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Chairman Yaw, Madam Chairman Comitta, Vice Chair Pittman, honorable Committee Members, thank you for the opportunity to discuss the deployment and utilization of carbon dioxide management technologies today. My name is Dr. Brian Anderson, and I am the Director of the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL).

NETL has applied research campuses in Pittsburgh, Pennsylvania; Morgantown, West Virginia; and Albany, Oregon, and the lab operates field offices in Anchorage, Alaska, and Houston, Texas. NETL focuses on science and technology development leading to commercialization of low-cost, reliable energy that spurs economic development while mitigating technical and environmental risks. NETL maintains nationally recognized technical competencies and collaborates with partners in industry, academia, and other national and international research organizations to nurture emerging technologies.

As the DOE's only Government-Owned, Government-Operated (GOGO) laboratory, NETL also implements R&D projects for DOE's Offices of Fossil Energy (FE), Energy Efficiency and Renewable Energy (EERE), Cybersecurity, Energy Security and Emergency Response (CESER), and Electricity (OE). The laboratory's research portfolio includes more than 1,000 research activities across all 50 states, with a total award value that exceeds $5 billion, including private sector cost-sharing of $1.3 billion.

DOE has been tasked with a critical role--to serve the Administration's bold climate agenda. It has been asked to develop innovative, cutting-edge carbon capture, utilization, and storage (CCUS) technologies from the bench scale at the laboratory into commercially deployable solutions. NETL is a major national resource for scientific research, discovery and development of new clean energy technologies. Those technologies will ensure America's energy security and prosperity. Today, I will highlight key technologies that are accelerating clean energy development utilizing CCUS.

Decarbonization Overview

While decarbonization is underway to varying degrees in many parts of the world and in the United States, achieving that goal requires transformational technology development. At present, carbon-laden fossil resources account for 80 percent of electric power generated domestically. Decarbonized fossil-based solutions are necessary as a bridge to carbon-free technologies.

In the near term, fossil decarbonization involves CCUS: removing carbon from fuels and/or combustion product streams for use and/or permanent storage in geologic formations. A further stage may focus on blue hydrogen, derived from fossil fuels in a carbon-neutral or carbon-negative manner, enroute to the eventual goal of using renewables-powered electrolysis to get hydrogen from water. That product is referred to as green hydrogen. The International Energy Agency (IEA) estimates that a changeover to green hydrogen could be feasible on a global scale around 2050, leaving us with at least 30 years of continued dependence on fossil energy sources.

As we transition to a decarbonized economy, we must minimize any added costs. One way to keep costs down is to leverage existing infrastructure for transport and storage. Adaptation of natural gas infrastructure to accommodate hydrogen will require advanced technology and code development; NETL is well positioned to lead that type of research.

Because most renewable energy is variable or intermittent, dispatchable fossil energy with CCUS will continue to be necessary in addition to grid-scale energy storage for grid reliability during this energy transition. Legacy fossil-fueled power plants suffer from reduced efficiency and need increased maintenance when used as backup power for intermittent resources. Adaptation of existing plants and development of technologies for new fossil power plants to increase their flexible use has been a chief R&D objective at NETL for the past several years.

Full decarbonization of the electricity sector will require a combination of (i) renewable resources, (ii) energy storage, and (iii) reliable, low-carbon energy generation to assure reliability and lower cost. Power plants with CCUS could lower the cost of decarbonized electricity generation by avoiding overcapacity of energy storage and renewable generation relative to peak demand, as long as the CCUS technologies capture carbon very efficiently (i.e., at 95% or greater efficiency), at competitive costs.

Key NETL Facilities to Advance Decarbonization

The **Science-based Artificial Intelligence and Machine Learning Institute (SAMI),** established in 2020, combines the strengths of NETL's energy computational scientists, data scientists and subject matter experts with strategic partners to drive solutions to today's energy challenges. The institute wants to leverage science-based models, artificial intelligence, and machine learning (AI/ML) methods, data analytics and high-performance computing to accelerate applied technology development. The goal is clean, efficient, and affordable energy production and utilization. SAMI is supported by NETL's cutting-edge computational infrastructure, including the Joule 2.0 supercomputer, the WATT GPU-based cluster, and the Energy Data eXchange (EDX®). Additional high-performance computation facilities are in the planning stages. EDX is an online public and private research curation and virtual data platform developed by NETL to improve access to trustworthy data products across DOE and beyond.

NETL's **Reaction Analysis & Chemical Transformation (ReACT) Facility** supports energy conversion engineering efforts, offering researchers innovative tools to advance the science of chemical reactions. ReACT's groundbreaking capabilities enable researchers to develop transformative technologies such as microwave-assisted chemical conversion that can reduce overall system energy requirements, decrease overall costs, and lower targeted emissions for energy systems. This facility has equipped NETL researchers to push the boundaries of microwave chemistry research. These reactors are among the most advanced in the world; they have been used for collaborations with the University of Pittsburgh, West Virginia University, the Rapid Advancement in Process Intensification Deployment (RAPID) Institute, Malachite Technologies, and others.

NETL's **Materials and Minerals Characterization Center** is designed to enable (i) efficient advanced energy systems; ii) carbon capture utilization and storage (CCUS) technologies, and (iii) effective processes to convert fossil resources to high value products. Materials characterization is a key element in the materials development research process. Characterizing natural (or geological) materials is also essential to further NETL's deep understanding of the interaction of natural materials with CO_2 (or H_2) needed to advance safe subsurface CO_2 (or H_2) storage and enhance resource recovery.

NETL has been developing plans to design, construct, house and operate a **Direct Air Capture Center (DACC)** for evaluating emerging technologies in direct air capture (DAC). The DACC would target technologies that are above lab scale but below full pilot scale. The center will provide a unique set of infrastructures to evaluate emerging and promising technology at scales and conditions facilitating industrial acceptance, resulting in rapid maturation into the commercial sector.

NETL's Carbon Capture Program and Technologies

U.S. industry has used solvents to capture CO_2 since the 1930s. Investments in R&D have led to improvements, and continued R&D could lower the cost and increase the scale of carbon capture technology. Recent efforts to effectively scale up and apply the technology to power plants underscore the need for further research and policy incentives. Tax credit programs offer opportunities but may not be enough to make the technology cost competitive.

The DOE-NETL Carbon Capture program addresses both capital and operating costs to improve the economics of carbon capture and provide a solution for the power sector. Over the last decade, the program has developed pilot-scale, second-generation technologies that are on a development path to be commercial ready by 2025. Transformational technologies that capture carbon highly efficiently are at earlier stages of development. In a comprehensive and sustainable approach for carbon management, The Carbon Capture Program at DOE/NETL is developing both Carbon Reducing Technologies and Negative Emission Technologies to achieve pollution-free power sector by 2035, and to put the United States on an irreversible path to a net-zero economy by 2050.

Carbon capture involves the separation of CO_2 into a pure stream and (in many cases) compressions to a supercritical fluid for transport via pipeline. Industry has a rich history of CO_2 separation, although few large-scale CCUS powerplants are currently in operation worldwide. Successful examples of carbon capture at scale have been achieved with government support and policy incentives. Challenges include the increased capital and operating costs of carbon capture and the possible reduction in net generating capacity relative to comparable plants with unabated carbon emissions. Investments in transformative technology can help to mitigate these challenges.

The Carbon Capture Program has over 90 active projects. They involve academia, national labs, small and large businesses to develop technologies that capture CO_2 from point sources at power plants and industrial facilities, as well as directly from air. The Carbon Capture Program at DOE/NETL has taken new approaches to carbon capture from bench- to pilot-scale demonstrations.

Top NETL Carbon Capture Research in PA

1. NETL is currently partnered with RoCo Global (formerly known as Liquid Ion Solutions), located in Pittsburgh, PA. RoCo Global is an advanced materials company that develops innovative technologies and specializes in two key areas: CarbonTech (CO_2 capture and CO_2 utilization) and Advanced Functional Materials. The project with RoCo Global, along with Carnegie Mellon University and Carbon Capture Scientific, aims to increase the efficiency of water-lean chemical solvent, thus lowering the capital and operating costs for CO_2 capture.
2. NETL is partnered with Media and Process Technology Inc. (MPT), located in Pittsburgh, and with the University of Southern California to advance membrane processes for pre-combustion CO_2 capture in an integrated gasification combined cycle (IGCC)-based poly-generation plant. MPT has a

complete state-of-the-art facility for membrane-related activities, ranging from R&D and pilot scale units to a field demonstration plant and ceramic membrane manufacturing facility.

3. NETL is collaborating with CONSOL Energy to design an advanced pressurized fluidized bed combustion power plant and complete a Front-End Engineering and Design (FEED) study. This will help CONSOL determine the technical and economic feasibility of building and operating such a plant with carbon capture technology. CONSOL is considering all currently available carbon capture technologies but is focusing on amine-based carbon capture. The potential host sites for the plant are located in southwestern PA or northern WV, areas that are part of CONSOL's Pennsylvania Mining Complex. This project will push CCUS technologies closer to commercialization by demonstrating its economic feasibility for this application.

Future Research in Carbon Capture

- In September of 2020 DOE and NETL announced the award of approximately $72 million in federal funding to support the development and advancement of carbon capture technologies under two funding opportunity announcements (FOAs).
    - DOE awarded a total of $21 million to 18 projects for direct air capture technologies that remove CO_2 from the atmosphere. Technologies developed to date have primarily focused on the capture of CO_2 directly from large point sources, such as industrial sources and fossil fuel power plant flue gas streams. The Carbon Capture Program aims to leverage this past research in materials, equipment, and process development for both current and transformational DAC technologies.
    - Although CCUS is often viewed in the context of power production, capture and storage of CO_2 from industrial sources and directly from the atmosphere is also vitally important to reducing greenhouse gas emissions. Nine projects received $51 million for cost-shared R&D focused on initial engineering studies of technologies to capture CO_2 generated as a byproduct of manufacturing at industrial sites.
- In January 2021, DOE announced an additional $15 million in federally funded financial assistance for cost-research projects to develop efficient processes and components utilizing transformational materials to lower the cost of DAC systems. Further research in the area of direct air capture will lead to a better understanding of system costs, performance, and other factors to accelerate development of this climate-critical technology.

NETL's Carbon Storage Program

Geologic storage involves the injection of CO_2 into storage complexes in the deep subsurface. A storage complex consists of (1) one or more storage reservoirs, with permeability and porosity that allow injection and storage of CO_2; and (2) one or more low-permeability seals that lie above the reservoir(s) and serve as barriers to the upward migration of CO_2. Since 1997, the DOE Carbon Storage Program has significantly advanced the knowledge base and validation of technologies for carbon storage through a diverse portfolio of applied research projects. Technologies being developed and the injection projects (large and small) conducted through the Carbon Storage Program increase our ability to safely and cost-effectively store CO_2 in the subsurface.

DOE's Carbon Storage Program aims to assess the subsurface storage capacity across the U.S., both onshore and offshore. To facilitate industry adoption of geologic carbon storage, DOE sponsors both

pilot and mid-scale injection projects to demonstrate the process, to provide examples for others to follow, and to reduce project risks and costs for future commercial projects. DOE has adopted a philosophy of learning by doing, carefully assessing every aspect of geologic carbon storage projects. While CO_2 has been used for decades in enhanced oil recovery, with incidental storage of the CO_2 used, DOE and NETL have promoted storage within saline (brine-filled) reservoirs, which represent a much larger and more geographically diverse storage opportunity than enhanced oil recovery fields and depleted oil & gas fields combined. Storage capacity across Pennsylvania -- in depleted oil & gas reservoirs, enhanced oil recovery opportunities, un-minable coal seams, and saline reservoirs – is estimated to be able to hold 18 and 20 billion metric tons of CO_2.

The primary goals of DOE's Carbon Storage Program include development of cost-effective technologies for mapping the location of CO_2 that has been injected underground and the associated fluid pressure increases, assessing and avoiding the risks of induced seismicity, using the pore space within reservoirs more effectively, identifying and quantifying migration of injected CO_2 in unintended directions, and assuring the integrity of wells, including old wells that represent potential leakage pathways.

Individual technologies and methods are developed through a combination of extramural and intramural R&D. Program participants include DOE's national labs, universities, private businesses (including members of the oil & gas industry, power generation industry and coal industry) and various other research institutions. NETL's Pittsburgh campus and the major regional universities (Penn State University, University of Pittsburgh, and Carnegie Mellon University) have played prominent roles. Pennsylvania industries, such as CONSOL, have also joined the efforts.

Top NETL Carbon Storage Research in PA

1. NETL was partnered with PA organizations such as CONSOL Energy, Wade LLC., NiSource, Babcock & Wilcox Company, Constellation Energy, and the PA Geological Survey in the Midwestern Regional Carbon Sequestration Partnership (MRCSP). This partnership was established to assess the technical potential, economic viability, and public acceptability of carbon sequestration within its region. It was one of seven Regional Carbon Sequestration Partnerships (RCSPs) established by DOE across the U.S. as part of an overall DOE strategy to develop robust, cost-effective options for mitigating carbon dioxide emissions that contribute to climate change. The partnership has now been replaced by the Midwest Regional Carbon Initiative (MRCI), with many of the same members and with the primary goal of assisting future geologic carbon storage projects within the region, including Pennsylvania.
    - The Pennsylvania Geological Survey's geological storage efforts have been coordinated by Kristin Carter, the Assistant State Geologist, through Battelle Memorial Institute as the lead for the local Regional partnerships (MRCSP and MRCI), under several DOE funded programs over the years. Significant progress has been made in understanding the geological storage options within the State. However, additional data collection in the deeper sedimentary layers can help refine estimates of storage resources. The Pennsylvania Geological Survey and Battelle have also collaborated on CO_2 storage options in the sub-sea sediments in the Atlantic Offshore region. These offshore reservoirs offer very large potential storage opportunity for East Coast regions, including eastern Pennsylvania.

- The MRCI has been supportive of emerging industries in the state, such as the KeyState Natural Gas to Ammonia project in Clinton County, by providing geologic information and insights.

2. NETL is partnered with Penn State University to develop and validate a suite of joint inversion methods – methods to convert two or more types of geophysical measurements into a self-consistent and physics-based interpretation of subsurface features. Joint inversion of two or more sets of monitoring data (e.g., seismic, electromagnetic, pressure, and petrophysical data) reduces the uncertainty in important subsurface aspects, such as rock properties, leak detection and quantification, as well as the location of injected CO_2.
3. In partnership with the University of Pittsburgh, Penn State University and Carnegie Mellon University, NETL is leading the Science-informed Machine learning to Accelerate Real-Time (SMART) initiative to explore the potential of applying machine learning approaches to enable more intuitive visualization of the subsurface and faster decision making through rapid and integrated data gathering and processing.
4. Also, in partnership with collaborators at Penn State University and Carnegie Mellon University, NETL's leads the National Risk Assessment Partnership (NRAP). NRAP is focused on developing, demonstrating, and disseminating robust, transparent, and science-based tools and methods to quantitatively assess the range of potential environmental risk factors at CO_2 storage sites as they evolve through time.
5. Recently, NETL initiated funding for a prefeasibility study of a possible CO_2 storage site at CONSOL's mining complex in Greene County, PA. This effort will focus on detailed planning and costing to characterize a potential 15,000-20,000 ft CO_2 injection well located on the project site. Existing geologic data, such as 2D and 3D seismic surveys, will be used. At the same time, a team member, Carbon Solutions, will review physical, logistic and economic parameters of an integrated CO_2 disposition plan that encompasses the broader region, to evaluate how on-site geologic CO_2 storage compares to other potential options for regional CCUS deployment (Enhanced Gas Recovery, conversion of depleted shale gas wells to CO_2 storage, carbon feedstock development, etc.).

Future Research in Carbon Storage

- In April of 2020, NETL announced the award of $85 million (Federal share) to five projects that will finalize their site characterization efforts and file permit applications to construct commercial-scale storage facilities – facilities designed to accept more than 50 million metric tons of CO_2 within a time period of 30 years or less during operations. These projects, if successful, should start operations by 2026. While none of these are located in Pennsylvania, they are expected to help launch a "geologic carbon storage industry" within the U.S., including in Pennsylvania.
- NETL is now reviewing proposals recently received under a funding opportunity announcement (FOA 2401) that aims to fund industry members, universities and research institutions to further develop technology (1) to assess and predict the probabilities and maximum likely magnitudes of induced seismicity, and (2) to determine the locations and magnitudes of unintended fluid flow through the main seal rock layers above storage reservoirs. Pennsylvania organizations have an equal opportunity to participate in most of NETL's funding opportunities, as most are not geographically limited (i.e., seeking projects only in specified geologic basins or offshore environments).

NETL's Carbon Utilization Program

DOE-NETL's Carbon Utilization Program aspires to develop technologies to transform CO_2 into valuable products in an efficient, economical, and environmentally friendly manner. Research and development activities address the challenges and potential opportunities associated with integrating a CO_2 utilization system with various power and industrial plants or carbon capture systems, such as waste heat integration, wastewater reduction, flue gas contaminant reduction, and reduced energy demand. An ongoing program objective is to make technologies applicable for near-term implementation. Developing advanced catalysts, reactor systems, and processes for more efficient conversion of CO_2 to valuable chemicals can provide a viable alternative to conventional manufacturing processes.

The emerging field of CO_2 utilization encompasses many possible products and applications: fuels, organic and inorganic chemicals, food and feeds, construction materials, enhanced resource recovery (e.g., oil, gas, water, and geothermal energy), energy storage, wastewater treatment, and others.

Top NETL Carbon Utilization Research in PA

- NETL is partnered with Advanced Cooling Technologies, Inc. located in Lancaster, PA to utilize CO_2 from power generation systems or other industrial sources to create valuable products that display beneficial aspects when compared to commercially available products. This will partially offset the cost of carbon capture while reducing net CO_2 emissions. The development of technologies that use CO_2 as a primary feedstock to generate environmentally sustainable and economic products such as value-added organic products, inorganic materials (i.e., solid carbon products and concrete/cement), and microalgae, will support cost-effective implementation of CCUS throughout the utility and industrial sectors.
- NETL is supporting Media and Process Technology Inc., located in Pittsburgh, through a Phase II SBIR project focused on the production of dimethyl carbonate from CO_2. Dimethyl carbonate is a commodity chemical that serves as a safer alternative to methyl halides or dimethyl sulfate in chemical production. This project supports bench scale testing of an integrated carbon molecular sieve membrane process developed by Media and Process Technology Inc., which if successful, could be further scaled with additional investment from additional sources.
- NETL researchers at the Pittsburgh research campus have demonstrated new approaches for controlling the chemistry and improving the energy efficiency of carbon conversion processes. In-house researchers produced several patented and patent pending technologies that use electricity and water to produce commodity chemicals and have reduced catalyst material costs by up to $50,000 per kilogram by eliminating the need for precious metals.
- NETL researchers have developed materials and methods to synthesize and demonstrate new microwave active metal oxide catalysts for converting CO_2 and methane into hydrogen and carbon monoxide. This invention will allow the development of modular reactors that use intermittent renewable electricity to power a reaction that is currently not economically viable due to extreme energy demands. The invention will consume 22 tons of CO_2 for every ton of H_2 produced. The alternative steam reforming process to convert methane into H_2 produces approximately 10 tons of CO_2 for every ton of H_2.

Future Research in Carbon Utilization

- DOE's Carbon Utilization Program, announced in January 2021, plans to make $8 million in federal funding available for cost-shared research, development, and testing of technologies

that can utilize CO_2 from power systems or other industrial sources for bio-mediated uptake by algal systems to create valuable products and services. The primary objective of carbon utilization technology development is to lower the near-term cost of carbon capture through the creation of value-added products from the conversion of CO_2.

Conclusion

In conclusion, science, technology, and research are powerful anchors of innovation and sustainable economic growth in Pennsylvania. Through DOE-NETL's world-renowned research facilities and technology development programs, a comprehensive portfolio of technological solutions to keep CO_2 emissions out of the atmosphere has been established. Thank you for the opportunity to discuss some of these cutting-edge innovations, which have applications within - and beyond - the energy sector.