White paper report on:

Convergence Accelerator Workshop on atmospheric carbon reduction

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Convergence Accelerator Workshop on atmospheric carbon reduction

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EXECUTIVE SUMMARY

In order to achieve ambitious national or regional net-zero greenhouse gas plans in the next several decades, we must capture billions of tons of CO_2 per year from our emission stream and store it securely. New carbon removal technologies need to scale at an unprecedented rate, and a new carbon economy needs to be embraced on a broad societal level over the coming decades. Industry, academic, and policy experts across a spectrum of carbon reduction and removal technologies agree that there are several ripe opportunities that could be accelerated on a **short timescale**. Advancement requires engagement at all levels of society and a re-envisioning of education, public awareness, and scientific inquiry. Carbon capture, use, and storage technologies need to be grounded in a framework that encompasses risk assessment and realistic cost models for novel and innovative approaches. The **convergence** of disparate groups and ideas can realize significant progress on relatively short timescales. Capturing carbon from point sources and directly from the atmosphere, finding high-profit uses for this carbon, and securing storage can help the US achieve economic growth, while also reducing the net greenhouse gas emissions from hydrocarbon-based energy sources.

Pressing need for acceleration

According to recent estimates, climate change has already led to an increase in global average temperature of 1.0°C since pre-industrial times and may reach 1.5°C between 2030 and 2050. CO_2 continues to accumulate in the atmosphere, as global emissions are on the order of ~40 billion tons per year, outpacing the global oceans' and ecosystems' ability to utilize and store that CO_2. A growing number of companies, organizations, and government entities have issued calls for net-zero greenhouse gas emissions with date-oriented goals. Companies like Walmart and Google have announced goals of achieving net-zero by 2030 and 2040, respectively. California has set a target for net-zero by 2045; with eight of fifty states joining them, 35% of the population of the United States live in states that have net-zero CO_2 targets. Net-zero plans will require a broad expansion of carbon capture, use, and storage (CCUS) technologies that do not currently exist at scale. Significant advancements in research over the past few decades, along with the expansion of the 45Q tax credit (i.e., Section 45Q of the U.S. tax code), have made some technologies technically and economically feasible, while others are on the cusp of being capable of capturing millions of tons of CO_2 per year from a variety of source types.

Topical workshop

We convened over a hundred experts across fields within carbon capture, removal, and long-term storage for a virtual workshop. All participants were provided an opportunity to suggest a “Jupiter-shot” (i.e., a grand vision for the future) to frame subsequent discussion, and through a natural self-selecting process, key approaches rose to prominence. These Jupiter-shots were framed in a variety of manners: from the global to the local, from the site-specific to the distributed, or in terms of function from capture, to use, and to storage. For example, **carbon capture at local scales** envisions a geographically distributed approach, but one that would have unique challenges that more site-focused approaches, such as **direct-air capture,** do not confront. Subsurface reservoirs, in turn, grapple with **characterizing the geosystem** and how to harness processes such as **mineralization** to sequester CO_2 in mineral phases for secure storage, and how to engineer reservoirs and caprocks to prevent leakage. In contrast, other parts of the Earth system, such as Earth’s **oceanic biomass, coastal ecosystems, forests, and grasslands** are available for easily-accessible carbon sinks . Private industry and public funding have made large investments in laying a **technological blueprint for a carbon economy**, but it is unclear how to scale it across the **multiple technological approaches needed to get to Gigaton (Gt) amounts** of carbon reduction.

Convergence

The above topics encompass a variety of cutting-edge issues across physical, social, and natural sciences, engineering, technology, and the humanities that are ripe, not only for acceleration, but also convergence. For example, due to the apparent novelty of carbon sequestration to many communities, and its perceived connection with the petroleum and coal industries many communities are skeptical of developing large-scale sequestration projects in their areas. Therefore, it is necessary to understand the culture of and appropriately team with communities and public stakeholders on the necessity and safety of carbon reduction technologies to facilitate widespread acceptance. For example, future distributed CO_2 storage projects should include engagement with community leaders during the design, development, implementation, and maintenance stages. Hurdles in resource policies at the state level, and purposeful engagement of the energy workforce - currently battling an economic downturn, are required if a multi-pronged approach is to succeed.

Solving complicated tasks presented by CCUS projects requires merging a wide range of skill sets, including uncertainty and risk quantification, reservoir and seismological modeling, capture and storage engineering, pipeline routing and optimization, behavioral and risk analyses, instructional design, and economic feasibility assessments. **Machine learning/artificial intelligence** will play a strong role leveraging large volumes of continuous data streams for real-time decision-making as well as proper quantification of risk to inform investment. These quantitative methods must be balanced with human-focused approaches that build understanding of local values and community goals. It is vital to provide current and future researchers, industry employees, government and policymakers with the proper tools to solve large-scale

CCUS deployment challenges. These challenges are common to virtually all of the envisioned carbon capture approaches.

To date, much of the U.S. eff orts to capture, use, and store CO_2 have focused on large federal and industry-funded sites in saline aquifers/reservoirs, basalt-hosted reservoirs, and, more recently, direct air capture (DAC). These efforts often have been single-source, single-sink projects; connecting Megaton (Mt)-scale projects could decrease project costs while also increasing project economic resilience. One way to accelerate innovation would be to formulate **innovation hubs/test-sites** that can achieve carbon-negative goals. These hubs would look to store multiple $MtCO_2$ per year from various capture technologies. Linking optimal storage sites with multiple capture technologies and viable pipeline routes will be key for establishing successful innovation hubs. DAC powered with renewable energy (e.g. wind and solar) would demonstrate that DAC could be carbon-negative rather than hydrocarbon-energy intensive, enhancing its effectiveness in lowering atmospheric CO_2. Alternatively, geoscientists are currently testing storage of CO_2 via **carbon mineralization** in the subsurface, or increased atmospheric exchange with the **oceans by seeding the environment with biomass-enhancing phosphate**.

Outside of DAC and oceanic reservoirs, many technologies for atmospheric carbon reduction hinge on subsurface storage, and even utilization. Such “blue energy” (H_2 produced from natural gas by catalysis) or even “green” fossil fuel production (secondary petroleum recovery coupled with CO_2 capture) are ripe for convergence and acceleration across multiple disciplines. **Subsurface characterization and verification** of suitable long-term storage sites, techniques for monitoring/verification, standardization of risk assessment, protocols for leakage mitigation, and recommendations for teaming with communities could converge on an accelerated pace to lead to distributed increase in carbon capture well above the current Mt levels currently realized. In turn, utilization of the reservoir-stored resources, whether CO_2, CH_4, H_2, or even processed high-efficiency biofuels, require an economic model that honors the societal needs throughout the geographically, culturally, and economically diverse US.

Finally, large-scale CO_2 capture, transport, utilization, and long-term storage require **on-roading from existing energy infrastructure and expertise**. An efficient carbon economy that removes and stores Gt-scale emissions can benefit by on-ramping or on-roading from existing industry infrastructure and talent. For example, the 45Q tax credit currently can be taken by utilizing CO_2 for enhanced oil recovery (EOR) and applied to offset tax expenses in other business operations. Several domestic energy companies have taken 45Q credits and expanded their plans as the tax benefit has increased in the last few years. While the updated 45Q tax credits are already impactful, uncertainty surrounding accounting, project start dates and duration requirements have made reduced investment in CCUS. The recent decrease in oil and gas prices have several impacts in the CCUS space. Across several economies, energy production from coal-fired power plants has declined, replaced by cheaper natural gas, which has driven reduced overall emissions of CO_2. The recent decrease in oil and gas prices have also inhibited growth and investment in developing CCUS projects, as CO_2-EOR projects have reduced returns. For example, in 2020, the successful Texas Petra Nova "clean coal" carbon capture project was shut down due to low oil prices because the captured CO_2 was cost-modeled to be utilized for EOR in a nearby oilfield at $100/bbl prices. Development of strategies geared towards increased resilience through storage in stacked reservoirs at one site and multiple capture streams at different price points would decrease uncertainty and advance investment in CCUS technologies.

Whether the CO_2 is released at a power plant, fertilizer plant, or a car tailpipe, a planet that climatologically sustains life requires the removal of that CO_2 either from the production stream or actively removing it from the atmosphere. Envisioning a world where the technology is adopted on a scale to make any impact in the next decade requires **substantial and swift action**. This can only be accomplished with input from the public, key scientists, political entities, entrepreneurs, and numerous industries.

TOPICS IN GREATER DETAIL

As stated in the Executive Summary, we identified several focused topics where convergence and acceleration are most feasible in the near future (a few years). The broader group of workshop participants generally felt that while these suggestions would lead to significant outcomes within 3 years. Support for these topics would contribute measurable progress towards the goal of significant, global, multi-decadal, and **societally-impactful** greenhouse gas reductions. The topics are classified in broad themes followed by details from small group discussions:

- **A. CARBON REMOVAL**
  - **A1. Carbon capture at local scales (city, community, and tribal) with funding to benefit the local community**
  - **A2. Direct air capture: Engineered carbon removal in marine and coastal environments**
- **B. LONG-TERM STORAGE**
  - **B1. Subsurface characterization**
  - **B2. Sinking CO_2 via mineralization and mineral weathering**
  - **B3. Ocean fertilization for long residence time carbon sequestration**
- **C. CO_2 UTILIZATION**
  - **C1. Create a prototype site for a CO_2 storage hub to enable upscaling of CCUS**
  - **C2. On-roading carbon storage and utilization with existing energy infrastructure and workforce for a carbon economy**

A. CARBON REMOVAL

A1. Carbon capture at local scales (city, community, and tribe) with funding to benefit the local community

Summary: Currently, many of the most impactful efforts to reduce emissions and adapt to climate change are not occurring at national levels; rather local communities, states, tribes, and regional businesses and industry are pushing forward toward a more sustainable and resilient future under climate change. To take advantage of these conversations and successes, there is a need for strong support of foundational work at the community-to-regional scale to develop and encourage decentralized carbon capture. While others focus on the technologies to do carbon capture and storage, this innovation requires links between social-behavioral sciences, education, communication, policy development, and technologies.

A first step is the support of community outreach to listen to concerns or questions about CCUS and to address community stakeholders with the basics of carbon capture, transport, utilization and storage, and the relationship with renewable energy. It is believed that greater community understanding of CCUS will change negative perceptions and lead to increased acceptance and . By helping communities make logical connections with familiar concepts and practices, people will be more accepting of novel infrastructure and technologies. For example, in most communities distributed waste management systems are commonplace - families, businesses, and buildings collect waste in bins that are collected and transported to refuse facilities by city workers. Through outreach efforts, communities will learn innovative solutions to make it possible for households to also remove carbon from the atmosphere and store it in a central location. The perception of such collection efforts may be more accessible and less risky than a complete carbon management by for-profit industries.

This topic will require conducting research on peoples' concerns, understanding, awareness, perceptions, and acceptance of new technologies. Further, community outreach will afford researchers the opportunity to ask questions, deepen understanding, and gain acceptance. Furthermore, information about the potential for job creation must also be widely shared. Ultimately, with local-to-regional support, new innovative technologies can gain wider community implementation. Two examples of this type of work is the CarbonSAFE program in the Powder River Basin, Wyoming and the San Juan Basin, New Mexico. For economically-challenged regions, opportunities for CCUS should connect with local needs and cultures. For example, because these facilities require monitoring equipment (including power and communications), systems could be teamed with climate/weather monitoring equipment, which can be sparse. Connecting weather stations with the CCUS facilities should help to develop a nation-side network of environmental observations that can be used for weather forecasting, climate adaptation, agricultural production, and many other applications, bringing something back to the communities involved.

***What will it accomplish**:* The focus is gaining measurable acceptance and educating the public. Other benefits to local communities and citizens include the establishment of pore space as a commodity for landowners, transitioning to a low-carbon environment, job creation, and increased funding for community initiatives from taxes paid by CCUS companies. By exploring these issues at the community-scale, people can take ownership of CCUS activities, cities can build a sense of collaboration, and manage their own storage wells. There may be the potential of creating networks for monitoring emissions using established weather and climate data-gathering infrastructure to broaden the type of data being collected.

How might we accelerate this now: In order to accelerate the idea of community-level understanding and advance efforts, the message about the advantages to the general population needs to be solidified. This message should focus on the social component - the benefits of

CCUS to the people, their receptivity to CCUS, and information people need to make informed decisions. The economic feasibility of innovative technologies and risk management strategies should be communicated to the community. Identifying communities where pilot studies can be carried out will be key to disseminating a message of value and exploring the benefits of these technologies. Governmental support (financial and otherwise) of innovations will be crucial for acceleration of community pilot projects. Venture capital is also a promising avenue for supporting community-scale projects, although these funding sources do not need to be mutually exclusive, as public-private partnerships could be promising.

What groups would converge: Community members must be engaged at all stages and in all aspects of CCUS, from foundational research, development of partnerships, adoption of new technologies, legislation, and implementation. Without community support of innovative efforts, projects are likely to fail. This means that citizens (landowners, private sector actors, tribal members, etc.) deserve inclusion in all economic, political, environmental, and technological conversations regarding CCUS. This represents a true convergence of thought, as experts in these fields will need to communicate effectively and clearly with citizens to ensure acceptance and success.

Education and training for the workforce of the future: A scientifically literate citizenry is the key to major changes in acceptance and understanding of new technologies. Education and public outreach efforts will be needed to ensure the industries and companies have the workforce needed to conduct CCUS in the future.

A2. Direct air capture: Engineered carbon removal in marine and coastal environments

Summary: Large volumes are required to be removed from the atmosphere and siting removal operations through DAC or other technologies near areas of long-term storage would be advantageous due to the added benefit of reduced transportation costs. DAC is often viewed as a large, industrial, stationary approach, such as the recently announced 2021 Oxy Low Carbon Ventures partnership for DAC[1]. Large volumes of storage are generally located along the coast or offshore of every continent and in other basinal environments. If offshore storage is feasible, DAC could be designed for floating platforms. The offshore or nearshore environment offers several tangible renewable technologies including wind (onshore and offshore) and solar, despite possible harsh environmental stressors on technologies including high moisture, chloride contamination, and sulfate contamination.

What will it accomplish: Coasts are attractive regions for DAC because they exist above geologic formations that are well-suited for large volume storage and have significantly reduced

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[1] Oxy Low Carbon Ventures (https://www.oxy.com/News/Pages/Article.aspx?Article=6095.html)

societal risk factors such as seismicity as might be encountered with the built environment near terrestrial storage (e.g., Zoback and Gorelick, 2012) and leakage into freshwater aquifers (e.g., Treviño, R. H., and Meckel, T., eds., 2017). The Gulf of Mexico and several other global areas are ideal candidates (Ringrose and Meckel, 2019).

How might we accelerate this now: Large-scale coastal projects could generate social capital from synergies with other environmentally restorative efforts, such as coastal protection, wetlands restoration, and habitat management. For example, CO_2 mineralization that can be used as concrete or other aggregates could be used to develop sea walls. Substantial R&D efforts are needed to optimize solvents and sorbents used in DAC that work well in coastal climates, including accounting for high brine, high humidity environments. The near-shore geology in the US, specifically on the East Coast, have quite favorable sites for storage - with natural sinks and seals.

What groups would converge: Biologists and biochemists are creating promising forms of low energy CO_2 removal, which would have strong potential to geographically locate near coastal environments. In coastal areas that are encroached by sea level rise and increased storm intensity, citizens and interest groups will be especially keen to mitigate climate change via CCUS.. There would need to be significant project buy-in from communities and this could be harnessed by identifying economic benefits early-on (job creation, coastal resiliency to storm surge, etc.). Since several population centers cluster on coasts, point-source capture at power plants and other facilities have favorable locations relative to eventual coastal or offshore long-term storage. The coastal storage zone would be essential for coastal communities to sustainably create net-zero plans, as significant transportation would not be required.

Education and training for the workforce of the future: There is a clear need for the engineering fields (chemical, mechanical, materials) to design new or optimize existing DAC technologies, as well as develop infrastructure and materials handling to withstand coastal conditions. Civic planners will clearly have a strong role in identifying industrial innovation zones needed to physically house the industrial infrastructure. Regulators (and regulations) need to be adaptable so that they can work across disciplines. Some curriculum on science communication to non-scientific audiences is clearly a strong need across all involved STEM-related fields.

B. LONG-TERM STORAGE

B1. Subsurface Characterization

Summary: Subsurface characterization draws on a wide variety of data, much of it to help geoscientists characterize reservoirs needed for CO_2 storage. The sequestration of CO_2 into a reservoir, either as a waste material or as an injected displacement fluid coupled with hydrocarbon production (e.g., for EOR), requires not only an understanding of both the geological and geophysical properties of the subsurface, but also the engineering response, the latter often deduced from historical operational information. Analysis of these characteristics can vary from the local- to basin-scale reservoir evaluation. Elements of subsurface characterization also include the monitoring and evaluation of current and post injection status changes of the reservoir. These include pressure changes within the reservoir due to leakage or an increase in local seismicity as the result of the injection of CO_2. Measurements of caprock strain may be a cost-effective way to monitor pressure changes in, or leaks out of an underlying reservoir. Increased acceptance of CO_2 sequestration can be attained by the public's understanding of these research goals, similar to goals described in Topic A1. Proper and efficient capturing or disposing of excess CO_2 will also allow oil and gas resources and infrastructure to remain viable. Inactive hydrocarbon production infrastructure, such as uncapped wells or producing wells that flare associated gas, are a major greenhouse-gas contributor and draw on the economic and environmental health of regions. Adaptation and reuse of this infrastructure would greatly aid both reducing atmospheric CO_2, and creating new economic activity nationwide.

What will it accomplish: Much of the work involved in utilizing the subsurface for CO_2 storage has been adapted from petroleum geoscience and engineering.t. Knowledge transfer of technical analysis of porosity, net pay thickness, permeability, pore pressures and other characteristics of carbonate and clastic reservoirs is key to successful storage. Geologic and seismic analyses also include temperature, caprock seal quality with depth, pressures, faults and fracture patterns and orientation, fluid types and drive mechanism. Such approaches draw from cutting-edge science advances in academic and industry geosciences and engineering disciplines. Sequestration of CO_2 through EOR involves the efficient disposal of excess CO_2 coupled with the production of additional oil reserves, but with a net reduction in CO_2 (and CH_4) if those remain in formation. Along with robust reservoir characterization approaches, geoscientists must also evaluate the hazards associated with capture and storage. In particular, an understanding of induced seismicity hazards associated with carbon storage. Monitoring and pre/post reservoir issues including pre-drill and pre-injection risk assessment is necessary, which can also include injection and post injection changes in pressure and strain. Impacts on regional water resources is also key. Altogether, these efforts will lead to large and dynamically evolving datasets that will need to be integrated; current methods in machine learning will be incredibly useful in such endeavors.

What groups would converge: The key convergence effort in making use of the nation's subsurface will necessarily involve facilitating partnerships between the oil and gas industry, environmental groups, and academia. Academia is especially important for preparing the next generation of students/workers in terms of education and research. The American public, CO_2 producers, regulators, and policymakers will all benefit by a robust subsurface characterization program from a reduced climate impact along with an increased trust and understanding of the sequestration process.

Education and training for the workforce of the future: The training of the workforce of the future inherently starts with training students in multidisciplinary topics centered around carbon capture and storage capacity projects that includes an increased emphasis on science, technology, engineering, and mathematics (STEM) fields at elementary levels. Geoscience expertise is currently on the decline as the business cycle disfavors traditional career opportunities, and the nation's universities are currently confronting a slight student-population decline. Maintaining expertise in this area for CCUS efforts is critical. An important aspect to workforce training would be to create and promote technical workshops and field trips for the education of policymakers, regulators, along with continuing education of teachers, principals, staff members, and professors at school and university levels.

B2. Sinking CO_2 via Mineralization and Mineral Weathering

***Summary*:** Mineralization offers one of the simplest, most secure, and easiest to communicate concepts for CO_2 sequestration—change it into solid. Whether this takes the form of carbonating ultramafic rock or relying on reactions with sedimentary brines, mineralization promises to turn CO_2 into durable minerals with little potential for leakage that could affect superjacent communities or enter the atmosphere. Such approaches can be coupled with CCUS, DAC, and geothermal energy production. Alternatively, mineral weathering involves the application of crushed minerals to agricultural lands to encourage drawdown of CO_2 from the atmosphere and soils or the deliberate carbonation of mine tailings or concrete.

CCUS efforts have targeted CO_2-rich fluid migration through mafic/ultramafic (magnesian-iron rich) rocks. In science explorations through subsurface drilling (Walulah project in Washington State, Oman Drilling Project), paired with US national energy and security foci (PNW labs), or in geothermally productive provinces (Iceland). CCUS amounts have rivaled those experimental-phase demonstrations in other areas. However, the complaint has been that the total storage in mafic systems has been insufficient relative to other areas, such as porous sandstones (e.g. Kelemen and Matter, 2008). Yet, the total storage may be higher than some analyses suggest because of the dynamic nature of porosity changes. Ultimately, mineralizing systems provide a high-reward, and arguably low-risk proposition. Mineralizing CO_2 in the subsurface has given rise to an entire language of "far-from-equilibrium" geoscience, that, if successful, could lead to large quantities of CO_2 being trapped in mineral form in the subsurface. However, scientific studies are needed to understand the chemistry and timescale for mineralization processes in a range of storage sites and their physico-chemical conditions. If such an effort is undertaken, mineralization could be used in a far wider range of subsurface and surface CCUS applications.

What will it accomplish: Mineralization and mineral weathering studies would overcome scientific knowledge gaps regarding mineralization/dissolution reaction rates, reservoir characterization, drilling and injection practices, multiphase reactive transport, geochemistry and petrophysics of reservoir (subsurface) and reactants (surface). Social science and economics studies would gauge the relative value to the general public of this form of durable storage compared to other CO_2 storage media.

How might we accelerate this now: Scientific drilling campaigns, similar to those done for ocean drilling composed of seismic surveying, continuous core recovery, and petrophysical well logging, could establish instrumented long-term "field laboratories" would help develop robust multi-proxy, "4D" datasets that fully characterize analog subsurface storage systems in space *and time*. These activities could incorporate industry partners and/or contractors. Surface mineralization may limit local environmental consequences (e.g., land use, water use) but could still potentially reach Gt-scale sequestration and net negative CO_2 emissions. Regardless of whether the project occurs at the surface or in the subsurface, the integration of lab-scale empirical studies can help predict injection performance and mineralization progress.

What groups would converge: Convergence around the idea of *subsurface mineralization* would involve resource industries, government regulators, and the scientific community. Resource industries could bring technology to explore, develop and produce hard rock deposits and operate them economically. Pairing the knowledge of mineralization with EOR and similar efforts could enhance the amount of CO_2 sequestered, and the stability of its storage, during paired carbon capture and hydrocarbon production. *Surface mineralization* would require convergence between the resource industry, agriculture, water rights holders, and highway departments to develop technologies and work practices that include maximizing the potential for CO_2 drawdown in their operations. Incorporating a range of science, engineering, and policy/economics expertise will need to be entrained to see that this is not a fringe element of what could be the largest volume of CO_2 sequestered. Finally, it will be important to characterize how valuable the durable form of storage provided by mineralization and mineral weathering is to society beyond our current anecdotal views that it is preferred to living over a plume of liquid CO_2.

Education and training for the workforce of the future: For mineralization to become a viable technology, we need to develop new STEM experts skilled in geology (subsurface mapping, reactive transport modeling, geochemistry, geomicrobiology, igneous and metamorphic petrology, structural geology, petrophysics) and engineering (reservoir modeling, drilling, sensors). We need STEM experts skilled in the field (mapping, well drilling and testing, *in situ* well monitoring) as well as in the lab (bench-scale or microfluidic reactive transport studies). Lastly, the economics and policy framework for mineralization is nascent. For mineral weathering, a throughgoing societal approach similar to that used for waste disposal, including composting and industrial waste treatment, could be transferred to the sector. For subsurface mineralization, incentivizing novel engineering industries would entrain a range of social, policy, and economic disciplines.

B3. Ocean Fertilization For Long Residence Time Carbon Sequestration

***Summary*:** The oceans are the largest passive sink for anthropogenic CO_2 (e.g., DeVries et al., 2017). Moreover, the oceans provide some of key data and observations of past global climate change, including: elevated sea-surface temperatures, changing seawater chemistries leading to degradation of coral reefs, enhanced atmospheric anomalies (e.g., El Nino, monsoons, Atlantic hurricane patterns), and flooding/drought patterns. Oceans have been a focus of preliminary work on active carbon capture efforts, from iron-seeding to aquaculture to hydrogen production. Many experts suggest that innovation in ocean sciences and technology offers a significant path forward for reducing atmospheric CO_2. One approach that we probe further here focuses on both the anthropogenic release of carbon dioxide (CO_2) as well as excessive introduction of elements such as phosphate (P) and nitrogen (N) into the land, river, and ocean environments (Mackeznie et al., 2002). Throughout the geologic past, global, natural organic and inorganic processes have dampened the extreme impacts of excess inputs of P and N to the ocean (Mackenzie and Pigott, 1981). Comparable processes could be geo-engineered, with similarly global impacts.

***What it will accomplish*:** In this approach, photosynthesis by natural phytoplankton is enhanced through nutrient loading surface ocean water with P, N, and other elements. Photosynthesis would recycle CO_2 through normal life cycles of phytoplankton and then deposit organic particles (i.e., organic C) into deep-water sediments (e.g., Wagner et al., 2020). Storage thus becomes stable not only over centuries, but over millions of years. In order to couple carbon and phosphate excess, the rate of the atmosphere-hydrosphere-biosphere cycling and lithospheric) cycling need to be better understood.

***How might we accelerate this now*:** Field experiments in the oceans could be conducted in carefully selected and controlled conditions. For example, if P is the introduced nutrient for marine phytoplankton C fixation, we can use a classic measure of the C:P ratio (the Redfield number) of 106:1. In such an estimate, if one could engineer a method that would take only about 3% of the amount of P human beings presently add into the oceans each year as wastewater, the extra anthropogenic carbon dioxide presently added into the atmosphere each year is more than compensated for. Evidence that natural systems are currently responding to elevated CO2 and excess nutrient loading through increased plant growth (e.g., algal blooms: Tillstone et al., 2017) and sedimented carbon (oceanic benthic dead zones: Lohrenze et al. 2008) strongly suggest that this occurs in nature. High-resolution studies of the geologic record combined with field and lab-scale experiments would produce one avenue to understand such cycles. Specifically, a set of field experiments in the Gulf of Mexico can be performed over a two- to three-year period to test nutrient application methods and any subsequent effects they have on phytoplankton life cycles within deep-water zones. Sensor arrays placed along existing cabling on offshore platforms and/or buoys would be a time- and cost-effective way to test marine carbon fixation in such environments. Marine fauna and other ecological metrics could be simultaneously monitored for unintended consequences caused by fertilization along with any potential increases in anoxic conditions in benthic zones. Eliminating risk to and impact on biodiversity will be paramount. While the experiments themselves would be localized in nature, regional currents will be closely monitored to ensure the applications remain local.

***What groups would converge*:** For the marine experiment, many opportunities exist along the Gulf of Mexico Coast with communities, environmental groups, and researchers all participating through active planning, execution, and real-time monitoring of the collected data. The science teams will include a wide range of disciplines such as oceanographers, marine biologists, geologists, ecologists, chemists, and theoretical modelers as well as those who investigate the means of terrestrially capturing wastewater P (e.g., Penn et al., 2014). Funding for this endeavor will require all groups working together with carbon market experts to produce a workable model, both in terms of sequestration and economic success; market interests from, for example, fisheries and sand resources will likely join this effort. As the efforts are upscaled, different nations will become stakeholders because of shared international waters. Others include: the energy industry, waste management industries, federal and local governments, conservation groups, and the tourist industry.

***Education and training for the workforce of the future*:** Because this effort requires the integration of geological knowledge, biological and chemical experimentation and theory, ecosystem response studies, and marine science and technology operations, the suggested field program would be an ideal training ground for the science and technology workforce of the future.

C. CO_2 UTILIZATION

C1. Create a prototype site for a CO_2 storage hub to enable upscaling of CCUS

***Summary*:** Renewable technologies and market interests (e.g., venture capital) are turning a corner in scale and interest in business opportunities partly driven by federal (e.g., 45Q tax credit) and state (e.g. California's Low Carbon Fuel Standard) incentives. Yet, to some degree these market changes are occurring slowly, and uncertain public acceptance and immature regulatory processes are hampering development. A focused project is needed dedicated to defining a roadmap to deal with those issues and facilitate deployment of CCUS at-scale, not only in the resource industries but in all industries that emit carbon. An open-access hub, incorporating some of the sociological aspects (e.g. Topic A1), could offer large-scale storage, available to all industries including those without the community engagement, technical expertise, or the finances to run a complete storage project on their own. The idea is to make the roadmap replicable to kickstart the creation of hubs across the US and ultimately the world.

What will it accomplish: First and foremost, a group could undertake a comprehensive study of best practices derived from previously-funded research results (e.g., DOE, international projects) to fast-track one or more large-scale (2 megaton per annum storage potential) CCUS full-chain projects with a focus on overall financial sustainability. It is conceivable they might identify the nation's largest industries and help them transition to lower carbon impacts through large-scale CCUS infrastructure,marketplace development, synergy with scalable energy, and other CO_2 emissions reduction opportunities. In this way, the transition would not harm the economy but still support power requirements for major industry, while meeting carbon obligations. Furthermore, CCUS infrastructure investment would drive a **socio-economically just** transition to re-energize the economy and generate new economic opportunities in diverse geographic locations.

How might we accelerate this now: As suggested previously, a complete study compiling and rigorously examining existing research and demonstration/pilot project outcomes as a guide to map out viable commercial sites and infrastructure, including a reporting out on the economic incentives, shared funds, and private support/contributions available for future efforts. There is a strong need for integration of existing DOE/NETL Regional Partnerships, CarbonSAFE programs, capture programs, existing research hubs, etc. Those programs were developed under intense regulatory and federal scrutiny. From those projects, we should be able to develop screening work flows to identify sites which can be commercially fast-tracked in a 10-year timeframe. These should integrate technical, financial, regulatory and social strands from the start to ensure promotion of projects with the greatest chance of success. Coupled with this, one could recommend a streamlined well permit process to identify obstacles, clarify requirements, and learn from denied permits. Considerable time could be spent laying out the benefits/consequences for whether state regulatory agencies should consider taking over permitting for CO_2 injections wells (so-called EPA Class VI wells). Finally, large-scale projects in the USA will need to have clearly defined project liability. An insurance market for commercial CCUS needs to be outlined. We need to inform insurance risk and the role insurance plays in the regulatory/permitting process and cost models.

What groups would converge: The groups that have the most to gain from such convergence include power providers, hydrocarbon industry, environmental groups/centers/consultants, other industrial CO_2 emitters, policy makers, pore space owners/landowners, insurance and banking, as well as previous and current CCUS project stakeholders. Policy would likely drive the convergence of these groups through incentivizing concentrating efforts.

Education and training for the workforce of the future: The workforce largely exists, though they may be dispersed in other industries such as oil and gas, government, and insurance/banking. Mechanisms to provide transitional training for the nascent carbon economy would be required to fully leverage this workforce. A need to improve marketing of opportunities for experienced workers in other industries to "retool" for the carbon economy. In addition, there needs to be development and funding support for technical courses in community colleges and technical schools to develop skills-based workforce. An initial focus on community-based education opportunities and learn from existing projects for education in the community.

C2. On-roading carbon storage and utilization with existing energy infrastructure and workforce for a carbon economy

***Summary*:** CCUS is necessary in almost every model for reaching climate goals while also addressing energy demand. Currently, the CCUS industry is largely segregated between capture technologies, pipeline routing, and storage mechanisms. This often leads to stand-alone projects that only include a single source and one storage reservoir. To reach impactful levels of carbon removal in the United States, industries must develop robust, integrated CCUS deployment plans that incorporate dozens to hundreds of sources and sinks. While some areas of the CCUS change are entirely new, the oil and gas industry has decades of experience in carbon utilization through enhanced oil recovery (EOR) and can expand expertise into carbon storage. The National Energy Technology Laboratory suggests approximately 85 billion barrels of oil (BBO) may be obtained by CO_2-EOR methods. This amounts to a significant and strategic component to the US' petroleum reserve. With further technology innovation in CCUS, the importance of EOR recoverable reserves would be substantially increased and become a strategic interest to the security of the US as well as a significant source for CO_2 sequestration. The long-term efficacy of storing CO_2 will have to be re-examined for most, if not all, EOR projects using the same criteria as that established for pure sequestration projects. An expanded CO_2 pipeline network beyond the Permian Basin and other high oil production regions into other parts of the country with large amounts of CO_2 sources and large storage capabilities would provide an integrated, resilient carbon economy that spans multiple regions of the United States. Beyond the techno-economic analyses necessary for developing large-scale CCUS projects, further legislation and policies that encourage oil companies to add CCUS to their portfolios are needed. With additional increases/adjustments to the 45Q tax credit and advancements in capture technologies, oil and gas reservoirs, as well as deep saline formations, could economically store all of the CO_2 captured by other industries.

What will it accomplish: Developing local-, regional-, and national-scale plans for CCUS is vital for the success of economy-wide carbon reduction. This will include integrating existing CO_2-EOR fields and pipeline systems with capture facilities and other storage mechanisms (deep saline formations). When planned projects contain multiple options at each stage in the CCUS chain (capture, transport, storage), projects are more resilient to changes in the economic environment. Without this planning, capture facilities may not be able to continue operations when oil prices drop, or storage fields may not be utilized at full capacity if the capture facility is unable to provide a steady CO_2 stream.

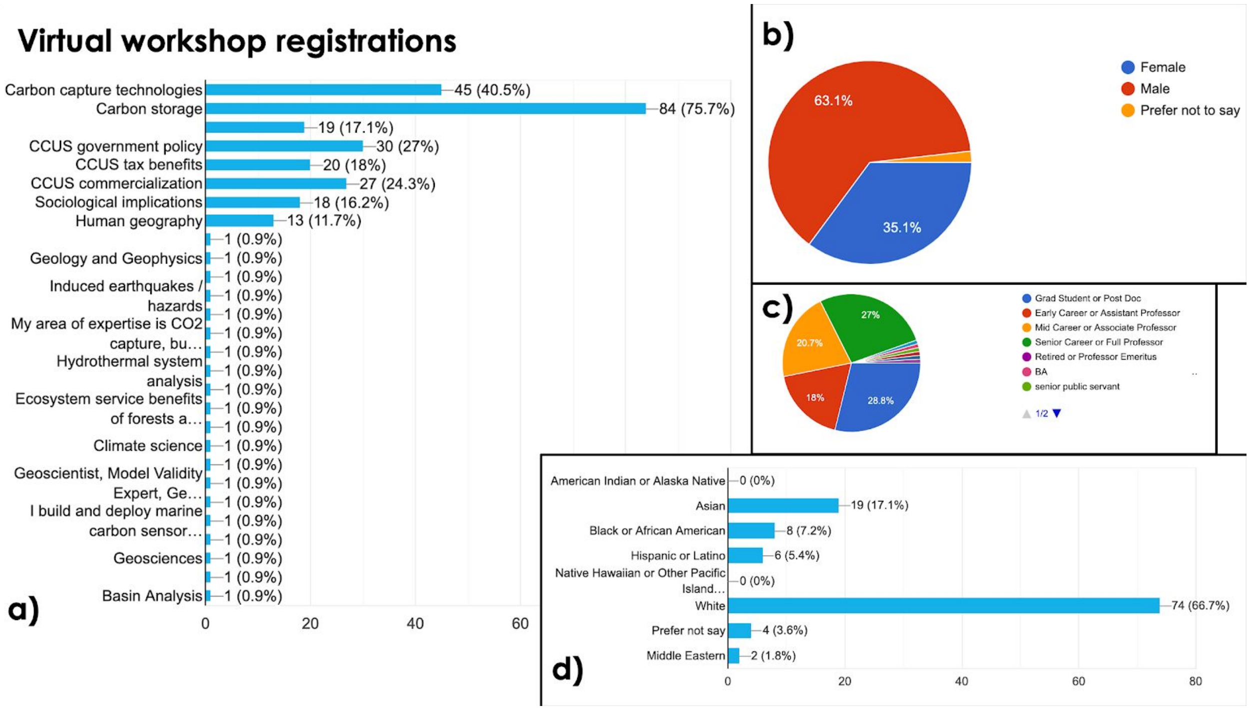
How might we accelerate this now: Acceleration can happen by recognizing opportunities for economic CO_2 capture facilities near existing oil and gas fields and optimizing 45Q tax credit usage. A vital step in accelerating CCUS is to provide risk and uncertainty assessments to companies looking to invest billions of dollars installing capturing technologies on multiple plants. Policy suggestions that promote captured CO_2 over natural CO_2 sources in CO_2-EOR operations could also accelerate the adoption of CCUS throughout the country.

What groups would converge: The on-roading of CCUS technologies with existing energy infrastructure will incorporate all sectors of the economy that either emit CO_2 or are capable of permanently storing CO_2. This could include electric utilities and other CO_2 emitting industries looking to capitalize on 45Q tax credits, or oil and gas companies looking to continue and increase operations in CO_2-EOR fields. Industries beyond oil/energy (e.g. concrete, wood pulp, chemical manufacturing, etc.) that are major emitters could take advantage of CCUS infrastructure when their respective capture technologies become economically and technically feasible. Finally, citizens wanting cleaner sources of electricity without large increases in cost will also be recipients of carbon reduction research that is being conducted now.

Education and training for the workforce of the future: In addition to the training required for specific capture and storage technologies described above, developing integrated projects requires being capable of conducting techno-economic feasibility studies, source-sink matching and pipeline routing, as well as developing policies that are favorable for CCUS. Educating the workforce of the future will require integrating traditional STEM education with public policy and economic education.

PARTICIPANTS

The workshop was advertised across several academic listservs, posted publicly, and the organizers solicited experts from carbon. Because there was no registration fee, we had broad participation by attendees from diverse backgrounds at various career levels. We encouraged participation by junior personnel and facilitators were instructed to create space and time for the junior voices to be heard during small group discussion. The list of participants and affiliations is included in Appendix A.



Registered participants were optionally asked to identify (a) topical interest/expertise participants brought to the workshop, (b) gender identity, (c) relative career level/stage, and (d) ethnicity.

VIRTUAL FORMAT

The workshop was held 12:00- 3:00 PM EST on September 28th, October 1st and October 6th, 2020. The first day consisted of randomly mixing attendees into small groups of 3 individuals for introductions. Next, over 180 “jupiter shots” were cast, which consisted of virtual “sticky notes” within KIstorm, a collaborative web-based software created by the workshop facilitators KnowInnovation. The ideas were then upvoted by all attendees so that several broader ideas emerged. Attendees selected which groups they might like to join and started working on discussion prompts within their groups.

Session 2 began with the small groups and another set of questions were posed. The prompts were designed to get the participants engaged on the big ideas and facilitate some discussion on how to emerge within a few years with tracked progress. We used a virtual tool where the small groups could post content during discussion.

Session 3 started with small group discussion to better document the feasibility of obtaining successful outcomes within a few years. After that time, groups reported back to the broader audience so that the groups could identify avenues for convergence. Finally, the conveners facilitated some open discussion on what topics might have been missed, etc.

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Appendix A: Workshop Participants

Last name	**First name**	**Organization/Company name**
Adams	Steven	University of Oklahoma
Anderson	Steven	U.S. Geological Survey
Avouac	Jean-Philippe	California Institute of Technology
Awolayo	Dapo	University of Calgary
Awoyomi	Adeola	Cranfield University
Baines	Shelagh	Redwing Geoscience LLC
Bikkina	Prem	Oklahoma State University

Boyd	Dan	Retired Oklahoma Geological Survey
Brennan	Sean	U. S. Geological Survey
Brooks	Colin	Oklahoma Corporation Commission
Brown	David	Oklahoma Geological Survey
Buck	Holly	University at Buffalo
Bump	Alex	University of Texas
Campbell	Lara	National Science Foundation
Cao	Ruoshi	Oklahoma State University
Carpenter	Steven	University of Wyoming - Enhanced Oil Recovery Institute
Chen	Xiaowei	University of Oklahoma
Clarens	Andres	University of Virginia
Clark	Ryan	Iowa Geological Survey
DaneshFar	Jamal	University of Oklahoma
Ehlig-Economides	Christine	University of Houston
Elias	Micah	UC Berkeley
Enechukwu	Chioma	Cemvita Factory
Fan	Maohong	University of Wyoming
Forero	William	NJDEP
Fulay	Pradeep	National Science Foundation
Full	William	GXStat LLC
G.Moghanloo	Rouzbeh	University of Oklahoma
Gallin	William	Washington Department of Natural Resources
Green	Matthew	Arizona State University
Greene	Scott	University of Oklahoma
Haagsma	Autumn	Battelle Memorial Institute
Hamilton	Bruce	National Science Foundation
Hasiuk	Franek	Kansas Geological Survey, xUniversity of Kansas
Hayman	Nicholas	Oklahoma Geological Survey
He	Xin	University of Wyoming

Henrion	Lucca	Global CO_2 Initiative, University of Michigan
Holubnyak	Eugene	Kansas Geological Survey
Hosseini	Seyyed	Bureau of Economic Geology
Hovorka	Susan	University of Texas at Austin
Jiang	Junle	University of Oklahoma
Kamali	Mehdi	Harvard University
Kammer	Ryan	Indiana Geological and Water Survey
Kaszuba	John	University of Wyoming
Kelemen	Peter	Columbia University
Khan	Hasan	University of Illinois at Urbana-Champaign
Kiran	Raj	University of Oklahoma
Knapp	Camelia	Oklahoma State University
Knapp	James	Oklahoma State University
Kolawole	Oladoyin	Texas Tech University
Kroll	Kayla	Lawrence Livermore National Laboratory
Lackner	Klaus	Arizona State University
Lethier	Samuel	Total
Li	Bing	Caltech
Luo	Guofan	Oklahoma State University
Matson	Mike	Carbon America
Matzel	Eric	Lawrence Livermore National Laboratory
Maughan	Douglas	National Science Foundation
McLaughlin	Fred	University of Wyoming
McPherson	Renee	University of Oklahoma
McQueen	Noah	University of Pennsylvania
Meng	Jenny	Kansas Geological Survey
Mohammadi	Sahar	Kansas Geological Survey
Mordick Schmidt	Briana	Lawrence Livermore National Laboratory
Newman	Matthew	ONEOK, Inc
Nygaard	Runar	University of Oklahoma

ORourke	Anastasia	Yale University
Pashin	Jack	Oklahoma State University
Person	Angela	University of Oklahoma
Pfennig	Karin	University of North Carolina, Chapel Hill
Phillips	Erin	University of Wyoming
Pigott	John	University of Oklahoma
Pigott	Kulwadee	University of Oklahoma
Pozmantier	Mike	National Science Foundation
Pranter	Matthew	University of Oklahoma
Regmi	Netra	Oklahoma Geological Survey
Reinhardt	Peter	Charm Industrial
Ringham	Mallory	MIT-Woods Hole Oceanographic Institute
Romanak	Katherine	The University of Texas at Austin
Rottmann	Kurt	RKR Services Co., LLC
Salehi	Saeed	University of Oklahoma
Saltzer	Sarah	Stanford University
Saraji	Soheil	University of Wyoming
Seyedolali	Abbas	Oklahoma Geological Survey
Shabani	Babak	Indiana University
Sick	Volker	University of Michigan
Silva	Lucas	University of Oregon
Smith	Christopher	Advanced Hydrocarbon Stratigraphy
Smith	Mike	Advanced Hydrocarbon Stratigraphy
Spain	Matthew	Independent
Steele	Amber	Missouri Geological Survey
Suriamin	Fnu	Oklahoma Geological Survey
Tinni	Ali	University of Oklahoma
Torres	Emilio	University of Oklahoma
Tran	Camly	UCLA
Ulmer-Scholle	Dana	NMT/Bureau of Geology

Walter	Jake	Oklahoma Geological Survey
Warwick	Peter	U.S. Geological Survey
Yamamoto	Casey	Caltech
Yunker	Molly	Oklahoma Geological Survey
Zapata	Yuliana	University of Oklahoma
Zhai	Rui	University of Oklahoma
Zhang	Qin	University Of Calgary
Zhu	Zhiliang	U. S. Geological Survey