigate engineered carbon reduction, where electricity is used to convert CO_2 to reduced carbon intermediates, such as carbon monoxide, formic acid, or methanol using catalytic methods. Such intermediates can then be upgraded to fuels and products through technologies such as gas fermentation or additional catalytical processes. This methodology will enable advances in CO_2 conversion to be rapidly integrated with established conversion technologies.

Role of Systems Analysis in Assessing CCUS Potentials

When developing new CCUS technologies, it is essential to evaluate the economic cost and environmental impact of each process or product through its life cycle encompassing extraction and processing of the raw materials, manufacturing, distribution, use, recycling, and final disposal. Vigilant carbon accounting is vital for understanding how activities affect emissions, and whether changes represent additions, mitigation, displacement, or removals to systematically achieve carbon reductions by CCUS technologies. The Systems Assessment Center (SAC) of the Energy Systems and Infrastructure Analysis Division at Argonne has been conducting modeling and analysis of the complete supply chains of CCUS, covering engineering process modeling, techno-economic analysis (TEA), life-cycle analysis (LCA), regional supply and demand CO_2 sources, and low/non-carbon electricity. A key tool in this space is the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model. Figure 2 below shows the LCA system boundary of CCU technologies in GREET.

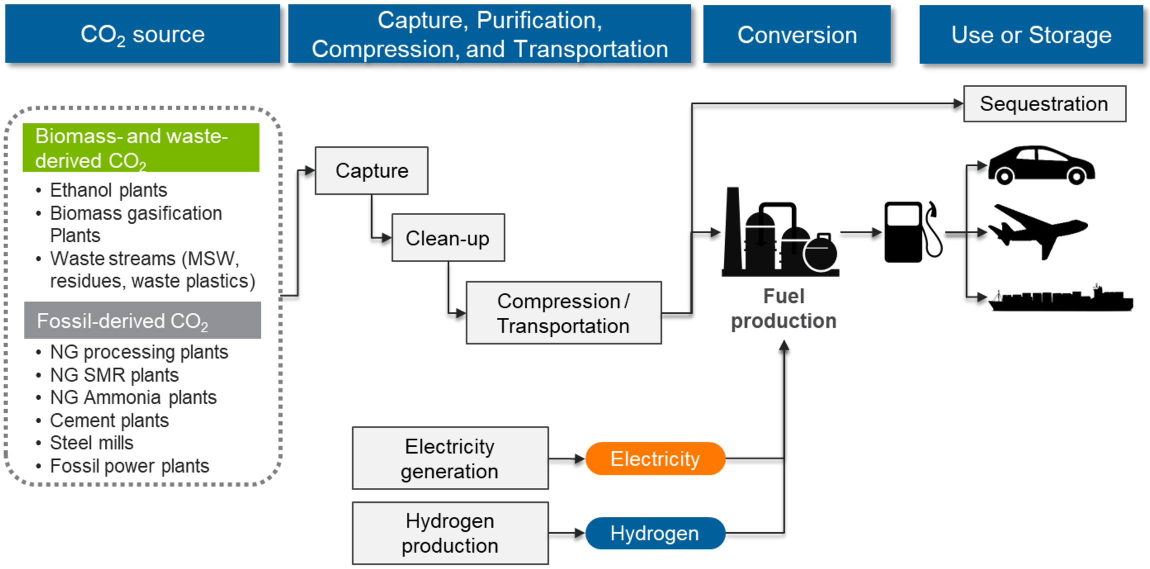

Figure 2: The GREET model is a valuable life-cycle analysis (LCA) tool. This flow chart depicts GREET's carbon accounting capabilities.

Particular system analysis capabilities at Argonne for CCUS include:

- Conducting comprehensive energy and environmental LCA of CCUS technologies by assessing GHG emissions, air pollutant emissions, energy use, and water consumption with detailed CCUS technologies and their supply chain stages in the GREET model
- Conducting detailed energy, environmental, and cost analyses of energy resources and supply chains, such as hydrogen production, storage, and delivery, which play an important role in synthetic hydrocarbon production process for CCU pathways
- Identifying CO_2 sources by quantity, location, and purity level from various industrial sources (facilities of ethanol, ammonia, natural gas processing, hydrogen, steel, cement, and petroleum refining) and power generation (natural gas and coal power plants)
- Estimating costs and energy use of CO_2 capture and purification from various sources as a function of purity level and capture scale for utilization and sequestration

- Estimating costs and energy use of CO_2 compression and transportation (leveraging natural gas pipeline cost estimates) as a function of pipeline diameter, length, region, and class location
- Identifying current and potential future sites for CO_2 storage, including salt dome, aquifer, and depleted oil and gas wells
- Detailed modeling of CO_2 conversion processes for various fuels and products including synthetic chemicals and fuels (e.g., Fischer-Tropsch fuels, methanol, and synthetic natural gas).

Carbon Capture

Beyond minimizing emissions, CO_2 capture and storage has been deemed technologically necessary in order to avert > 2 °C by 2100 by both the IEA and IPCC. The minimum energetic price for CO_2 removal from a coal power plant is ~1.5 GJ/ton; for DAC it is 15 GJ/ton. This order of magnitude difference is directly related to the concentration of CO_2 in the respective streams: the concentration of CO_2 in the air, as high as it may be in terms of global warming potential, is still challengingly small for separation engineering. Nevertheless, when this metric of GJ/ton is incorporated into techno-economic analysis, it emerges that both kinds of capture have advantages. PSC makes sense at natural gas and/or coal power plants and other such industrial sources like cement, fertilizer, and steel processing plants. DAC is the fallback when point sources are inflexible and storage sites are nearby. DAC also provides an interesting pathway for the "storage" of renewable energy via the formation of hydrocarbons from captured CO_2. These considerations have impacted the calculation of the 45Q tax credits announced in 2018 and updated in 2022 through the Inflation Reduction Act (Congress.gov 2022). The aforementioned GJ/ton values are thermodynamic minima, non-negotiables. But our current capture technology operates at ~20 times that level of energy input, so there is room for improvement. Process engineering, computational science, basic chemistry, membrane synthesis, and techno-economic and life-cycle assessment, are all fronts on which this improvement is taking place.

Summary of current capabilities / state-of-the-art

Howard Meyer from GTI Energy summarized for us the various technologies being taken seriously in PSC: chemical looping with solvents/sorbents, oxy-fuel separation, and membrane separation. The projects GTI Energy works on have removal rates of 70-90% and cost between \$28 to \$48 per ton of CO_2. For reference, the tax credit for CO_2 capture without enhanced oil recovery (EOR) was recently increased to \$85 per ton. Meyer also shared examples of successful CO_2 capture projects. The Boundary Dam Unit, the first successful CCS technology in the world, continues to operate at 115 MW and is a great source of many "real-world" lessons in improving CO_2 capture technology. Petra Nova was the world's largest point source capture plant operating at 240 MW and built on a budget of \$635 million. It captured CO_2 for EOR until May 2020, when it became uneconomical to do so. The Archer Daniels Midland's CO_2 capture from biofuels production is an illustrative example of how capture technology is deployed during corn-to-ethanol fermentation, and is the largest saline storage demonstration project in the US.

Nwike Iloeje, an Argonne researcher, is studying a means to bypass the regeneration cost (the amount of energy spent restoring the captured material after it is saturated with CO_2): to convert the CO_2 *then and there* to value-added products. This is an example of reactive capture. He stressed the importance of a fundamental-to-applied workflow, or "Density functional theory (DFT) to computational fluid dynamics (CFD)" as he put it.

Uuganbayar Otgonbaatar, a director at Constellation (a key partner in the $2.5 million DOE-funded front-end engineering and design [FEED] study for a DAC plant powered by nuclear energy in Byron, IL) showed a promising path to scale DACs as true net-negative emissions technologies. The manner of CO_2 capture proposed is unique: water that is vaporizing in cooling towers is doped with solvent suitable for capturing CO_2 directly from the air. He compared this to Carbon Engineering's liquid-filled packed bed columns, where the pressure drops are much higher.

Vyaas Gururajan, an Argonne researcher, showed detailed calculations relating to the performance and scaling of hollow-fiber membrane contactor systems, a technology currently being used by GTI Energy and Aramco for point-source and mobile carbon capture, respectively. Of note is the interplay between physico-chemical parameters (solubility, diffusivity, reactivity, geometry) in determining mass transfer rates and pressure drops, both of which are typically at odds with one another. The development of a software platform to perform rigorous CFD on carbon capture technologies is rare, and this effort attempts to fill a gap in this space. The computations can be used for exploring design spaces that would be prohibitively expensive if done solely experimentally.

Sebastiano Giardinella of the University of Illinois drew attention to the plethora of opportunities for CO_2 capture in Illinois, given that it is a "Confluence of Geology, Technology, and Investment." Byron, Gary, Springfield, Champaign-Urbana, Fairfield, Olney, Robinson, Carmel, Decatur, and, quite aptly, Carbondale are all involved in some form of carbon capture and storage. Carbon capture is a crucial player in industrial decarbonization (note the St. Genevieve MO Cement kiln with post-combustion capture and Champaign IL's Combined Heat and Power with Post-Combustion Capture demonstration projects).

Joe Zhou, a chemist from Texas A&M University, shared his recent results in his evaluation of amine-incorporated porous polymer networks (PPNs) as sorbents for post-combustion carbon capture. These PPNs offer a greater thermal and chemical stability to standard metal-organic frameworks (MOFs), with extremely high and synthesizable areas per unit mass (~6000 m^2/g, compare to activated carbon, which is 400-1200 m^2/g, hollow fibers at 450-1100 m^2/g, and amine-based reactors at 5-500 m^2/g). Fundamental experiments and computations have been carried out to reveal the chemical kinetics of their adsorption. The scalability in manufacture of these PPNs is still an open question.

Priority science and technology needs

Workshop participants followed with a lively discussion on pressing needs. These are summarized as follows.

Fundamental research needs

Development of new solvents, sorbents, and membranes that reduce energy consumption: Solvents may have too high a heat of absorption to economically operate at a given temperature. Additional caution is required as they can thermally degrade. Sorbents experience plummeting performance in the presence of water vapor: the diffusivity of CO_2 in water is 1,000 times lower than that in air, so the accumulation of moisture can drastically slow down CO_2 transport in sorbents. Membranes are still faced with the Robeson limit: the trade-off between selectivity and permeability.

- **Screening and selection of solvent-catalyst pairs for “reactive capture”:** Since the chemical kinetics of even the simplest solvents is still largely unknown, the screening of materials (which depends on certain model inputs) becomes challenging.
- **Thermochemical and transport databases:** For computational optimization, solvers require plug-and-play libraries of thermochemistry and transport data: this is to compute Henry law constants, activity coefficients, diffusivities, etc. on the fly. Due to the lack of databases, there is a lack of computation, and hence a lack of reliable optimization in this space.
- **Open-source platform for computations relevant to CO_2 capture:** A significant impediment to making collective advancements is the growing amount of proprietary information in this space: solvent and sorbent properties are largely unknown and the ones that are known are bundled in commercial software packages like Aspen. The 45Q tax code makes clear that CO_2 capture is directly incentivized and paid for by taxpayers, and therefore a minimum usable amount of information and software that appropriately processes it should be available for public benefits, some of which include verification, standardization, and enhanced research throughput.
- **Deeper understanding of material structure:** The informed design of materials directly profits from fundamental material science advances. Mono/polycrystalline data and Nernst structures of porous polymers and amorphous materials are valuable in the development of sorbents. Resources like the Advanced Photon Source (APS), using X-ray nanotomography and other techniques, can be utilized for membrane characterization.

Applied research needs

- How do DOE’s interests in utilization compare to sequestration? This is important to gauge priorities in reactive capture. Integrated projects in the US so far demonstrate sequestration mostly, and not so much utilization.
- How does bioenergy with carbon capture and storage (BECCS) compare to DAC and PSC? What are the GJ/ton equivalents and how are resources (water and land for reforestation, for instance) accounted for?
- In the envisioned hydrogen economy, what will be the magnitude of carbon capture required in hydrogen hubs? If hydrogen is obtained from gasification, point-source CO_2 capture will be necessary if the hydrogen is to be “blue.”
- Is it energetically and economically cheaper to burn fuel in pure oxygen (so work is required to separate oxygen from air) to obtain high-concentration CO_2 streams that are preferable for CO_2 capture systems (where work is required to separate CO_2 from exhaust)? The verdict by most of the participants was affirmative, but now the challenge of oxy-fuel combustion is transferred to engine design.
- Besides NETL’s national carbon capture center, will there be other sites to verify carbon capture equipment, especially in the context of DAC?
- Co-optimization, i.e., the simultaneous improvement of devices to improve mass transfer and heat utilization, while minimizing pressure drop, is a computational problem. Whether addressing the design of fan blades in DAC or the solvent chemistry of PSC, there needs to be broad agreement on data and best practices in these computations.
- Some funding for early and intermediate TRL work, especially in the IL area, will help close the gap between fundamental investigations and deployment.

Carbon Utilization

Achieving the goal of net-zero emissions by 2050 requires scientific and technological innovations that enable conversion of captured CO_2 to valuable products to meet demands for chemicals and fuels. A fully realized set of CO_2 utilization technologies would have an enormous impact on the carbon management deployment in the U.S. and provide economic benefits. Point-source CO_2 utilization transforms current industrial processes into environmentally benign facilities; otherwise, certain sectors will be difficult to decarbonize without more expensive carbon management. DAC and conversion represent an opportunity to roll back the accumulation of anthropogenic CO_2 in the atmosphere. CO_2 utilization can leverage renewable energy sources and green hydrogen to convert CO_2, circumventing the energetic penalty of current carbon capture and conversion technologies. Most CO_2 utilization technologies are still in the embryonic or pre-commercial stage. There is a need to establish common metrics to systematically evaluate new technologies at multi-scales, develop scenarios for near- and long-term demonstrations, identify barriers, and provide broader transparency to determine possible unintended consequences.

Summary of current capabilities / state-of-the-art

CO_2 captured from either point-source emissions or the atmosphere is first reduced through engineered non-photosynthetic carbon dioxide–reduction pathways (electrocatalytic, thermocatalytic, photocatalytic, biocatalytic, etc.). These approaches convert CO_2 to reduced carbon intermediates, such as carbon monoxide, formic acid, or methanol. These intermediates can be upgraded to fuels and products through more established conversion technologies.

Laurel Harmon from LanzaTech summarized how LanzaTech leveraged and transitioned their existing gas fermentation technology for ethanol production from industrial emissions to capture carbon. LanzaTech's gas fermentation can flexibly add green H_2 to tailor carbon capture and produce carbon-free chemicals. Harmon also shared examples of successful CO_2 utilization projects where ethanol is a starting point for multiple conversion pathways (ethanol to ethylene, then to olefins, paraffins, and isoparaffins, or ethylene to polyethylene, polyethylene terephthalate). She emphasized the ethanol production from limitless CO_2 and green H_2, which are the main feedstocks that will be used as future building blocks to produce fuels and chemicals. LanzaTech anticipates approximately 1,000,000 metric tons of carbon capture from two existing operational commercial plants, seven plants currently under construction (scheduled for completion in 2022), and seven additional plants located in North America, Europe, Asia, and Oceania.

Jose Leboreiro, a VP at Archer Daniels Midland, summarized the outcomes of ADM's carbon capture projects. Within the Illinois Basin Decatur project*,* 1,000,000 tons of CO_2 were injected and stored over the course of three years. Additionally, advanced CCS technologies were demonstrated at industrial-scale facilities to capture CO_2 produced during corn-to-ethanol fermentation at ADM's Decatur facility. 2.3 million metric tons of CO_2 were injected through a 1-mile pipeline to Mt. Simon Sandstone at a depth of ~7,000 ft. This project is the largest CO_2 capture project in the United States. ADM plans to use the captured CO_2 for different applications, including (1) fermentation feedstock to produce algal oil, organic acids, and proteins, (2) separations processes as an eluent to aid in chromatography-based separations processes or extraction with hexane-free vegetable oil, and (3) chemical transformation via non-hydrogenative (organic carbonates, carbamates, and urea), hydrogenative (methanol, formic acid), and inorganic carbonates formation pathways.

Joe Powell, President of ChemePD LLC (retired Shell Chief Scientist, NAE, and AIChE Fellow), provided an overview of gaseous carbon waste streams found in the US (e.g., emissions from manufacturing and production activities and combustion of fossil fuels) and summarized a recently published report by the National Academy of Sciences (2019). This report is a comprehensive assessment of future research and development needs to advance the science and engineering required for carbon utilization at a commercial scale. He also summarized the findings from a report on carbon utilization infrastructure, markets, research, and development published by the National Academies (2022). Powell emphasized the importance of broad international collaboration in carbon utilization research and development to accelerate the pace of innovations and field demonstrations.

Integrated carbon capture and utilization has been a promising approach to overcome the high cost associated with CO_2 compression and transportation. Recently, most of the efforts have focused on developing a combination of engineered carbon dioxide capture and reduction pathways such as photocatalytic processes for the reduction of CO_2 and electrochemical and thermal approaches for the conversion to take advantage of different processes. This hybrid approach provides not only the elimination of energy-intensive CO_2 compression and transportation but also enables process intensification (e.g., a reduction in the number of reactors).

Hydrogen plays a vital role in CO_2 utilization and allows for the production of diverse fuels and products. Current hydrogen production approaches that utilize electrochemistry-based methods also represent significant opportunities for CO_2 utilization by using renewable energy sources (e.g., wind, solar, hydrothermal, and geothermal energies). DOE's Hydrogen Earthshots Initiative aims to reduce the cost of hydrogen (~$5 /kg) by 80% to $1 per kilogram of hydrogen within one decade (EERE undated). This initiative would accelerate breakthroughs in CO_2 utilization and pave the way for significantly reducing CO_2 emissions and producing more abundant, affordable, and reliable fuels and products. One of the main barriers to integrating CO_2 capture and utilization with electrochemistry-based processes using renewable energy is the lack of efficient delivery of high-concentration, high-purity CO_2 to the reactor. Capturing solutions (e.g., amines and alkaline hydroxides) and new materials such as membranes and covalent organic frameworks have been used to generate a high-purity concentrated CO_2 stream needed for reactor operations to achieve high Faradaic efficiency.

Di-Jia Liu, a senior scientist from Argonne, summarized his efforts to develop a new amalgamated lithium metal (ALM) method for catalytic electrolyzers, which offers unprecedented control on the size, tenability, uniformity, and composition of the catalyst. The ALM method can be applied to many metal elements in the periodic table and allows size-modulated CO_2 conversions to different chemicals for the first time. The new catalysts showed the highest Faradaic efficiency and the lowest overpotential for CO_2 to several chemical conversions with multiple electron transfers. Liu also discussed the importance of developing a *"CO_2 refinery"* concept that uses renewable energy to electrify the US chemical industry via low-temperature electrochemical conversion to value-added chemicals. Switching catalysts in the electrolyzer electrode module results in a different product profile. This modular refinery approach offers many advantages, including process intensification (a one-step conversion with a small footprint), fast response to intermittent renewable electricity, increased grid stability (by converting excess to value-added chemicals), and flexible operation with different CO_2 emission sources at near-ambient temperature and pressure.

Ksenija Glusac, an Argonne scientist, shared her research on value-added chemicals production using photoreactive CO_2 capture-based methods to provide less expensive and more environmentally friendly alternative catalysts and membrane materials. Photo-reductive CO_2 capture includes photo-generation of metal hydrides in metal organic frameworks (MOFs), followed by capture of CO_2 via insertion into an M-H bond to produce formate ions. Electro-reductive CO_2 capture combines capture and electrochemical conversion to formate or CO, while thermo-reductive CO_2 capture combines capture and thermal hydrogenation processes. Her team has also been developing electrode and membrane materials for CO_2 electrolyzers. Using a molecular approach, Glusac functionalized a carbon electrode with a molecular catalyst (CO_2RR catalyst), developed COF-based membranes for H+/OH- conduction and prevention of methanol crossover, and then coupled the CO_2R electrolyzer with anodic water oxidation.

To realize "no carbon left behind" from CO_2 emissions, we need to consider all CO_2 emissions in the supply chain and in the conversion process. While the capability to convert CO_2 into valuable products has been developed, the natural weathering process, where the reaction of CO_2 with basaltic silicate minerals (e.g., serpentine, olivine) results in the precipitation of carbonate minerals, is a pathway for the ultimate utilization of excess CO_2. This process can be achieved by injection of CO_2 (either as supercritical CO_2 or CO_2 dissolved in aqueous solutions) into continental or oceanic basalt formations that are globally abundant. Current results reveal extremely nonlinear variations of the sequestration capacity and reaction kinetics, associated with changes in operating conditions.

Priority science and technology needs

Workshop attendees had a lively discussion on the challenges, needs, and opportunities related to CO_2 utilization.

Fundamental science needs

- **Improve material (e.g., catalysts, sorbents, membranes) lifetime and increase their tolerance for impurities:** To increase process efficiency, further studies need to be carried out for high feedstock conversion and product yield and selectivity.
- Scaling up three-phase reactions within current reactor configurations challenges technology demonstrations at pilot- and field-scale: There is a need for the design of specialized reactors.
- **Data-driven approach for the design of new materials and reactor configurations:** Combining computational chemistry and AI/ML methods would be helpful to increase CO_2 uptake capacity, catalytic activity and stability, and product selectivity.
- **Matching CO_2 capture and conversion reaction kinetics**: In most cases, integrated CO_2 capture and conversion occur within the same reaction vessel. Therefore, there is a need for conducting dynamic process simulations and techno-economic analysis to identify the optimum operating conditions and heat management strategies.
- **Robust predictive understanding of the conditions under which facile CO_2 mineralization occurs in Earth's subsurface:** Understanding is needed to expand the efficacy of CO_2 sequestration. These behaviors are not well understood but are thought to be related to reactions occurring in fractures and pores of the subsurface rocks.

- **Quick screening analysis:** Development of an informed framework that identifies potential pathway scenarios is needed to guide R&D efforts. High-level TEA and LCA would be helpful in this exploratory analysis.

Applied research needs

- Process development should be done on a real stream, rather than mock air and flue gas streams.
- DAC: A large area of land is required to utilize a 5% CO_2 stream in an algae field. There is a need to develop new configurations to concentrate algal growth.
- Industrial-scale electrolyzer designs and operations need to be engineered to overcome transport-related limitations and complex chemistries. The same holds for industrial scale photoreactors.
- What makes a case for CO_2 utilization deployment in the U.S. even more compelling is the issue of decarbonizing the energy-intensive industries. Connections between CO_2 source, capture, and utilization are essential. Understanding the availability of CO_2 by different facility types as well as regional availability, renewable electricity sources, and the purity of CO_2 would enable siting of emerging technologies.
- Industry considers flexible, modular, resilient processes. The development of scalable modular technologies that can be applied to multiple products will have more commercial flexibility and profitability.
- Process intensification at modular scales with the objective of deployment at different CO_2 sources. Demonstrate the modular unit operation having a large turndown ratio, which can operate under varying CO_2 feed rates and composition.
- Various CO_2 utilization technologies currently at either embryonic stage or pilot-scale will soon be scaled up to large-scale applications. Field-scale demonstration of such technologies should not be viewed only in terms of performance and economic feasibility at the specific scale. Multiple driving forces across the value chain need to be considered, including but not limited to performance, cost, environmental benefits, availability/suitability of CO_2 streams, policies and regulations, and social changes and adoption (e.g., social justice).
- There is a need for tools to accelerate scale-up and demonstration and determine showstoppers to drive R&D. Scientifically, there is no available assessment tool to determine the leading technologies and take the industry to the next level. There should be more technology transfer mechanisms to address transitions from the bench- to pilot- and field-scale, such as figuring out how to do product developments with demonstrations of what will succeed and what will fail.
- The incorporation of systemic approaches during the development stage of new CO_2 utilization technology is beneficial in determining the impact of multiple driving forces, hence accelerating the field-scale demonstrations. There is a need to establish common metrics to systematically evaluate new technologies at multi-scales, develop scenarios for near- and long-term demonstrations, identify barriers to implementation, and broaden transparency to determine possible unintended consequences.

Carbon Sequestration

Carbon management culminating in permanent carbon sequestration from the atmosphere is critical to reverse the effects of anthropogenic displacement of carbon. Storage and sequestration approaches are inherently intertwined with carbon capture technologies, particularly when one considers the need to concentrate and/or pressurize carbon for effective sequestration. It is expected that energy consumption on the same order of magnitude as that generated since the industrial revolution will be required to permanently sequester carbon and counter the anthropogenic carbon flux into the atmosphere. An additional challenge is identifying appropriate locations for sequestration, which will minimize potential unintended negative environmental effects. Demonstration of efficient and cost-effective carbon storage and sequestration, therefore, necessitates engineering and scientific innovations to reverse the anthropogenic release of carbon into the atmosphere over the previous 150 years.

Summary of current capabilities / state-of-the-art

Geological carbon storage in IL region: Steven Whittaker, Director of Energy & Minerals at the University of Illinois and Illinois State Geological Survey, outlined the geological storage of carbon in Illinois. While the discussions throughout the day on current capabilities covered terrestrial carbon storage locations and concepts in general, Illinois and the surrounding area is a uniquely important location for carbon capture and sequestration. The Illinois Basin's geological structures consist of porous reservoir layers interlaced with sealing (hard rock) layers. This provides an ideal set of properties for ground CO_2 storage, including effective containment, capacity, and permeability (i.e., injectability). Based on the favorable geology, the Illinois Storage Corridor is a region with significant previous and current CCS-related activity: Illinois Basic Decatur Project, CarbonSAFE projects, and other commercial site developments.

There are technical, political, and scientific challenges that remain, however. First, improving safety through monitoring and modeling CO_2 in the subsurface can be done by instrumented monitoring wells, surface seismic detectors, and downhole sensors. Expanded installation and improved sensors are needed to further mitigate risks and verify storage. For instance, natural seismic activity can have deleterious effects on the CO_2 wells, but little is known on the role the wells themselves may play on causing or altering seismic activity. Another challenge discussed is the cost and technical challenges with capturing and storing CO_2 2–2.5 km underground, where CO_2 reaches supercritical fluid conditions.

Land management for soil carbon storage: Michael Ricketts is a postdoctoral appointee in the Environmental Science Division at Argonne, and he presented the concepts that underly the mechanisms of soil carbon storage, its potential, and the challenges. The importance of soil carbon storage is seen in the 2,500–3,000 GT of carbon stored in soil worldwide, which is approximately three times that stored in the atmosphere and six times that in plant and animal biomass. The soils in the American Midwest, in particular, are optimal for carbon storage and accrual. Strategies to managing the carbon flux to be net positive in the soil were discussed to increase carbon inputs (via photosynthesis and plant production) and decrease carbon outputs (respiration and decomposition). The primary goal is to mitigate organic mass decomposition/mineralization. Preserving existing soil carbon stocks is the most cost-effective strategy, however. Active land management solutions include restoration, sustainable agriculture practices, active carbon burial, and crop selection. Ongoing research needs are to better understand the mechanisms that govern carbon uptake, storage, and turnover in plant biomass and soils through models and experiments.

Leveraging the power of photosynthesis and dissolution: Ken Anderson, Professor of Geology at Southern Illinois University, presented a unique idea to address the energy requirements to generate a counter flux to the release of carbon in the atmosphere. Specifically, direct air capture from dilute sources requires concentration, which is a massive energy challenge. By harnessing agriculture as "industrialized photosynthesis" to concentrate carbon from the atmosphere, this process can be conducted with minimal external energy input. Per his calculations, 1 kg of raw biomass contains the equivalent carbon of 2 million liters of air. The proposed "indirect air capture" process entails recovering biomass waste before it decomposes and releases the captured carbon to the atmosphere as CO_2. Sequestration is enabled through an oxidative hydrothermal dissolution at supercritical heated water conditions, a thermochemical vs. biochemical process. The resultant low-viscosity aqueous solution contains ~90% of the carbon from the original biomass and can be injected directly into geological reservoirs.

Instrumentation and computational analysis: Mitchell Barklage, a research scientist at the Illinois State Geological Survey and Northwestern University Department of Earth and Planetary Science, presented the need for improved instrument development. Distributed acoustic sensing (DAS) based on fiber optic cables enables truly broadband seismic recording, but requires development of better instrumentation and computational analysis tools and capabilities.

Natural sequestration of eroded soil carbon: Neal Blair, Professor of Civil and Environmental Engineering and Earth and Planetary Sciences at Northwestern University, discussed the sequestration of eroded soil carbon from a local and global perspective. As an example, he described the impact of lateral disruption to the planet's landscape. Nearly 50% of the landscape has been moved/altered by humans through deforestation, agriculture, and construction. Soil erosion can be a net atmospheric source or sink of carbon depending on location. The concept of locating carbon deposits in anaerobic settings rather than oxidative ones fits the common themes heard throughout the discussions. Through a better understanding of the implications of soil erosion and land alteration on carbon storage, improved strategies of land management can be achieved.

Priority science and technology needs

Workshop participants followed with a lively discussion on pressing needs. The breakout group broadly agreed that applied and fundamental research needs were convoluted in the field of carbon sequestration, particularly in the case of sensor development and analysis.

Fundamental and applied research needs

- **Collection and analysis of data related to storage environment.** Broadly speaking we need to develop a better understanding of the subsurface. This can be done through ML/AI algorithms to inform our understanding and will require better sample collection practices. This includes microbiology and geonomics, which is currently poorly understood. Additionally, the geologic structure, stress fields, and stability are areas of needed understanding.

- **Managing carbon phase/chemistry for storage.** Development of perennial food crops to encourage subsoil carbon. Mineralization was not discussed in detail; however, it is identified as an underdeveloped process for carbon sequestration.
- **Interactions between carbon and storage environment**. The soil carbon cycle is not fully understood. Improved fundamental knowledge on this topic can be used to develop useful policy/guidelines/practices. Additionally, the seismic effects from and on carbon storage can be studied through better sensors enabling resolving seismic features and improving frequency bandwidth. Real time field injection / CO_2 plume monitoring can be achieved.
- **Life cycle analysis**. Focus on the life cycle analysis of systems comparing carbon sequestration vs. other technologies (e.g., biofuels) needs to be developed. The benefit of reversing the flux of anthropogenic carbon into the atmosphere is an agreed-upon goal; however, the best practices remain a topic for further study.

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