Senate Environment & Public Works Committee
Subcommittee on Clean Air and Nuclear Safety
Developing and Deploying Advanced Clean Energy Technologies
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Written Testimony

Thank you for giving me this opportunity to share our insights into the current status and future of carbon capture, utilization, and storage. My name is Steve Bohlen, and I lead the advanced energy technologies and energy security portfolio at Lawrence Livermore National Laboratory (LLNL).

My testimony seeks to provide an update on the status of carbon capture, use, and storage (CCUS), with emphasis and focus on CO_2 utilization (CO_2U) and carbon removal (CR). This includes assessment of current technologies and their readiness, activities in technology development at my Laboratory (LLNL), and several projects and initiatives ongoing around the world in which LLNL has been involved that foreshadow a future in which CO_2 becomes a feedstock for valuable products.

Management of carbon dioxide emissions is not just viable – the technology exists today, is deployed and operating, and functions as designed. Technology for converting CO_2 into materials we use every day is developing rapidly. These provide new possibilities for commercial enterprise in the US, as well as to provide opportunities for commercial and technical leadership. It is possible to improve the environment while generating revenues. Innovation lies at the heart of this new carbon economy, and both basic and applied R&D are needed to make best advantage of the opportunities in this competitive and dynamic landscape.

Clean energy demand continues to grow worldwide, with investment of nearly $400B in 2015 and 2016, and carbon capture, use, and storage (CCUS) remains a growing, but underutilized element in the clean energy industry. CCUS includes carbon capture and storage (CCS), CO_2 enhanced oil recovery (EOR), CO_2 conversion and use (CO_2U), and even carbon removal technology (so called negative emissions approaches which pull CO_2 from the air and oceans). These different pathways provide commercial and environmental opportunities for companies, communities, and governments.

Technical progress in CCUS is significant with unrealized potential to manage carbon emissions. Today, 16 commercial plants operate worldwide, and with six more planned, 22 will be operating by 2020 (Figure 1). These include power and industrial projects, new build and retrofits, and both CO_2-EOR and saline storage, with over a third in North America. Costs have come down, performance has improved, and new technologies have been born that show that CCUS can be cost competitive today with many clean energy technologies in many markets (Lazard, 2016, see below). In some sectors, like heavy industry (refining, cement manufacture), CCUS is the only option available at scale today for carbon management.

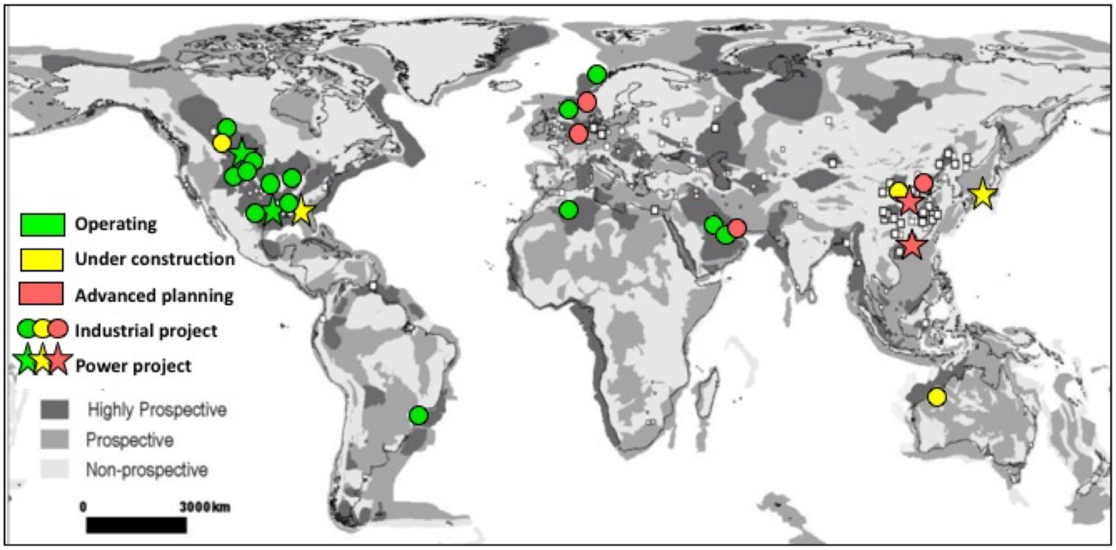

Figure 1: Operating and soon to be operating CCUS projects worldwide. Over one third of these are in North America.

The mission of the Department of Energy's National Laboratories is to advance science and technology that address issues of today and to foresee important pending national and global challenges and help provide solutions to them as well. Much effort is focused on developing new technologies, often in close partnership with companies who can bring these technologies to market. The challenges of a sustainable national and global environment, threat reduction from extreme climate events, and providing an engine for US competitiveness have led to federal investment in research and analysis conducted at LLNL and other Labs on projects and problems to manage carbon through CCS, CO_2U, and Carbon Removal.

Grounded in our expertise in novel materials, modeling and simulation, and carbon life-cycle expertise, for nearly two decades LLNL has been funded to work on CCUS and has been a partner in most of the carbon capture and sequestration projects nationally and globally. As a result, LLNL has developed analysis tools and early-stage technologies for CO_2 removal from the air and oceans. Recently, this has expanded to include conversion of CO_2 to useful products such as methane, methanol, and ethylene, much of which is enabled by advanced manufacturing technologies and advanced computer simulation of catalyst efficacy.

In dealing with the problems of today, LLNL and other laboratories provide technical expertise, modeling and simulation, and actionable solutions for the challenges of EOR and CCUS.

- Today, LLNL provides the most advanced 3-D fracture mechanics modeling for industrial partners for managing the risk of induced seismicity for hydraulic fracturing operations, EOR, and underground carbon sequestration projects.
- LLNL scientists have provided technical and modeling expertise for most large-scale geologic carbon sequestration projects globally, and the safe long-term storage of several tens of millions of tons of CO_2 underground.
- LLNL has developed technology that can feed CO_2 to algae with low cost, high efficiency, and minimal CO_2 losses. This could improve biofuels production cost, performance, and geographic range.

- In partnership with Iowa State University and Easy Energy, LLNL has launched an effort, funded by the California Energy Commission, to convert forestry wastes to biofuels through fast pyrolysis. This technology also produces biochar, a charcoal-like substance that improves soil performance while storing air-removed carbon. A pilot field project is anticipated by 2019.

In looking to the future, LLNL is engaged in the development of revolutionary new technologies with industrial partners that seek to manage CO_2 emissions by turning CO_2 into a valuable feedstock for new industries and technical capabilities that are economically viable and convert CO_2 into useful products – fuels (methane and biofuels) and chemical feedstocks (methanol, ethanol, and ethylene). Indeed, we see a society that is poised at the edge of a new carbon economy – one that harnesses innovation and entrepreneurship to create new products, companies, and wealth through capturing and converting CO_2 into value-added products. Many see this industry as potentially enormous, possibly of a size and scale comparable to agriculture, oil and gas, or power sectors today.

- Combining simulation, advanced manufacturing, and new materials, LLNL has discovered both direct and biologically mediated pathways to convert CO_2 to chemical feedstocks and fuels. The current work focuses on converting CO_2-to-ethylene, a critical feedstock for plastics and petrochemicals.
- LLNL is embarking on a bold, new approach to managing at a large scale and simultaneously providing sand for cement manufacture or beach replenishment and elevation gain.

Though in its embryonic stages, the process takes advantage of the ocean's high calcium carbonate content. By removing CO_2 from ocean water, excess calcium carbonate precipitates as fine grains of sand. This happens naturally, particularly in the Caribbean and the Red seas, but can also be induced by using LLNL's encapsulated solvent technology to remove CO_2 from ocean water. The sand that precipitates can be used to build beaches in remote areas such as the US missile test site on Kwajalein Atoll. Currently the only source of building material in the southern Pacific islands comes from the destruction (dynamite) of the reefs to provide material, for example, protection from rising sea level. With advancements in this new technical approach, it could become possible to generate large amounts of carbonate sands for increasing low-lying island elevations and protecting infrastructure. With the removal of CO_2 via LLNL's encapsulated solvents, CO_2 produced must be stored underground in the volcanic core of the atoll, or, more beneficially, converted into a useful product such as gasoline using technology like that developed by 3M and Oxide Materials. Renewable energy would power such systems.

During the March 2, 2014 overwash event in the Republic of the Marshall Islands, seawater regularly topped the manmade perimeter berm on the island of Roi-Namur and covered large areas of the adjacent land surface. Shown are runways and radar dishes on the US Army Base Kwajalein Atoll Missile Range https://walrus.wr.usgs.gov/climate-change/atolls/news.html#oct15 The LLNL technology could *potentially* create carbonate sand to provide a berm perimeter and raise the elevation in important areas.

Like the National Labs, groups within US universities are also making advances in CCS, CO_2-EOR, and CO_2U. As examples, the US DOE Hub at the California Institute of Technology has led a program for over seven years in converting CO_2 to fuels photochemically (using sunlight to make fuels). Stanford, MIT, and Northwestern University have similar programs. Iowa State University and University of Illinois have programs on bioenergy with CCUS. And recently, Arizona State, Iowa State, and Purdue University launched a new consortium[1] with LLNL and the Center for Carbon Removal focused on creating the knowledge and practice needed to draw economic value from carbon removal and CO_2 conversion and use.

US institutions are not alone in this effort. Universities, research institutes, and National Labs in other countries have taken up this challenge as well. Groups in Canada, Mexico, Europe, the Middle East, and East Asia are busy and growing, and governments in those regions are increasing their investments in CCS, CO_2-EOR, CO_2U, and carbon removal. Despite US progress and investment to date, it is not clear that the US leads the world in this area.

Global Operational Project Review

As noted, numerous projects are operating in the world today, with several more coming online by 2020, in total over 20 projects that sequester CO_2 at industrial scales. Together, these will inject 40 million tons of CO_2 underground – like pulling eight million cars off the road. The overwhelming majority of these projects has been completed on time and on budget, and has a successful high-capacity operating history.

[1] https://www.newswise.com/articles/new-carbon-economy-effort-launched-at-arizona-state-university

Among these projects, there are several noteworthy projects for the Committee's consideration.

PetraNova[2]: NRG, in partnership with JX Nippon and Hilcorp Energy Company, retrofit the W.A. Parish power plant near Houston, TX. Roughly 1.6 Million tons are captured by the liquid solvent technology, provided by Mitsubishi Heavy Industries, and stored during enhanced oil recovery. The project came in on time and on budget. The operators and partners say that a second project at the same site could be done for roughly 20% lower costs.

Port Arthur[3] **and Quest**[4]: These two industrial projects capture and store CO_2 which is a byproduct of converting methane to hydrogen. This produces very low-cost, zero-carbon hydrogen – the cheapest in the world so far. The Air Products project at Port Arthur stores the CO_2 through EOR. Shell's methane reform project at Quest stores CO_2 in a saline formation.

China: Many CCUS projects are moving forward quickly in China. Dr. James Wood's testimony will explain this in some detail. However, it is worth noting that three large commercial projects are coming on line in the next four years, and that the Chinese Academy of Sciences has tasked a new research institute in Shanghai[5] for the sole purpose of CO_2 conversion to useful products.

NetPower Pilot Plant: NetPower[6] is a North Carolina-based company that uses "Allam cycle" combustion – oxygen-fired natural gas turbines that use supercritical CO_2 as both the working fluid and mass to the turbine. The NetPower system has the same cost as a natural gas power block, has a physical footprint, and requires no water for cooling (in some configurations, the plant produces water). A pilot demonstration[7] near Houston has finished construction and begun component testing - it should be operational in fall 2017, with Exelon, Chicago Bridge and Iron, and Toshiba as commercial partners.

Climeworks Direct Air Capture Plant[8]: A small Swiss company, Climeworks, has created the first commercial, for-profit project that captures CO_2 directly from the air. They capture and sell 900 tons per year of CO_2 to an organic greenhouse. This technology is mass-producible, scalable, and robust.

Carbon removal power plant: Climeworks is partnering with Reykjavik Energy in Iceland and Lawrence Livermore National Laboratory to make the world's first power plant with less-than-zero carbon emissions. Based at the Hellisheidi Geothermal Power Station[9], Climeworks is installing their direct-air capture system. CO_2 drawn from the air will then be injected into the deep basaltic rocks below the plant, part of the CarbFix project[10]. LLNL will work on the monitoring and validation of the CO_2 injection as well as the life-cycle analysis of the carbon footprint.

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[2] http://www.globalccsinstitute.com/projects/petra-nova-carbon-capture-project
[3] http://www.globalccsinstitute.com/projects/air-products-steam-methane-reformer-eor-project
[4] http://www.globalccsinstitute.com/projects/quest
[5] http://english.sari.cas.cn/
[6] http://www.netpower.com
[7] https://www.forbes.com/sites/christopherhelman/2017/02/21/revolutionary-power-plant-captures-all-its-carbon-emissions-at-no-extra-cost/#5db22e3d402d
[8] http://www.climeworks.com/
[9] http://www.onpower.is/about-us
[10] https://www.or.is/english/carbfix-project

Carbon Recycling International's Renewable Methanol Plant[11]: Also in Iceland, Carbon Recycling International has built and operated a plant that converts CO_2 to methanol, a chemical feedstock and transportation fuel. Using clean electricity from the Svartsengi geothermal power station, they make hydrogen from water and combine the renewable hydrogen with CO_2 to make methanol. This fuel is sold to ferries in Europe which use the methanol to power fuel cells.

NOTE: The increased availability of low-cost, distributed clean power and heat helps to create new industries like Carbon Recycling International that convert CO_2 to products. Part of the likely market value of these products is the low carbon footprint. If so, then the demand for clean energy will grow as these companies gain market share – part of a new carbon economy.

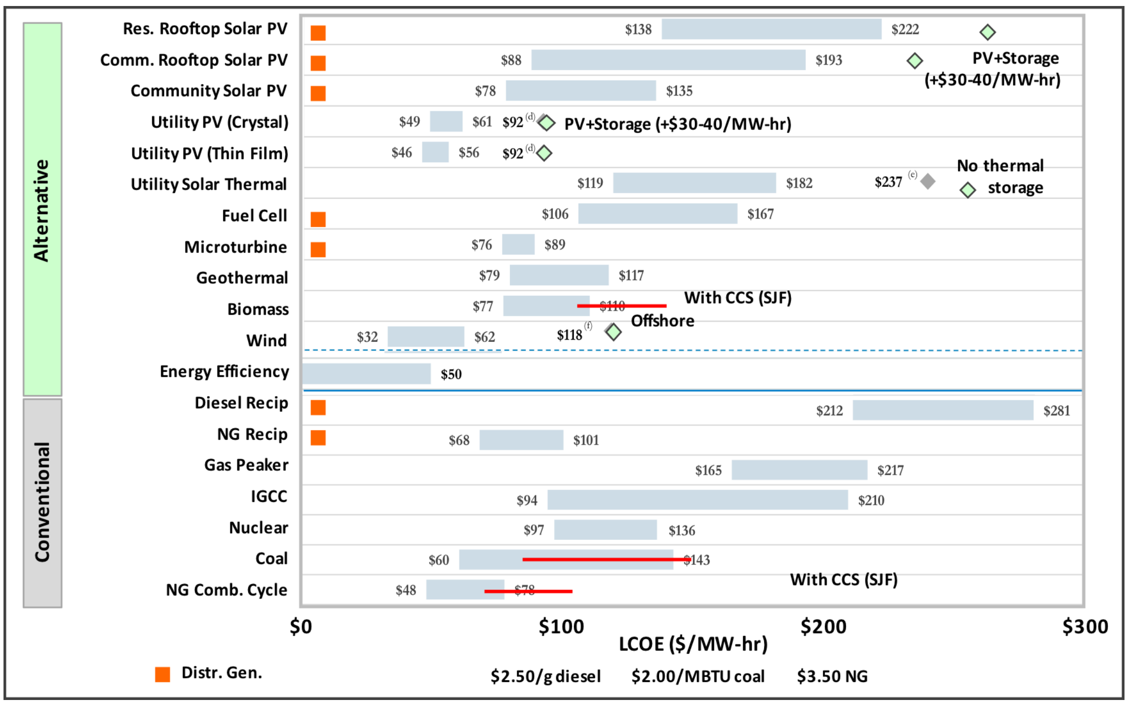

Figure 2: After Lazard (2016). Red bars reflect reported costs from commercial projects and price estimates based on DOE and NETL reports on existing technology in the market today.

Power Applications: Range of Costs and comparisons to other technologies

CCUS has many applications, including power, heavy industry (see below), and achieving negative emissions. Though commonly considered a coal-power sector technology (for which the technology would be most valuable in reducing emissions), the same or similar technology can also be applied to biomass, natural gas, biogas, and even fuel cell power systems. Contrary to common opinion, the CCUS power costs are rapidly becoming competitive today on an unsubsidized cost basis with many other technology options (Figure 2). On an unsubsidized basis for the levelized cost of electricity (LCOE)[12], power from gas, coal, or biomass (with CCS, noted as a red line in the figure above) is cheaper than that of

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[11] http://carbonrecycling.is/

[12] Lazard, 2016. Levelized cost of electricity analysis 10.0. https://www.lazard.com/perspective/levelized-cost-of-energy-analysis-100/

offshore wind, new nuclear power, rooftop solar PV, concentrating solar, and community solar PV with batteries in many US markets.

Today, post-combustion retrofits on a supercritical coal plant using amine-based solvents are possible and in some case the lowest cost pathway to decarbonization. For example, the PetraNova plant described above reduced 90% of the emissions from one unit without derating or decline in power output. In addition, opportunities for cost reduction are significant even with the same CCUS-systems. Coal-plant operators in the US and Canada have stated that they could reduce costs by 20% redoing the same plant, and that the fourth plant would achieve 40-50% cost savings relative to the first.

Industrial CCUS in the US

Many heavy industries, representing 20% of global emissions, lack other options to decarbonize. Cement, steel, refining (and biorefining), chemicals, and glass making are particularly difficult cases. For cement and steel making, much of the emissions are a direct consequence of fabrication chemistry. For such systems, CCUS is currently the only available option.

In many cases though, by-product CO_2 is highly-concentrated (e.g., for ethanol, biodiesel, fertilizer production, natural gas sweetening, refining, and petrochemicals). These can be captured and stored at relatively modest cost. In the US, the all-in-cost of CCS, including polishing, compression, transport, and storage, is less than $30 per ton CO_2 – in some cases less than $20. ***Over 43M tons per year could be stored at this low cost.*** [13]

For this reason, perhaps unsurprisingly, most CCUS projects around the world are industrial projects. These include Emirates Steel (the first ultra-low C metallurgical plant), the Uthmaniyah refinery in Saudi Arabia, the Quest upgrader project in Alberta, the ADM ethanol plant in Decatur, Illinois, and the Air Products plant in Port Arthur, TX.

[13] www.betterenergy.org/American_CO2_Pipeline_Infrastructure

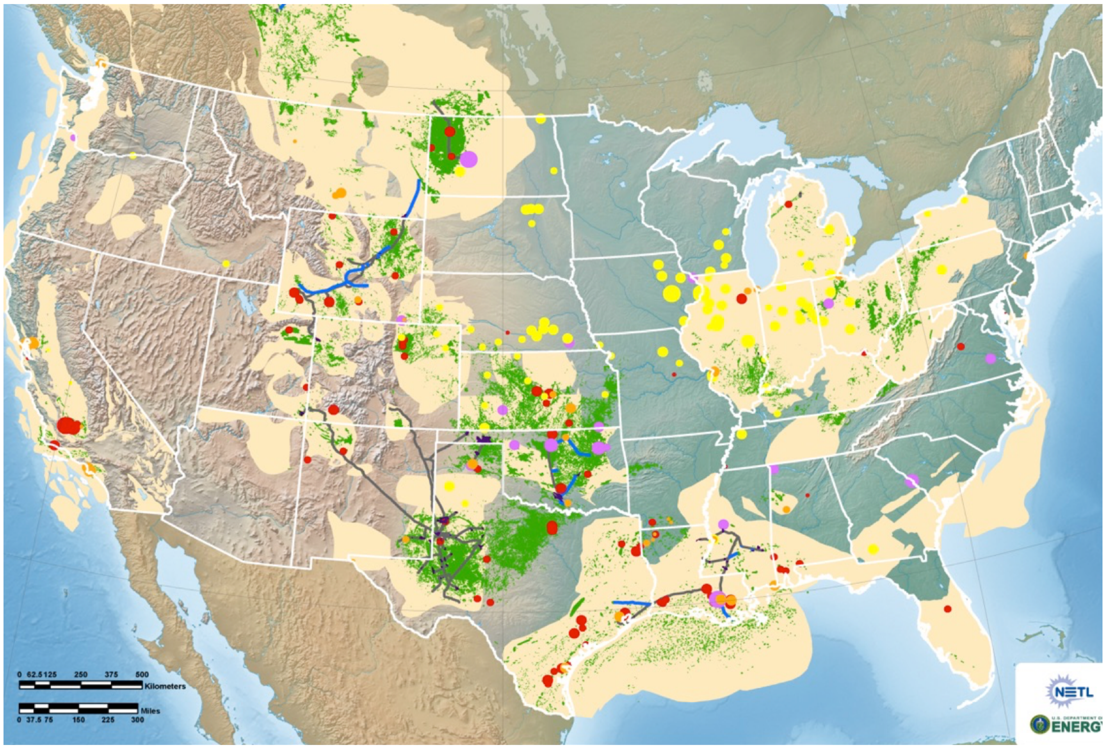

Figure 3: High-purity CO_2 sources within 100 miles of potential CO_2 storage sites. Green areas represent oil fields; light beige areas represent saline formations for storage.
Yellow dots = ethanol plants; purple dots = fertilizer plants; red = petrochemicals plants; orange = oil and gas refineries.

Summary

As stated at the outset and recapitulated here, management of carbon dioxide emissions is not just viable, it is a technology that exists today, is deployed and operating, and works as designed. Technology for converting CO_2 into materials we use every day is developing rapidly. These provide new possibilities for large-scale commercial enterprise in the US, as well as to provide avenues for commercial and technical leadership. Improving the quality of the environment and generating revenues is not a dream, it is a reality today. Innovation lies at the heart of this new carbon economy, and both basic and applied R&D are needed to make best advantage of the opportunities in this competitive and dynamic landscape.