Departmental Response:
Assessment of the Report of the SEAB Task Force on CO_2 Utilization

Introduction

On June 7th, 2016, Energy Secretary Ernest Moniz charged the Secretary of Energy Advisory Board (SEAB) to create a Task Force that would describe a framework for a Department of Energy (DOE) research, development, and demonstration (RD&D) program on carbon dioxide (CO_2) utilization technologies that have the potential to reduce CO_2 emissions and/or introduce negative emissions at the gigatonne (Gt) scale. The Task Force was asked to review current activities in the DOE, industry, national laboratories, academia, and non-profits, and identify new opportunities for research and cooperation between different disciplinary groups.

In response to this charge, SEAB created a Task Force, led by SEAB Vice Chairman Arun Majumdar, composed of 3 SEAB members and 8 other prominent scientists and engineers from academia and industry. The resulting report was developed through discussion with relevant DOE programs, including Science (SC), Fossil Energy (FE), Energy Efficiency and Renewable Energy (EERE), and Advanced Research Projects Agency – Energy (ARPA-E), and through Task Force deliberations. The report was subsequently reviewed by a second group of 8 experts from relevant disciplines, including 1 SEAB member, who provided suggestions for the report. The report was reviewed by the full SEAB and approved at the December 12th, 2016 meeting of the Board.

The framework developed by the Task Force clearly demonstrates the complexities inherent in this enormous challenge. In each of the Task Force's recommendations, fundamental scientific research is needed in order to make progress, and the report helpfully lays out several of the most important focus areas in its appendices. Many of the suggested areas for research overlap with current research directions in SC and applied RD&D programs managed by FE, EERE, and ARPA-E. Critically, the Task Force has recognized that progress depends not only on development of new fundamental knowledge and applied R&D, but on an systems-based approach that integrates the scientific and engineering efforts of all relevant stakeholders, including the DOE, other Federal agencies, academia, the national laboratories, industry, and non-profits. While financial support for basic research comes completely from the DOE's Office of Science, DOE support for energy technology projects include some level of cost sharing with the award recipient. Such public-private support for RD&D promotes the systems approach recommended by the Task Force, ensuring that stakeholders, especially industry, are financially engaged even in the early stages of technology development, that the research portfolio remains relevant to stakeholder interests, and that public sector risk is reduced.

Summary of Task Force Report

The rate of global CO_2 emissions is approximately 40 $GtCO_2$ per year ($GtCO_2$/yr), approximately half of which is taken up by the ocean and terrestrial biosphere. The other half, approximately 18 $GtCO_2$/yr, accumulates in the atmosphere, contributing to radiative forcing and global warming. Reversing the current trend represents a monumental effort in emissions reduction across the entire energy system and potentially additional net CO_2 removal from the atmosphere, also known as negative emissions. There are increasingly viable technological options that, if widely implemented, would enable significant emissions reductions from the electricity sector. The diffuse nature of emissions from the transportation and industrial sectors make deep de-carbonization significantly more challenging without scientific and technological breakthroughs.

Given the enormous scale of the problem, the Task Force has developed a framework encompassing a variety of pathways, each of which could enable emissions reduction and/or negative emissions through utilization and/or sequestration at the 1 $GtCO_2$/yr scale. Several technological approaches show promise for enabling $GtCO_2$/yr reductions if a sustained effort is made in research, development, and demonstration (RD&D). Rather than investigate each of these options in detail, the Task Force has considered RD&D options within a larger, holistic framework. This framework recognizes that for every emissions reduction pathway, a decision must be made on whether CO_2 will be captured from the air or from a point source, on a capture and/or conversion process to convert the CO_2 into a form suited to reuse and/or sequestration, and on whether to use the product or permanently sequester it to remove CO_2 from the atmosphere.

The approaches described in the Task Force's five recommendations have a relatively high degree of confidence in their scalability and represent a significant RD&D opportunity. RD&D in each of these approaches has the potential to significantly progress the technology. The five recommendations are summarized below.

> **Recommendation 1: Systems Modeling**. New systems models that go beyond today's integrated assessment models and include the non-linear impacts of technological pathways at the $GtCO_2$/yr scale that are critical for understanding positive and negative environmental impacts. Such models could predict optimal combinations of emissions reduction approaches described in the following recommendations and could guide the development of an RD&D portfolio that provides the maximum potential for reduction and minimal environmental impact before investing in any one technology or combination of technology pathways. Given the necessity of private sector investment in scaling up different technological approaches, new systems models will help explore scenarios and quantify the risks inherent in the different approaches of Recommendations 2 through 5.

> **Recommendation 2: Harnessing the Natural Biological Carbon Cycle**. Photosynthesis in plants drives the largest flux of carbon between the land and atmosphere (440 $GtCO_2$/yr). Manipulating the natural carbon cycle to absorb more carbon from the atmosphere and store more carbon in the land represents one of the largest opportunities for realizing negative emissions. This approach has positive potential co-benefits for production of food,

fuels (in the form of biofuel), and fiber, but also a large potential for risk and the requirement for fastidious management of the resource well after it stops contributing to atmospheric CO_2 reductions. A robust RD&D program in this space should focus on maximizing photosynthetic efficiency in plants while maintaining or reducing resource input, understanding the benefits of marine microalgae for land-based energy and liquid fuels, engineering of the rhizosphere for greater carbon sequestration, and stabilizing soil carbon through sustainable agricultural techniques.

Recommendation 3: Synthetic Transformations of CO_2. Carbon dioxide is a chemical feedstock capable of being converted into a variety of chemical compounds having significant commercial value. This includes direct conversion into carbon-based fuels, or conversion to precursors used to synthesize more complex compounds. This transformation is driven along one of four pathways and requires significant energy input. An RD&D portfolio for energy efficient synthetic transformation should focus on discovering new electro- and photo-electrocatalysts made from earth abundant elements, identifying new materials that enable lower temperature thermochemical transformations, engineering organisms that use non-photosynthetic catalysts for CO_2 fixation, and designing new chemical reactors scalable to the $GtCO_2$/yr scale.

Recommendation 4: Carbon Dioxide Sequestration in Geologic Formations. Geological storage is the only method of sequestering CO_2 that offers $GtCO_2$/yr capacity on the millennial time scale. The combination of storage in depleted oil and gas reservoirs and saline formations provides orders of magnitude more capacity than is needed to realize negative emissions. However, storage generally has no economic value in the absence of policy drivers except in the case of enhanced oil recovery, the value of which also depends on external factors. A RD&D portfolio for geological storage needs to address basic science (long term fate of geologically confined CO_2, CO_2 mineralization, and the impact of scale up), create a robust monitoring system to ensure safe storage, and conduct jointly funded public-private pilot scale demonstration projects to test co-optimized CO_2-enhanced oil recovery (CO_2-EOR) and CO_2 storage methods. Finally, a Data Commons should be created that serves as a shared resource for all stakeholders to use in developing new techniques and creating models to predict long-time scale behavior of stored CO_2.

Recommendation 5: Carbon Dioxide Capture and Other Separation Technologies. CO_2 utilization and storage generally require concentrated streams of CO_2. This necessitates separating the CO_2 from other gases in a mixture, for example from a power plant or from the atmosphere. Overcoming the entropy of mixing requires the input of energy. Reducing the energy, and therefore the cost, of separation and transformation requires a robust RD&D program for new sorbents having both low binding enthalpy and high binding rate constants, new non-aqueous liquid solutions (e.g. ionic liquids) or adsorption based solids (e.g. zeolites and metal organic frameworks) that selectively bind CO_2, novel membranes, and new materials for separating miscible liquids.

Additional Recommendations. The Task Force has identified two topics that are worth deeper exploration but currently have a lower degree of confidence in their scalability and the RD&D opportunity. The first topic, direct air capture (DAC), has been estimated to cost about

\$600/tCO_2. Lowering this cost will require both basic research into new sorbents as well as RD&D in systems integration. The Task Force notes that DAC would benefit from the RD&D programs recommended for conversion (recommendation 3) and separations (recommendation 5). The second, mineralization in oceans, requires RD&D to discover new methods to induce mineral formation without further acidifying the ocean. This approach is inherently very risky due to the uncertain response of ocean ecosystems to mineralization at the GtCO_2 scale.

Cross-cutting Issues. The Task Force identifies several cross-cutting issues that underpin the above recommendations. First and foremost, any and all technological approaches to capture, separate, transport, convert, or sequester CO_2 require the input of energy. It is counterproductive if the source of this energy is not derived from carbon neutral or carbon free sources. An extensive RD&D program that strives to dramatically reduce the cost of clean energy remains a critical piece of a negative emissions program. Second, in order to quickly drive down the cost of negative emissions technology, basic science, systems engineering, economics, and policy must be integrated with significant feedback mechanisms built into the system. Third, the GtCO_2/yr scale will inevitably have impacts, intentional or otherwise, on the biosphere. This necessitates a parallel RD&D effort and widespread monitoring of the climate and biosphere. Fourth, community workshops will be critically important in formulating the RD&D efforts for each recommendation. Finally, technology development and implementation at this scale requires a large, skilled workforce. Investments in education will be critical to meeting this need.

DOE Response to Task Force Recommendations

Recommendation 1: Systems Modeling.

The Office of Science will continue to prioritize fundamental research focused on obtaining a mechanistic understanding of how biological systems — both plant and microbial — interact with biotic and abiotic factors to affect carbon cycling and storage at the ecosystem scale. Quantitative and predictive models reflecting key parameters of nutrient use, plant-microbe interactions, plant architectures, and biogeochemical cycling that successfully scale from the molecular to the ecosystem level will be developed through field experiments, in-situ sensor and genomic technology development, and cyberinfrastructure to facilitate data analysis and multiscale modeling. Scientific workshops and joint principal investigators' meetings will be organized to bring different research communities together to discuss technical challenges and opportunities and develop a common vocabulary.

The Office of Fossil Energy will continue to support development of models for its energy technologies, including advanced cycle fossil power plants, carbon capture, carbon storage, CO_2 utilization, industrial CO_2 management, and CO_2-EOR. These models will be used to explore and optimize scenarios for deployment of multiple technology solutions, provide predictions of carbon management potential, and be paired with technology-specific lifecycle analysis and techno-economic modeling. An integrated representation of infrastructure and integration including CO_2 pipelines and transportation, CO_2 markets, as well as policies and regulations will allow the implications of different scenarios to be explored. Technology modeling will continue to be integrated with R&D programs to promote deep systems understanding, cost and risk analyses.

The Office of Science efforts above will seek to combine the latest scientific information on carbon fluxes in natural and managed ecosystems with integrated assessment models, ultimately providing a systems-level model of the global carbon balance at different degrees of spatial and temporal resolutions. The Office of Fossil Energy will also identify opportunities to enhance representation of emerging technologies and system interactions in integrated assessment models. Office of Science computing facilities will continue to provide key infrastructure and data analysis capabilities as integration of multiple models requires increasing resolution and compute power. Engagement of and collaboration with the relevant research communities will be important in determining their computational needs and requirements.

Recommendation 2: Harnessing the Natural Biological Carbon Cycle.

The United States has vast terrestrial resources (over 520 million hectares of crop, range and forestland) that are a strategic asset essential for sustainable economic growth. Advances in technology have resulted in a ten-fold increase in crop productivity over the past hundred years at the cost of declining soil quality. This progress has incurred a soil carbon debt equivalent to 65 parts per million (ppm) of atmospheric CO_2. The soil carbon debt has also increased the need for costly nitrogen fertilizer, which has become the primary source of nitrous oxide (N_2O) emissions, a potent greenhouse gas. The soil carbon debt also impacts crop water use, increasing susceptibility to drought stress, which threatens future productivity. Given the scale of domestic (and global) agriculture resources, there is tremendous potential to reverse these trends by harnessing the photosynthetic bridge between atmospheric carbon, plants, microbes and soil. Efforts in several DOE programs are currently tackling this challenge.

Research in SC on natural, model, and engineered plant species is greatly expanding fundamental understanding of plant growth as well as photosynthetic efficiency, and carbon capture and adaptation in both plants and microbes. Approaches range from basic biochemical and biophysical studies of photosynthesis and carbon dioxide reduction to genomics-enabled breeding and biodesign to engineer new or improved traits for growth under varying environmental conditions. Scientific user facilities such as the Joint Genome Institute and the Environmental Molecular Sciences Laboratory currently offer enabling tools and technology to the broad research community. Similarly, high-resolution imaging capabilities at SC synchrotron and neutron sources facilitate analytical characterization of key photosynthetic processes, apparatus, and subcellular components.

Several current SC-sponsored research programs are seeing success leveraging new science to modify plants and confer enhanced efficiency and resilience. Other SC research programs supporting biochemical and biophysical research on photosynthetic antenna complexes are providing fundamental insights on how these natural complexes work and how they may be redesigned to enhance light capture. Synthetic pigment-protein molecules that are based on knowledge derived from the natural complexes are already being used to test hypotheses about efficient photon capture and excitation distribution in natural photosynthesis. Such synthetic pigment-protein molecules could one day be used to expand the spectral range of sunlight that can be captured by natural photosynthetic organisms and/or artificial photosynthetic systems. Fundamental biochemical research and genetic engineering approaches have enabled accelerated recovery from photoprotection mechanisms, which has been proven in field studies to increase plant productivity by enhancing photosynthetic efficiency. New efforts to leverage advances in tunable, synthetic pigment design, catalytic function and regulation, and genome editing and engineering may reveal novel biological and bioinspired systems with synergistic capacity for improved light and carbon capture. Joint scientific workshops and principal investigator meetings will facilitate information exchange and build new research collaborations with combined strengths in the physical and genomic research communities.

ARPA-E recently launched the Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS) program with the selection of 10 projects that seek to develop advanced technologies and crop cultivars that enable a 50 percent increase in soil carbon accumulation while reducing N_2O emissions by 50 percent and increasing water productivity by 25 percent. Development of new root-focused plant cultivars could dramatically and economically reduce atmospheric CO_2 concentrations while improving productivity, resilience and sustainability.

The Office of Energy Efficiency and Renewable Energy is sponsoring a Small Business Innovation Research (SBIR) funding opportunity directed at optimizing biomass carbon conversion efficiency through arrested methanogenesis and carboxylate upgrading. EERE is also working to establish and sponsor additional efforts to optimize biomass carbon conversion efficiency including strategies that employ thermocatalytic, biocatalytic or unique combined processes. These novel biomass conversion strategies would leverage carbon-free energy resources to achieve 100% biomass carbon conversion efficiency thereby providing complimentary biomass conversion optimization technologies to those being developed to optimize biomass generation. This idea, initially proposed at the DOE’s Big Ideas Summit in April, is continuing to see development by SC and EERE.

The Office of Fossil Energy is sponsoring research that uses organisms to convert CO_2 to harvestable biomass, oils, or other high value products such as pharmaceuticals and nutraceuticals. This research builds on the fundamental knowledge and tools developed by SC and the EERE biomass program. Existing applied R&D in FE is focused on supporting feasibility and engineering design studies on how to efficiently integrate algae based photo bioreactor and pond systems into coal based power plants at scale. Some of the work has focused on genomic research to identifying strains of organisms which are resistant to trace contaminants present in coal power plants and characterizing the biomass to make a variety of bio-products. Further research will be necessary to validate these new strains of organisms and the processes innovation proposed for power plant integration.

The oceans offer a unique opportunity to sidestep many of the challenges associated with terrestrial biomass production systems, particularly the growing competition for land and freshwater resources. ARPA-E has recently released a FOA for the Macroalgae Research

Inspiring Novel Energy Resources (MARINER) program that intends to develop the critical tools that will allow the nascent macroalgae industry in the United States to leverage this tremendous resource and grow into a world leader in the production of marine biomass. The program focuses on developing advanced cultivation technologies that enable the cost and energy efficient production of macroalgal biomass in the ocean at a scale suitable as feedstock for the production of fuels and chemicals. Specifically, the program is interested in new designs and approaches to macroalgae cultivation systems, with harvesting and transport being an integral component. These new systems may leverage new material and engineering solutions, autonomous and robotic operations, and advanced sensing and monitoring capabilities. To further accelerate the development and deployment of such systems, the program focuses on the development of computational modeling tools and ocean-deployable sensor platforms, as well as advanced macroalgal breeding tools. ARPA-E expects that the MARINER program will support development of technologies that will accelerate the deployment of advanced ocean farming systems capable of delivering renewable biomass feedstock at a cost competitive with terrestrial biomass feedstocks.

Recommendation 3: Synthetic Transformations of CO_2.

The Office of Science is supporting research at multiple scales in photo-, electro-, and biocatalysis relevant to CO_2 conversion. This includes research by single-investigators and small-teams via the core research programs, and large, multi-disciplinary, multi-institutional collaborations in several Energy Frontier Research Centers and the Fuels from Sunlight Energy Innovation Hub. Multidisciplinary chemical and biochemical approaches are revealing catalytic mechanisms of water splitting and CO_2 reduction that is increasing our fundamental understanding of natural photosynthesis and establishing a foundation for enhancing natural photosynthetic efficiency and for developing artificial photosynthetic systems. Other basic research is providing insights into the conversion of CO_2 to products such as carbon monoxide, formate, alcohols, methane, and even higher hydrocarbons. All of these products either have significant economic value currently or have value as precursors to other high value chemical products. This research continues to provide foundational knowledge broadly applicable to CO_2 reduction as well as other electrochemical reactions, including proton and dinitrogen reduction reactions that are necessary for several novel hydrogen and ammonia production processes, respectively.

This in-depth understanding of mechanisms and structure/function relationships is providing the insight needed to develop biomimetic catalysts and to improve biological and synthetic systems. Foundational studies of electron transfer processes in biological and chemical systems are also providing clues in how to reduce overpotentials in electro- and photoelectrochemical systems, generate low-potential reductants via electron bifurcation, and exploit the property of catalytic bias observed in some enzymes. Other research efforts are examining the fundamental electrochemistry of materials as well as the chemical transformations of materials in operational environments.

Critically, the DOE is also supporting R&D across the Department to develop new methods that will cost-effectively scale to meet current and future demand for CO_2-derived products. Three of the recently announced projects in the ARPA-E program Renewable Energy to Fuels through

Utilization of Energy-Dense Liquids (REFUEL) program are developing scalable electrochemical technologies for converting CO_2 into energy-dense carbon-neutral liquid fuels using electrical energy from renewable sources. EERE is sponsoring a SBIR funding opportunity directed at identifying novel non-photosynthetic strategies to reduce carbon oxides from waste gas streams or atmospheric carbon dioxide. Proposals are being accepted for biological, non-biological, or unique combined strategies that can reduce the carbon oxides to fuels, products, or relevant chemical intermediates.

CO_2-derived products at the industrial scale that are cost effective and energy efficient requires that chemical precursors be available at similar cost and scale. For synthetic transformation of CO_2, this means providing a suitable reductant that can be produced from clean energy sources at sufficient scale. Hydrogen (H_2) is one option that is already widely used in the chemical industry for CO_2 reduction and many other critically important chemical transformations. Today, over 90% of the H_2 produced in the US per year comes from natural gas. The EERE-sponsored H_2@Scale initiative is developing new methods for the production of clean, low cost H_2 from domestic renewable and nuclear power. Developing low cost, high efficiency, and low emission methods for H_2 production would be enabling for synthetic transformations of CO_2. Building on the foundational science supported by SC, EERE is also exploring renewable hydrogen production from several water splitting pathways through the HydroGEN Consortium. Established in 2016 as part of DOE's Energy Materials Network, HydroGEN is a consortium of six DOE national laboratories that will address advanced water splitting materials challenges by making unique, world-class national lab capabilities in photoelectrochemical, solar thermochemical, and low- and high-temperature electrolytic water splitting more accessible to academia, industry, and other national labs.

R&D and associated efforts sponsored by FE is targeting reduced barriers to CO_2 use in the production of low carbon products and in offsetting the cost of Carbon Capture and Storage (CCS) technologies. The goal is to identify and mature opportunities that could enable more near-term and rapid deployment of CCS. FE funded projects since 2010 have focused on chemicals, fuels, polymers, cement/aggregates, and products from algae. Currently, project selections are being made from a recent FOA that covered mineralization concepts, biological-based concepts, and novel physical and chemical processes.

Fossil Energy is supporting R&D efforts in electrocatalysis and photoelectrocatalysis and actively seeks to identify such catalysts made of abundant elements and having low overpotentials. In separate work on fuel conversion, FE supports R&D involving thermochemical redox reactions for relaying oxygen and producing hydrogen at temperatures in the vicinity of 1000°C. Many FE projects are considering novel reactor designs and systems architectures, including modular systems that can facilitate early adoption and more quickly demonstrate a positive operational track record.

Ongoing EERE investments through the Advanced Manufacturing Office, such as the Institute for Advanced Composites Manufacturing Innovation and the Carbon Fiber Test Facility, along with recent investment additions such as Reducing Embodied energy And Decreasing Emissions (REMADE) are helping to create pathways for industrial products to be sourced from non-petroleum sources and for reclamation of carbon from products at the end of their life cycle.

For example, plant fibers can be used as an alternative to petroleum sources to produce high value carbon fiber as a commercial product. Technologies like these essential sequester CO_2 in long-lived fiber-based commercial and industrial products. Recycling these and other materials at the end of their life-cycle using technologies developed from EERE resources such as the REMADE institute rather than placing them in landfills, where they can decompose and release CO_2 back to the atmosphere, or burning them can also enhance long term sequestration of CO_2 within useful products.

The Office of Science is currently planning several workshops relevant to synthetic transformations of CO_2. Three Basic Research Needs workshops on catalysis, hydrogen, and solar energy will be updated with new workshops and reports over the next year or two. As appropriate, these workshops will be joint efforts with EERE, FE, and ARPA-E. Critical information about current technological barriers within these areas will be provided by EERE, FE, and ARPA-E, providing important foundational knowledge for the identification and prioritization of basic research challenges and gaps. The Office of Science will also conduct a roundtable-type workshop on research gaps in catalysis in early 2017. Fossil Energy, EERE's Bioenergy Technology Office, and SC have also been working together to engage with the National Academies on a deeper study of CO_2 utilization R&D areas that would serve to continue where the SEAB study left off on this and other topics. Finally, EERE is sponsoring a workshop at the 2017 International Solar Fuels Conference in San Diego looking at the state-of-technology and research paths forward for non-photosynthetic carbon reduction.

Recommendation 4: Carbon Dioxide Sequestration in Geologic Formations.

The Task Force emphasizes the important connection between enhanced oil recovery (EOR) and CO_2 sequestration (CCS) technologies as a means of reducing the overall cost of large-scale CO_2 storage in geologic formations, a strategy that is likely essential to achieving negative carbon emissions. Office of Science research is providing the basic science knowledge that underlies the reservoir engineering necessary to achieve the goals laid out in the Task Force report. Through the Subsurface Science, Technology and Engineering R&D (SubTER) Crosscut, efforts from SC are tightly coupled to ongoing efforts in DOE's applied energy programs, in particular the Oil and Gas and Carbon Storage programs in the Office of Fossil Energy (FE). Effective reservoir management and monitoring activities (including optimizing the connection between CO_2-EOR and CCS) requires a fundamental understanding of multiphase fluid flow and of the connection between injection rates and the state of stress in crystalline basement rocks that potentially triggers induced seismicity, as well as of the behavior of CO_2-H_2O films that govern wellbore and caprock integrity.

Through the core SC Geosciences program and three CCS-focused EFRCs, supported research activities include the development of novel full-waveform seismic inversion techniques capable of imaging the evolution and mobility of multi-phase fluids in response to changes in stress; the influence of chemical reactions in altering the state of permeability of subsurface formations; and biomineralization processes that impact caprock and well sealing, the rheological behavior and stress response functions, and time-dependent permeability of materials under extreme conditions in the cores of major fault zones. The programs are also strongly invested in fundamental science underlying the distribution and dynamics of multiphase fluid mixtures in geomaterials, as well as the phase equilibria, crystallization sequences, and kinetics of carbonate cements that alter the permeability of caprock over geological time scales.

Office of Fossil Energy is supporting research for risk assessment quantification for geologic storage operations including migration through geologic strata, well bores, faults, and fractures; effects and mitigation of induced seismicity due to pressure perturbations in the subsurface; geochemical changes affecting permeability and porosity; as well as developing monitoring and simulation tools to quantify storage performance and fluid migration. In addition the program is working to develop field test sites for storage in different classes of geologic formations; test innovative injection control schemes to maximize storage efficiency; and characterize future commercial storage facilities throughout the United States. All of this is done with the intent of archiving the data collected form this research in a central database such as the Energy Data Exchange system.

Going forward, DOE will be enhancing and integrating these efforts, in part through the SubTER Crosscut that continues through FY 2022. As an example, SC, FE, and the EERE-Geothermal Technology Office are jointly working with the Board on Earth Sciences and Resources of the National Academy of Sciences to organize a workshop defining the current state-of-the-art in imaging state-of-stress and wellbore integrity associated with H_2O-CO_2 injection into the crust. DOE is also active in the international Carbon Capture Innovation Challenge, for which a technical workshop will be hosted by the U.S. in the summer of 2017. The workshop will convene top experts to discuss breakthrough opportunities and find international RD&D synergies in carbon capture, geologic storage, and CO_2 utilization.

Recommendation 5: Carbon Dioxide Capture and Other Separation Technologies.

Separating the CO_2 from mixtures for storage or further conversion demands a large fraction of the overall energy and operating cost of chemical processes. Fundamental principles of thermodynamics and reaction kinetics underlie the challenges impeding such advances. Enhancing partition coefficients via novel liquid absorbents or solid adsorbents, advanced selective membranes and polymers, and hybrid liquid-porous systems offer opportunities for lower-cost, higher-capacity separations.

The Office of Science is currently pursuing many of these opportunities in both core research activities and Energy Frontier Research Centers. Well-represented areas that could be applied to separation processes include molecular binding energies, molecular dynamics, transport in macrostructures, molecular recognition principles, and the relationships between molecular and material structures and their binding properties. Polymeric, inorganic, biomolecular, and hybrid organic-inorganic membranes, all strengths of the SC research program, are enabling for the design of separation media for some gas mixtures. Areas in which SC-supported research could be strengthened to better address the recommendation include competitive binding and selectivity in complex mixtures, design of membranes for complex liquid mixtures, separations for dilute streams, and more generally the combined application of multiple specialized fields of knowledge in the context of novel separation mechanisms. Basic research in the separation of salts and ions using solvent extraction methods has the potential to reduce the energy intensity of other separations such as sea-water desalination or metal extraction from minerals, thereby reducing CO_2 emissions.

The Office of Fossil Energy is moving toward large scale demonstration of advanced carbon capture technologies that can reduce the cost of carbon capture significantly below the current state-of-the-art solvent based technologies. Research over the past several years has developed over a dozen novel separation technologies, including non-aqueous solvents, solid sorbents, and novel membranes. These 2nd generation technologies are expected to be ready for commercial demonstration by 2020. In 2017, the FE is starting a program to leverage national laboratories capabilities to begin scaling transformational technologies developed by the EFRC and others. A program focused on materials discovery using advanced computational capabilities, leveraging the lab and industries investment in advanced manufacturing, and establishing a partnership with industry on process design and integration will accelerate the pace at which novel materials come to the market.

The Office of Science will continue to sponsor workshops that include separation topics and/or that will identify molecular and materials research priorities relevant to separations. Going forward, there is a need to focus on achieving deeper understanding of separation processes at the interfacial, transport, molecular, atomic, and electronic levels, as well as on the design of separation media, in order to significantly move forward the field of separations of complex gas or carbon-containing mixtures. The Office of Science will explore opportunities to enhance and integrate these activities.

Additional Recommendation: Direct Air Capture and Mineralization in Oceans.

Direct Air Capture. There is currently no large scale RD&D programs in direct air capture (DAC) of CO_2 from the atmosphere that are sponsored by the DOE. Several recent studies referenced in the Task Force report have estimated the cost to be approximately \$600/tCO_2, if not higher. In the absence of other drivers, reducing this price necessitates scientific and/or technological breakthroughs. As noted by the Task Force, many of the most important science drivers described in response to recommendation 5, including developing novel liquid absorbents and solid adsorbents, membranes, and hybrid systems, would contribute to developing low cost DAC and are being addressed through current Office of Science and Fossil Energy-sponsored research. This research agenda has significant potential benefits for areas with much greater, and more immediate, economic impact than DAC, including waste water treatment, sea water desalination, and mineral extractions, among others. Advances in these areas could help drive down the cost of DAC. Addressing the complex engineering issues inherent in DAC at the GtCO_2 scale through targeted RD&D will be predicated on breakthroughs that bring the cost and energy intensity of separation down substantially.

Mineralization in Oceans. The DOE recognizes oceans as an important component of the Earth system, including understanding how the carbon and water cycles interact with regional and global climates. The Office of Science's Earth System Modeling program includes ocean research activities focused on enhancing and analyzing models of sea ice physics, ocean mixing, circulation dynamics, and larger scale oscillations such as El Nino. These research activities focus on numerical methods, model integration, and analysis. The development of models that accurately represent the complex behaviors of the ocean are a critically important component to any future RD&D effort that targets the oceans for long term CO_2 sequestration.

DOE scientific workshops and principal investigators' meetings that cover relevant topics will be organized to include various ocean research communities to discuss technical challenges and mutual opportunities. These meetings are expected to help improve model parameterizations based on field observations collected by other agencies, and reduce uncertainty in describing how the oceans interact with other components of the Earth system across a variety of scales. Field-scale experimental activities, including ocean mineralization approaches described in the Task Force report, are currently outside the mission scope of the Department.

Conclusion

Considered together, the RD&D programs described in the responses to the Task Force's recommendations represent a significant effort to develop both the multi-disciplinary foundational knowledge and early-stage technology necessary for a CO_2 utilization and/or sequestration program at the gigatonne per year scale that could realistically realize dramatic reductions in, or negative, CO_2 emissions across the entire energy sector. The new science and technology derived from these RD&D programs will also pay dividends by helping increase efficiencies, lower production costs, reduce energy and water consumption, reduce emissions, and increase product yields across a multitude of sectors. As such, these RD&D efforts contribute to both the economic and national security of the United States.

It's important to consider the crosscutting issues identified by the Task Force. The capture, separation, transportation, conversion, or sequestration of CO_2 requires the input of energy. In the case of CO_2 emissions reduction, sourcing the energy for these processes primarily from non-renewable sources would be counterproductive. The DOE's diverse energy technology RD&D portfolio has contributed to reductions in the cost of renewable energy. The DOE will continue to support a robust clean energy RD&D portfolio to continue this trend. Collaboration among DOE programs, through topical crosscuts like SubTER, and among the DOE, national laboratories, academia, and industry, are helping to create an integrated system that can drive down costs for the technologies necessary to realize significant emissions reductions or negative emissions, as well as the clean energy technology that will power those activities.

Implicit in these discussions is that international cooperation is essential for research development and implementation of energy efficiencies within a global market, and for realizing the subsequent and associated emissions reductions and/or negative emissions. Developing a robust, internationally recognized observation network ensures that all parties are meeting commitments to emissions reduction and supports international efforts in earth and climate monitoring that are necessary to understand the global environmental impacts of any effort at the 1 $GtCO_2$ scale. This international challenge is as important, and possibly as difficult, as the technical challenges described above. The DOE can leverage its existing relationships with international partners through meetings and technical workshops to meet the technical and sociopolitical targets necessary to realize a 1 $GtCO_2$/yr goal.