House Science and Technology Committee

The Future of Fossil: Energy Technologies Leading the Way

July 17, 2018

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Written Testimony

Thank you for giving me this opportunity to share our insights into the current status and future of fossil energy and carbon capture, utilization, and storage. My name is Roger Aines and I am the Chief Scientist of the energy program at Lawrence Livermore National Laboratory (LLNL).

This testimony provides an update on emerging fossil energy technologies, including the status of *carbon capture, carbon storage, carbon utilization, advanced energy systems,* and *removing carbon dioxide from the atmosphere*, with emphasis and focus on CO_2 utilization and carbon removal. It includes an assessment of current technologies and their readiness, activities in technology development at my laboratory (LLNL), and the current state of CO_2 utilization in American industry. This current state foreshadows a future in which natural gas and CO_2 become feedstocks for valuable products, creating an economic opportunity for all regions of the United States by using abundant resources and new technology.

The technology to manage CO_2 is already deployed and operating, and functions as designed. New technologies for converting CO_2 into materials we use every day are developing rapidly. These developments provide new possibilities for commercial enterprise in the US and opportunities for commercial and technical leadership by our country. Innovation lies at the heart of this new carbon economy, and both basic and applied R&D are needed to take best advantage of the opportunities in this competitive and dynamic environment. An exciting example of the science and technology that is sure to drive new economic growth in CO_2 utilization is additive manufacturing, or 3-D printing, which is already beginning to revolutionize U.S. manufacturing. It will be a major technology component of this new landscape.

Demand for low-carbon energy continues to grow worldwide, with investment of nearly $400B in 2015 and 2016. Carbon capture, use, and storage (CCUS) remains a growing, but underutilized element in the low-carbon economy. CCUS is a technology category that includes carbon capture and storage, CO_2 enhanced oil recovery (EOR), CO_2 conversion and utilization, and even carbon removal technology (so called "negative emissions" approaches that pull CO_2 from the air and oceans). CCUS technologies provide commercial and environmental opportunities for companies, communities, and governments, particularly in parts of the country where CO_2 and natural gas are readily available, and electricity is inexpensive. This is particularly applicable to the center of the country.

Technical progress in CCUS is significant, but there is unrealized potential to manage carbon emissions. Today, 16 commercial CCUS plants operate worldwide, and with six more planned, 22 will be operating by 2020. These include power and industrial projects, new build and retrofits, and both CO_2-EOR and saline storage. More than a third of them are located in North America. Costs have come down, substantially through R&D by DOE Fossil Energy. In some sectors, like heavy industry (e.g., refining, cement manufacture), CCUS is the only option available at scale today for carbon management.

The mission of the Department of Energy's national laboratories is to advance science and technology that addresses issues of today, anticipate important pending national and global challenges, and help provide solutions to them. Much effort is focused on developing new technologies in close partnership with companies that can bring these technologies to market. The need for more efficient fossil fuel technologies that can provide an engine for enhanced US competitiveness have led to DOE research and analysis conducted at LLNL and other national labs.

Grounded in our experience in novel materials and modeling and simulation, LLNL has been funded to work for nearly two decades on CCUS. LLNL has been a partner in many of the carbon capture and sequestration projects nationally and globally and has developed analysis tools and early-stage technologies for CO_2removal from flue gas, air, and oceans. Recently, this effort has expanded to include conversion of CO_2 to useful products such as methanol and ethylene.

At LLNL we are focused on tomorrow's clean fossil energy system. I would like to comment on five areas of our work that are critical for a strong energy future: **carbon capture, carbon storage, carbon utilization, advanced energy systems,** and **removing carbon dioxide from the atmosphere**.

Carbon Capture affects our ability to use and manage carbon dioxide. We need to be able to capture CO_2 from flue gas in power plants and heavy industry. LLNL has worked in this area for ten years. We are focused on reducing the cost of carbon capture by reducing the capital expense of capture systems. LLNL is funded by the Fossil Energy Program to develop new carbon capture approaches that use additive manufacturing to make systems that are more efficient. Additive manufacturing can make capture equipment smaller, which can reduce the capital investment. Because capital costs can be half of the lifetime cost of a CO_2 management system, we believe that capital cost reductions are the best target for reducing the cost of carbon management.

Natural gas will grow in importance as our nation moves to use its extraordinary resources of this fossil fuel to create efficient industry and power. The technology that DOE has developed for coal-fired systems can also be applied to natural gas systems but has not been tested at large scale. There is a need to transfer that DOE knowledge to industrial natural gas users.

In **Carbon Storage** LLNL provides the most advanced 3-D fracture mechanics modeling for industrial partners to help them manage the risk of induced seismicity for underground carbon sequestration projects, hydraulic fracturing operations, and enhanced oil recovery. We are particularly interested in engaging the US oil industry, including independent producers, by taking advantage of their skills, workforce, and economic desire to make CO_2

storage a reality. For example, the Mt. Poso Cogeneration Company LLC is the largest biomass fueled power plant in California. It is located on an oil field with a depleted portion potentially suited for CO_2 storage. The geology there seems to be good and the Mt. Poso power plant may be one of several good sources of CO_2 for storage. The economic benefits from the 45Q storage tax credit and the California low-carbon fuel standard make this an attractive option that the site partners are considering. This is an excellent example of industry willing to step up, but in the design phase they will need help absorbing the knowledge developed in DOE programs to date. LLNL is working with them to do that and to help determine if CO_2storage is a safe and economical option for them.

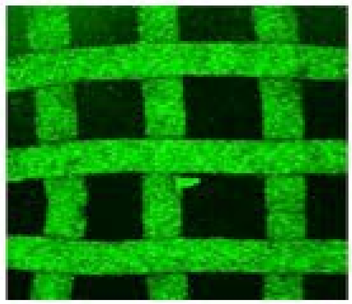
Carbon Utilization (or as some call it, *carbon recycling*) is poised to become a major new industry in the United States. Last month twenty companies from Exxon to 3M to Nike attended our workshop in Livermore for corporations interested in this new way to use CO_2. All of them are interested in how their products can be improved with materials fabricated from CO_2. We will be releasing a report on the conclusions from this workshop in the next few weeks. This is an area ripe for basic research, and not ready to jump to major production yet. Most of the work in this area is going on in university labs (like Pulickel Ajayan's at Rice University and Tom Jaramillo's at Stanford University), where the basic science of the reactions is being worked out.

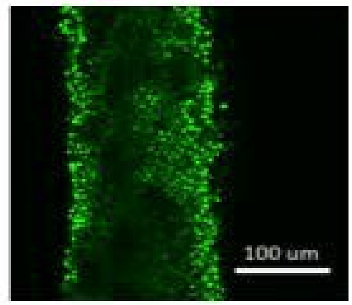
In the Texas to Iowa corridor, *CO_2 is an abundant feedstock*, and the new wind turbines in that region routinely sell their power on the wholesale market for less than 2 cents a kilowatt hour. New industries can use that electricity and CO_2 to make exactly the desired chemical product in high yield, and they will not need much of the expensive separations equipment currently required for production of chemicals. When you look at a refinery or chemical plant today, most of that complex maze of equipment is for purifying the final product. By using simple feedstocks like carbon dioxide and natural gas, new factories can make our carbon products like textiles, plastics, and even fuels.

Wyoming has led the way in CO_2 utilization efforts with development of a CO_2 test center where entrepreneurs can demonstrate their new technologies. This kind of support for technology innovation will speed implementation of these new technologies.

The concrete and carbon fiber industries are also on the forefront of finding new economical uses of CO_2. *Concrete can be made stronger by adding CO_2* to it, and a number of companies are pursuing this goal including New Jersey's Solidia, which makes stronger precast concrete items with CO_2. Interestingly, one of Solidia's major business challenges is having an assured supply of CO_2 so that they can take on major contracts. Carbon fiber is just starting to be made from CO_2 in the laboratory, as are carbon nanotubes and other exotic materials for the light-weighting and electronics industries. C4 Composites in Santa Monica, CA, is working to make carbon fiber directly from natural gas, while simultaneously making hydrogen gas for use in chemicals or as fuel.

Additive manufacturing, or 3-D printing, is a game-changing innovation that allows complicated products to be built in ways that can't be done by conventional manufacturing. Additive manufacturing is very important for using CO_2 in new industrial processes. At LLNL we use 3-D printing to create chemical reactors that combine the natural gas, CO_2, and water in the exact proportions and perfect conditions to make a desired product. We can even use bacteria that have been modified to make the product we want and *build the reactor out of those bacteria* (along with a binder to hold them in place). Working with the National Renewable Energy Lab (NREL), which designs and supplies the bacteria, we have made reactors that produce valuable organic acids (like lactic acid) and methanol from natural gas.

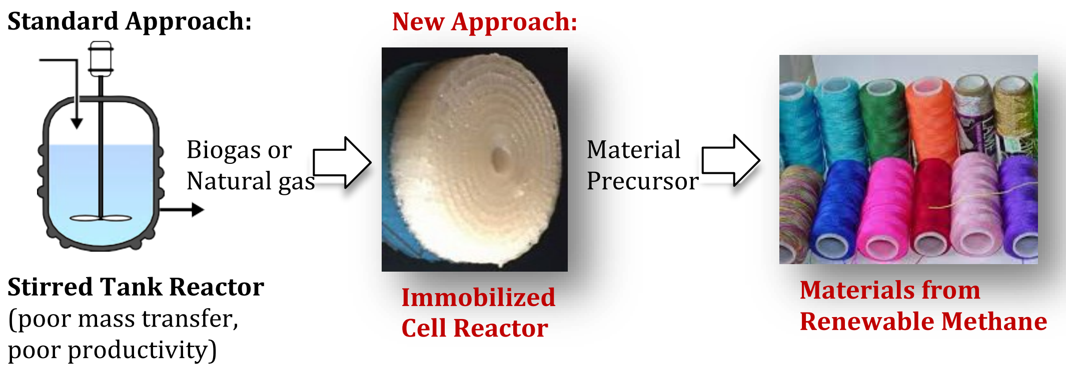


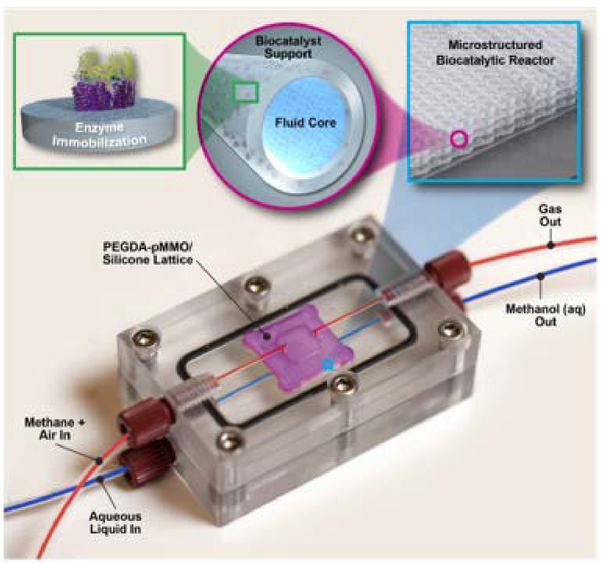


Live yeast cells have been combined with a binder, then put in a 3-D printer to make the fabric at left. The green color shows the location of the cells in the fabric. This material converts sugar to ethanol. The cells are alive and reproduce in the printed material: the reactor is a living thing. This technology could dramatically change the way chemicals and bioproducts are made.

These reactors will be the heart of new chemical plants building products from CO_2 and natural gas. The early products that companies are interested in are high-value organic chemicals that are best made by living organisms. This new reactor technology will create new businesses and jobs in the United States. They could also be used to convert small sources of natural gas into methanol, a liquid, that can be collected and transported in trucks, turning waste into a valuable resource.

These technologies are part of an LLNL program to use abundant energy resources to make new products. We are investigating the use of electricity to convert carbon dioxide and water to ethylene, the most abundant chemical feedstock. This could enable distributed generation of ethylene in parts of the United States where CO_2 is abundant and electricity is inexpensive today (much of the central part of the country).





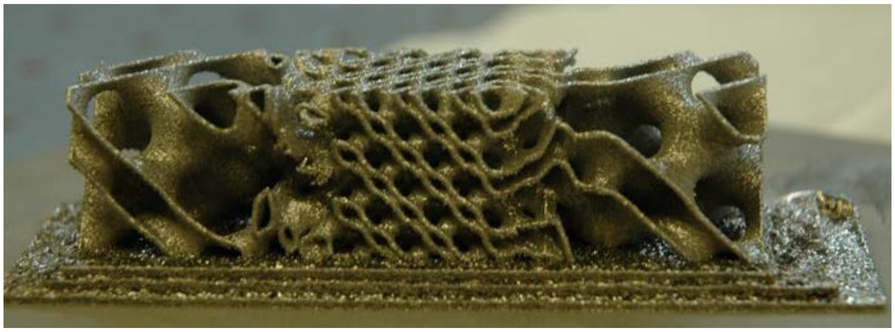
Additive manufacturing is an important part of utilizing CO_2 to make products. It allows us to balance many factors to get pure products. In this chemical reactor the cell wall of bacteria called *methanotrophs* are printed into the polymer walls of the device. The enzymes in those cell wells convert natural gas to methanol, a valuable industrial chemical. No added electricity or heat is needed. *Natural gas flows in, methanol flows out.*

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.

Looking to the future, LLNL sees great promise in revolutionary new technologies 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 valuable products. We see this industry as potentially enormous, possibly of a size and scale comparable to today's agriculture, oil and gas, or power sectors.

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

Advanced Energy Systems operate at high temperatures and pressures to achieve their high efficiency. Supercritical CO_2 systems that use highly pressurized CO_2 instead of water to drive turbines are a huge step change that can make America's power more efficient using our abundant natural gas. One of the most remarkable examples of this is NetPower,[2] a North Carolina-based company that uses "Allam cycle" combustion – oxygen-fired natural gas turbines that use supercritical CO_2. The NetPower system costs the same as a natural gas power block but produces more power and captures 100% of the CO_2. A pilot demonstration[3] near Houston has finished construction and begun testing—it should be fully operational in fall 2018, with Exelon, Chicago Bridge and Iron, and Toshiba as commercial partners.



This is the first Inconel 3-D printed heat exchanger, made at LLNL for the DOE's advanced energy systems program. Devices like this will allow higher-temperature and more efficient energy systems, while making economical use of valuable materials like nickel stainless steels, reducing the capital cost of new energy systems.

The very high efficiency with which the NetPower plant turns natural gas into electricity relies on high temperature components made of nickel steel. This metal is hard to machine and weld but at LLNL we are printing these components using laser 3-D printing. This allows us to work with the difficult nickel alloys and create unique shapes that can only be done by building the part up from powder instead of machining a metal block.

Carbon Removal from the atmosphere is the long-term challenge. The climate models tell us that in order to achieve a future with no more than two degrees of warming, we will need to remove billions of tons of CO_2 from the atmosphere. The United States is already testing carbon removal at the Archer Daniels Midland ethanol plant in Decatur, Illinois where the CO_2 from fermenting corn is captured and injected deep underground – *the first large-scale carbon removal plant in the world*.

The farming industry can also contribute to carbon removal by encouraging practices that *replace carbon in soil* that has been lost over the years. This has the added benefit of creating better soil. Imagine if everyone had the same soil quality as Iowa. Those soils are so good principally because they contain a lot of carbon that the plants and microbes recycle constantly, creating a rich environment for plant growth. LLNL has a large program looking at the science of soil improvement, focusing particularly on how deeply rooted plants can both

[2] http://www.netpower.com
[3] https://www.forbes.com/sites/christopherhelman/2017/02/21/revolutionary-power-plant-captures-all-its-carbon-emissions-at-no-extra-cost/#5db22e3d402d

improve yields and soil quality at the same time. We believe that deep soil carbon will be an important tool for carbon dioxide removal because: (1) soils have a huge capacity to hold carbon, (2) adding carbon improves crop production, (3) it engages farmers (who understand how to improve soil quality), and (4) it is a long-term way to keep carbon out of the atmosphere.

Another carbon removal approach leverages the mechanism that the Earth already uses to remove CO_2 from the air: *reacting it with rocks*. This natural process creates limestone, a permanent storage form for CO_2. Peter Kelemen at Columbia University has pioneered work using rocks called ultramafics, which come from deep in the earth. They react with CO_2 in the air, removing it permanently. He is examining whether these rocks, commonly found in the United States, can be forced to react more quickly by circulating water through them, forming a limestone-like rock at the surface.

Seven firms are exploring another carbon removal approach through the use of chemical processes known as *direct air capture*. Although this technology is in its infancy and additional research and development is needed to discover how expensive it will be, it is already of great interest to the corporations that want to use CO_2 in their chemical processes. If CO_2 can be captured from the air, it means these corporations would have access to an unlimited supply of feedstock. For large-scale efforts, after extraction, the CO_2 will probably need to be stored underground. Although we expect that this is fairly easy to do based on DOE's existing storage program, this is an area where demonstration and validation are important to develop confidence that this combination of new technologies (air capture and carbon storage) is a robust approach.

A small Swiss company, Climeworks,[4] has created the first commercial, for-profit project that captures CO_2 directly from the air. Climeworks captures and sells 900 tons per year of CO_2 to an organic greenhouse. This technology is mass-producible, scalable, and robust. A US corporation, Global Thermostat, is completing a demonstration capture plant in Alabama that will be much larger than the Climeworks project when it begins operation this fall.

Summary

The United States is poised to be the leader in the use of CO_2 and natural gas for new carbon products – a new carbon economy. This will improve national security as it makes us more energy self-sufficient and will create new economic opportunity. Development and demonstration of innovative technologies in which the U.S. already leads will be key to that process. Because energy and the necessary feedstocks—CO_2 and natural gas—are abundant in the central United States, we anticipate that new industries will thrive there. Both basic R&D and transfer of that research to corporate users will be important accelerators for the new carbon economy. The research and development done by the national laboratories strives to bring that vision to fruition.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

[4] http://www.climeworks.com/

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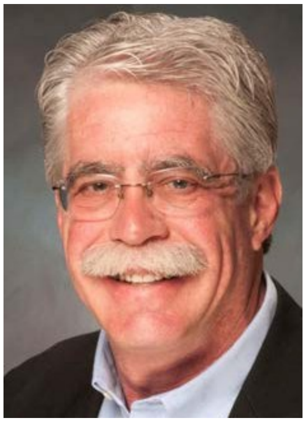

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Roger Aines is the Energy Program Chief Scientist in E Program, which conducts government and private sector research in clean energy technology. He is a Senior Scientist in the Chemistry, Materials, Earth and Life Sciences Directorate at LLNL. He holds a Bachelor of Arts degree in Chemistry from Carleton College, and Doctor of Philosophy in geochemistry from the California Institute of Technology. He has been at LLNL since 1984 working on nuclear waste disposal, environmental remediation, application of stochastic methods to inversion and data fusion, management of carbon emissions including separation technology, and monitoring and verification methods for sequestration.

Roger's career has involved a close coupling of scientific research, engineering, field demonstration, and assessment of future development needs for technology. His research interests include the chemistry of natural and engineered processes, including carbon dioxide separation and water treatment. Roger's current research includes application of 3-D printing to chemical reactors and gas separations, development of catalysts for carbon dioxide capture, management of pressure in geologic sequestration through brine withdrawal and treatment, and encapsulation of carbon dioxide capture solvents. He previously led LLNL's Carbon Management Program, which takes an integrated view of the energy, climate, and environmental aspects of carbon-based fuel production and use. It supports DOE projects in sequestration technology development for capture, and carbon recycling. Roger directs the LLNL program in developing better understanding of hydraulic fracturing and tools and methods around shale gas development. He holds twenty-two patents in the areas of carbon capture, shale gas production, *in situ* degradation of organic chemicals through heating, and the mechanisms of thermally assisted remediation, and has eighty publications.

LLNL-MI-642887

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