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RANGE OF INNOVATIVE, NON-GEOLOGIC APPLICATIONS FOR THE BENEFICIAL REUSE OF CARBON DIOXIDE FROM COAL AND OTHER FOSSIL FUEL FACILITIES

HEARING

BEFORE A

SUBCOMMITTEE OF THE

COMMITTEE ON APPROPRIATIONS

UNITED STATES SENATE

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WEDNESDAY, MAY 6, 2009

U.S. SENATE,
SUBCOMMITTEE ON ENERGY AND WATER DEVELOPMENT,
COMMITTEE ON APPROPRIATIONS,
Washington, DC.

The subcommittee met at 9:04 a.m., in room SD–192, Dirksen Senate Office Building, Hon. Byron L. Dorgan (chairman) presiding.

Present: Senators Dorgan, Tester, and Bennett.

OPENING STATEMENT OF SENATOR BYRON L. DORGAN

Senator DORGAN. I am going to call the hearing to order.

This is a hearing of the Energy and Water Subcommittee on Appropriations in the U.S. Senate. Today, we are going to hold a hearing on the beneficial reuse of carbon dioxide, CO_2. The $3.4 billion for carbon capture and sequestration funding that was put in the stimulus program, or the economic recovery program, includes beneficial use in that solicitation.

And one of the reasons that we wanted to have this hearing is I am convinced that we will need to continue to use coal in our future. Fifty percent of the electricity comes from coal. The question isn't whether we use coal. The question is how.

And my belief is that we will continue to use coal, but in a different way. We need to make a significant effort to decarbonize coal, and the question is what do you do with that carbon?

Perhaps some will be used for enhanced oil recovery. Already that is the case with a project in North Dakota, and that makes a lot of sense. Some will be sequestered somewhere, and some will be used for, we hope, beneficial use. And that is the purpose of this discussion.

We need to look at a wide range of options for sequestering CO_2 and using CO_2. The issues that we will discuss today increase those options.

We know that there are benefits that can come from storage in soils of CO_2. We have a project in North Dakota, sponsored by the North Dakota Farmers Union, which has established carbon credits on the Chicago Climate Exchange. They are the largest aggregator of agricultural carbon credits on the CCX, with more than 5 million acres enrolled in 31 States.

But there has been growing interest and need to support carbon capture and storage on a very large scale, both in this country and around the world. The Department of Energy Technology Laboratory study shows that if the United States emits about 2 gigatons of CO_2 a year from coal-fired power plants, then there could be more than 40 years worth of storage for enhanced oil and gas recovery, more than 35 years worth of storage in unminable coal seams, perhaps 500 to 1,600 years worth of storage in saline aquifers.

And North Dakota, as I said, has played a significant role here with the Great Plains synthetic fuels plant. I was just there a week and a half ago. They strip off 50 percent of the CO_2 from the facility. They compress it and put it in a pipeline, shipping it to the Weyburn oil fields in Canada for enhanced recovery. And they are sending about 3 million tons a year for that purpose.

This leads us to the issue of beneficial reuse and the primary focus of the hearing. When we talk about beneficial reuse, it is important to make a distinction between the terrestrial offsets that absorb CO_2 from the atmosphere and processes that directly capture CO_2 from coal and other fossil-burning plant emissions and convert it into usable products.

Well, algae biofuels are an example, I think, of beneficial reuse. They have a chart, I think, that shows algae tanks. Algae are the fastest-growing plants in the world. They can double their bulk in very short period of time. They can grow in wastewater and convert CO_2 into a liquid fuel that is compatible with our existing fuel structure.

This is an algae tank chart. We had stopped research on algae for about 15 years, I believe. And we began in the subcommittee to start that research once again. The circumstance in this case should be to take a product, such as CO_2, and turn it into a usable product.

We have a project that I looked at in Arizona, where they are taking the CO_2 from the flue gas and growing algae and then harvesting the algae for diesel fuel. Well, that is a beneficial use.

There are other projects that have been described to me, including patents that would turn CO_2 into a product, one product similar to concrete. Harder than concrete, they say, with significant value. A beneficial use because that would capture all of the CO_2.

Another company came to me and described a process by which they create chemically I believe it is nitrogen, hydrogen, and baking soda. And the equivalent of baking soda contains all the CO_2.

There are a lot of interesting ideas out there. My hope is that the funding that we are making available will allow us to scale up a range of these ideas to find out what works at scale? What is the silver bullet, if there is one? And let the free market then beat a path to their door to say you have demonstrated something that we are very interested in and want to do.

This chart, by the way, shows that some folks came to my office with a plate of cookies and said this comes from coal, cookies from coal. But, in fact, it was a description of storing CO_2 in what is commonly called baking soda.

So beneficial use of CO_2. What are the ideas out there? What might or might not be the case? What will we find? Will science and technology and research unlock the mystery of how to do this at scale and in a way that perhaps reduces the price of carbon that is limited by legislation, reduces that price to near zero? Who knows?

And so, we will hear from four witnesses today.

Senator Tester?

STATEMENT OF SENATOR JON TESTER

Senator TESTER. Thank you, Mr. Chairman.

Only in America could you make cookies out of coal.

Senator DORGAN. That is right. It is good.

Senator TESTER. I don't want to repeat what you said, but I fully agree with the fact that we are going to be burning coal for a long, long time. Montana happens to be America's version of the Saudi Arabia of coal, and we need to figure out ways to deal with the CO_2 issue. I think everybody understands that.

I guess the only thing I will ask of you guys, and the chairman alluded to it, is how close are we to commercialization on each one of the things that you are going to talk about? I think that is really what is critically important as we try to address the CO_2 issue.

And as I get people from the State of Montana coming into my office every day saying, "We can't do this. We can't deal with the CO_2 issue. We have got to keep doing business in the same way." What that tells me is that there are not a lot of known options out there, and we need to make them known, the options that are real.

So, with that, thank you, Mr. Chairman. And I look forward to the hearing.

Senator DORGAN. Senator Tester, thank you very much.

As you say, Montana has a lot of coal. So does North Dakota. And as I have indicated before, I don't think we are going to see a future without coal. I think we are going to see a future in which we use coal differently, and that is decarbonizing the use of coal. The question is can we do that in a manner that provides benefits, or is it just a liability to try to do that?

So we have witnesses today that come from a variety of areas. Mr. Scott Klara is the National Energy Technology Laboratory at the U.S. Department of Energy. Mr. Klara, welcome.

Mr. Jeff Muhs, executive director of the Center for Biofuels, USU Energy Laboratory at Utah State University. He will be talking about algae fuels.

Dr. Brent Constantz, chief executive officer of Calera Corporation, will be talking about mineralization and some other issues.

And Ms. Marjorie Tatro the director of fuel and water systems at Sandia National Laboratories in Albuquerque, New Mexico is here.

Let me thank all of you for being here. We are going to have a hearing that is a bit shorter this morning because the Energy Department is beginning the markup of the energy bill, and I am a member of that committee and will have to be there in a while. But I am really appreciative of all of you coming.

Mr. Klara, why don't you proceed? And let me state that the entire statements that you have will be made a part of the permanent record, and you may summarize.

Mr. Klara.

STATEMENT OF SCOTT M. KLARA, DIRECTOR, STRATEGIC CENTER FOR COAL, NATIONAL ENERGY TECHNOLOGY CENTER, DEPARTMENT OF ENERGY

Mr. KLARA. Thank you.

Mr. Chairman and members of the subcommittee, I appreciate this opportunity to provide testimony on behalf of the U.S. Department of Energy's carbon capture and storage research, with particular emphasis today on CO_2 reuse.

The Department has supported research on CO_2 reuse for more than a decade. When the sequestration program was initiated in the mid-1990s, it was recognized that technologies such as mineralization, chemical conversion to useful products, algae production, enhanced oil recovery, and enhanced coalbed methane recovery could play an important role in mitigating greenhouse gases.

Although the CO_2 reduction potential of these approaches is limited, due to factors such as cost and market saturation of saleable byproducts, these approaches are logical first-entry candidates for greenhouse gas mitigation due to their ability to produce revenue from the use of CO_2 to offset costs.

Enhanced oil recovery and enhanced coalbed methane recovery represent attractive beneficial reuse options of CO_2 that produce oil and natural gas while permanently storing the CO_2 in geologic formations. Current research activities in these areas now focus on developing reservoir management strategies to increase oil and gas production while maximizing CO_2 storage, ultimately leading to best practices and protocols for using these approaches as a carbon mitigation option.

Chemical conversion methods represent another approach that can be used for CO_2 reuse. CO_2 can provide the carbon source for many chemical reactions that range from simply producing mineral carbonates to serving as chemical building blocks to make chemicals such as methanol and urea and, ultimately, making other organic products such as plastics, composite materials, and rubber, which have useful applications and represent long-term storage.

The key hurdle to these opportunities as potential CO_2 mitigation approaches relates primarily to cost and volume. CO_2 is a stable molecule. Hence, chemical conversion to these useful end products often requires expensive processes with high temperature and high pressure that are typically not competitive with conventional methods.

Also, these potential applications are likely to utilize relatively small volumes of CO_2 compared to the large volumes produced from power plants. However, even with that, chemical conversion approaches could still offer beneficial early market opportunities that provide a smoother transition to geologic sequestration.

As the Senator stated, biological capture of carbon dioxide through algae cultivation is another CO_2 reuse option that is gaining attention. Algae, the fastest-growing plants on Earth, can double their size as frequently as every 2 hours while consuming carbon dioxide.

Algae can be grown in regions with desert climate so as not to compete with farmlands and forests, and they do not require fresh water to grow. They can often grow in brackish, salty water.

Algae has the desirable feature of having a considerably high oil content with yields of oil that are orders of magnitude higher than those of traditional plant materials that could be used to produce biofuels such as ethanol and biodiesel.

While it is recognized that the greenhouse gases stored by the algae will ultimately be released to the atmosphere, there is a net carbon offset by more effectively utilizing the carbon contained in the coal. The coal is used to produce power and then again for algae production. Hence, a net carbon offset is realized by an increase in the energy extracted from the coal when compared to using that same coal for just power generation only.

In conclusion, advanced CCS technology will undoubtedly play a key role in mitigating CO_2 emissions under potential future carbon constraint scenarios. CO_2 reuse technologies with saleable byproducts are logical first-entry market candidates for greenhouse gas mitigation due to their ability to produce revenue from the use of the CO_2.

These options will likely provide a technology bridge and smoother transition to the deployment of large-scale geologic sequestration that ultimately will be needed to stabilize greenhouse gases. The Department's research programs are critical to ensure the availability of all these enabling technologies.

PREPARED STATEMENT

I applaud the efforts of this subcommittee and the members for taking a leadership role on these significant issues. And this completes my statement, and I would be happy to entertain questions at the appropriate time.

Thank you.
[The statement follows:]

PREPARED STATEMENT OF SCOTT M. KLARA

Thank you, Mr. Chairman and members of the subcommittee. I appreciate this opportunity to provide testimony on the United States Department of Energy's (DOE's) research efforts in carbon capture and storage (CCS), with a particular focus on carbon dioxide (CO_2) reuse technologies.

INTRODUCTION

Fossil fuel resources represent a tremendous national asset. An abundance of fossil fuels in North America has contributed to our Nation's economic prosperity. Based upon current rates of consumption, the United States has approximately a 250-year supply of coal. Making use of this domestic asset in a responsible manner will help the United States to meet its energy requirements, minimize detrimental environmental impacts, positively contribute to national energy and economic security, and compete in the global marketplace.

Fossil fuels will play an important role in our Nation's future energy strategy throughout the remainder of this century. A key challenge to the continued use of fossil fuels, especially coal, will be our ability to reduce greenhouse gas emissions from fossil fuel processes. By developing technologies to mitigate the release of CO_2 into the atmosphere, we can continue to use our extensive domestic coal resource, while reducing the potential impacts on climate change. CCS can play a central role in fossil fuels remaining a viable energy source for our Nation. CCS is the primary pathway DOE is pursuing to allow continued use of fossil fuels in a carbon-constrained future.

COAL RESEARCH AND DEVELOPMENT PROGRAM

The coal research and development program—administered by DOE's Office of Fossil Energy and implemented by the National Energy Technology Laboratory—is designed to address environmental concerns over the future use of coal by developing a portfolio of revolutionary CCS technologies. In partnership with the private sector, efforts are focused on maximizing efficiency and environmental performance, while minimizing the costs of these new technologies.

In recent years, the program has been restructured to focus the urgent need on CCS technologies. The program is focused on two major strategies:

—Capturing and long-term storing greenhouse gases; and

—Substantially improving the efficiency of fossil energy systems.

The first strategy will reduce emissions of CO_2 from fossil energy systems. The second strategy will improve the fuel-to-energy efficiencies of fossil-fueled plants, thus reducing pollutant emissions, water usage, and carbon emissions on a per unit of energy basis. The improved efficiency strategy also provides a positive efficiency impact to partially offset the efficiency penalty incurred when CCS is added to a plant. Collectively, these two strategies comprise the coal research and development program's approach to develop technologies that will help current and future fossil energy plants meet requirements for a safe and secure energy future.

Coal research has resulted in important developments and insights regarding future technology innovations. New engineering concepts have been developed to convert coal into gases that can be cleaned and then used to generate power or produce fuels. New approaches to low-emission power generation are emerging that hold promise for integration with coal-based or combined coal-and-biomass energy plants. Technologies for achieving CCS are stretching beyond basic research, defining pathways in which greenhouse gas emissions can be permanently diverted from the atmosphere. With these building blocks, a new breed of coal plant can be created—one that generates power and produces high-value energy with dramatically reduced environmental impact. The Department's activities are focused on high-priority CCS enabling technologies, such as advanced integrated gasification combined cycle, advanced hydrogen turbines, carbon capture and storage, coal-to-hydrogen conversion, and fuel cells. These research areas provide the supporting technology base for all CCS development.

CARBON CAPTURE AND STORAGE

The coal research and development program is addressing the key technology challenges that confront the wide-scale deployment of CCS through research on cost-effective capture technologies; measuring, monitoring, verification, and accounting technologies to ensure permanent storage; permitting issues; liability issues; public outreach; and infrastructure needs. As an example, it is estimated that today's commercially available CCS technologies would add around 80 percent to the cost of electricity for a new pulverized coal plant, and around 35 percent to the cost of electricity for a new advanced gasification-based plant.[1] The program is aggressively pursuing developments to reduce these costs to less than a 10 percent increase in the cost of electricity for new gasification-based energy plants, and less than a 35 percent increase in the cost of electricity for pulverized coal energy plants.

The coal research and development program has been performing CCS field tests for many years. For example, the Regional Carbon Sequestration Partnerships are drilling wells in potential storage locations and injecting small quantities of CO_2 to validate the potential of key storage locations throughout the country, as well as conducting large-scale carbon sequestration field tests. Geologic sequestration projects at key locations across the country are being pursued. Substantial progress has occurred in the area of monitoring, verification, and accounting with the development and refinement of technologies to better understand storage stability, permanence, and the characteristics of CO_2 migration.

Research is also focused on developing technology options that lower the cost of capturing CO_2 from fossil fuel energy plants. This research can be categorized into three pathways: post-combustion, pre-combustion, and oxy-combustion. Post-combustion refers to capturing CO_2 from the flue gas after a fuel has been combusted in air. Pre-combustion is a process where a hydrocarbon fuel is gasified to form a synthetic mixture of hydrogen and CO_2, and the CO_2 is captured from the synthesis gas before it is combusted. Oxy-combustion is where hydrocarbon fuel is combusted in pure or nearly pure oxygen rather than air to produce a mixture of CO_2 and water that can easily be separated to produce relatively pure CO_2. This research includes a wide range of approaches: membranes, oxy-combustion concepts, solid sorbents, CO_2 clathrates, and advanced gas/liquid scrubbing technologies. These efforts will produce meaningful improvements to state-of-the-art technologies and seek to develop revolutionary concepts, such as metal organic frameworks, ionic liquids, and enzyme-based systems.

A center piece of the program is DOE's field test program, carried out by the Regional Carbon Sequestration Partnerships. Each Partnership comprises State agencies, universities, and private companies, which are a "capacity building" enterprise with the goal of developing the knowledge base and infrastructure needed to support the wide-scale deployment of CCS technologies. Each Partnership is focused on a separate and specific region of the country with similar characteristics relating to CCS opportunities.

Collectively, the seven Regional Partnerships represent more than 350 unique organizations in 42 States, three Native American Organizations, and four Canadian Provinces. Collectively, these Partnerships constitute a significant national asset in that they represent regions encompassing 97 percent of coal-fired CO_2 emissions, 97 percent of industrial CO_2 emissions, 96 percent of the total land mass, and essentially all the geologic storage sites in the country that can potentially be available for carbon sequestration. The non-Federal cost share in the efforts being pursued by the Partnerships is greater than 35 percent, which is a key indicator of industry and technology vendor involvement that will help to ensure that developments are ultimately deployed. Together, the seven Partnerships form a network of capability, knowledge, and infrastructure to enable carbon sequestration technology to play a major role in a national strategy to mitigate CO_2 emissions.

Over the course of these CCS activities, DOE will develop Best Practice Manuals on topics such as site characterization, site construction, operations, monitoring, mitigation, closure, and long-term stewardship. These Manuals will serve as guidelines for a future CCS industry, and help transfer the lessons learned from the Department's program to current and future stakeholders.

CO_2 RE-USE TECHNOLOGIES

The coal research and development program has supported research on CO_2 re-use technologies for more than a decade. When the Sequestration Program was initiated in the mid-1990s, it was recognized that technologies such as mineralization, chemical conversion to useful products, algae production, enhanced oil recovery (EOR) and enhanced coalbed methane recovery (ECBMR) could play an important role in mitigating CO_2 emissions. Although the CO_2 reduction potential of these approaches is limited, due to factors such as cost and market saturation of salable by-

[1] Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, U.S. Department of Energy/National Energy Technology Laboratory, DOE/NETL–2007/128 1, Final Report, May 2007.

products, these approaches are logical "first-market entry" candidates for greenhouse gas mitigation, due to their ability to produce revenue from use of the CO_2 that could be used to offset the costs for these "early adopters." Hence, these options provide a technology bridge and smoother transition to the deployment of the large-scale, stand-alone geologic sequestration operations that will ultimately be needed to achieve the much larger reductions that would be required to approach stabilizing greenhouse gas concentrations in the atmosphere.

EOR and ECBMR represent attractive beneficial re-use options for CO_2 that produce oil and natural gas while permanently storing the CO_2 in these geologic formations.

The Department has recognized the importance of CO_2 EOR for more than 40 years. As early as the 1970s, DOE-funded projects were developing concepts to improve the effectiveness and applicability of CO_2 EOR. DOE also has a long history in conducting research on the benefits of unconventional gas recovery with technologies such as coalbed methane recovery. Due in part to research conducted by DOE, coalbed methane production has increased for each of the last 15 years due to advances in production methods and now accounts for roughly 8 percent of the United States' natural gas production.

More recently, the Department has been studying the technologies needed to ensure permanence of CO_2 storage in "enhanced" coal bed methane recovery, where natural gas production is "enhanced" by injecting CO_2. The CO_2 displaces the methane on the coal surface and the CO_2 remains stored in the formation. Relative to CO_2 storage, current research activities in EOR and ECBMR now focus on developing reservoir management strategies to maximize and ensure permanence of CO_2 storage, while increasing oil/gas production; along with the development of technologies for measuring, monitoring, verification, and accounting that will validate permanent CO_2 storage in these applications while providing best practices and protocols for using these approaches as a carbon mitigation option.

Chemical conversion methods represent another technology approach that can be used for CO_2 re-use. CO_2 can provide the carbon source for many chemical reactions that range from producing mineral carbonates, to serving as chemical building blocks to make chemicals like methanol and urea, and ultimately making other organic chemicals, plastics, or composite materials that could have useful applications and represent long-term storage opportunities. Some industries that currently use relatively small quantities of CO_2 in their operations include metals; manufacturing and construction; chemicals, pharmaceuticals, and petroleum; rubber and plastics; and the food and beverage industries. Also, most of the baking soda (sodium bicarbonate) produced in the United States is manufactured by reacting soda ash with CO_2 and water.

The key hurdles to these new opportunities as potential CO_2 mitigation approaches relate primarily to cost and volume. CO_2 is a stable molecule; hence, chemical conversion to useful end products often requires expensive processes (high temperature and/or high pressure) that are not competitive with conventional manufacturing methods. These applications are also likely to utilize relatively small volumes of CO_2, as compared to the large volumes produced from powerplants.

The Department had previously supported a working group for several years that consisted of several Universities and National Laboratories working on the science and economics of speeding the reaction of carbon mineralization as a potential option to permanently sequester CO_2. Carbonation reactions were investigated that combined CO_2 with alkaline earth elements (predominantly magnesium, but also calcium and other elements) derived from silicates to yield thermodynamically stable solid mineral carbonates—essentially, rocks. The team focused on conducting laboratory experiments and modeling the complex chemical reactions associated with this process. It was ultimately concluded that the process could not be cost effective as a CO_2 capture mechanism, and that numerous mining and storage issues also existed as key barriers. However, the knowledge-base gained from these efforts is proving valuable in pursuing applications where mineralization can be used to produce salable byproducts that might make this concept practical for a limited set of applications.

In the past few years, DOE has refocused research efforts on using mineralization chemistry as a possible means of "solidifying" CO_2 after it is stored in a geologic formation, thereby, ensuring permanent storage. A category of geologic formations called "Basalts" have emerged as leading candidates where this approach may someday have merit. Basalts are silica-rich volcanic rock that contains key minerals—such as calcium and magnesium—that can combine with CO_2 to form carbonates.

The Department is supporting the Big Sky Regional Carbon Sequestration Partnerships and Pacific Northwest National Laboratory in conducting research focused on enhancing the mineralization process in these formations. The Big Sky Partnership is conducting small-scale CO_2 injection in the Columbia River flood Basalts, with the goal of confirming feasibility of safe permanent storage in these formations. Successful research in Basalts could expand the viable geologic options for CO_2 sequestration in the continental United States, and provide unexplored options for CO_2 sequestration in developing countries that have extensive Basalt formations, such as India.

Biological capture of CO_2 through algae cultivation is another CO_2 re-use option that is gaining attention as a possible means to achieve reductions in CO_2 emissions from fossil-fuel processes. Algae, the fastest growing plants on earth, can double their size as frequently as every 2 hours while consuming CO_2. Algae can be grown in non-arable regions, such as deserts, so as not to compete with farmland and forests, and they do not require fresh water to grow. Algae will grow in brackish water, plant-recycle water, or even in sewage streams, and, when cultivated within closed systems, these waters can be recycled, thereby minimizing further water use. Algae has the desirable feature of having a considerably high oil content, with yields of oil per acre that are orders of magnitude higher than those of traditional plant materials used to produce biofuels, such as ethanol or biodiesel. The oils in algae can be extracted and converted to liquid transportation fuel. While it is recognized that the CO_2 stored by the algae will ultimately be released to the atmosphere, there is a net-CO_2 emission decrease because the CO_2 released from coal combustion for algal growth reduces demand for petroleum without increasing coal consumption The coal is used to produce power and then again for algae production, hence, a net-carbon offset is realized by an increase in the energy extracted from the coal, compared to that same coal being used for power generation only.

A cost-effective, large-scale production system for growing algae using CO_2 from a powerplant has not yet been demonstrated. DOE is sponsoring a project with Arizona Public Service (APS) to develop and ultimately demonstrate a large-scale algae system coupled with a powerplant. APS is examining the use of coal gasification for the production of substitute natural gas. The utilization of algae for carbon management and recycle is an integral part of the project. The project has already proven the process at a small scale using a one-third acre algae bioreactor that has been operating for weeks using powerplant stack emissions to produce sustained algae growth. Additionally, a prototype algae cultivation system is being evaluated for continuous operation. The project will ultimately assemble a fully integrated energy system for beneficial CO_2 use, including an algae farm of sufficient size to adequately evaluate effectiveness and costs for commercial applications. To complement the engineered system in Arizona, DOE has solicited Small Business Innovation Research proposals to explore novel and efficient concepts for several processing aspects of CO_2 capture for algae growth. Projects are addressing novel approaches for extracting oil from algae, and for converting algae oil to transportation fuel, focusing on technology consideration for integration with power or syngas production so as not to duplicate biofuels work being conducted by DOE's Office of Energy Efficiency and Renewable Energy. The results from these efforts should prove useful to future algae farming applications at power and synfuel plants.

THE AMERICAN RECOVERY AND REINVESTMENT ACT

The American Recovery and Reinvestment Act (Recovery Act) appropriated $3.4 billion for the Fossil Energy Research and Development (FER&D) Program. As reflected in the Joint Explanatory Statement of the Committee of Conference leading to the act, these Recovery Act funds will support activities targeted at expanding and accelerating the commercial deployment of CCS technology, thus providing a key thrust to the FER&D Program to accelerate, by many years, the advances needed for future plants with CCS. Although specific details are still being worked on by DOE, CO_2 re-use technologies will be addressed in the following activities of the Recovery Act.

New CCS Initiative for Industrial Applications.—$1.52 billion is to be used for a competitive solicitation for a range of industrial carbon capture and energy efficiency improvement projects, including innovative concepts for beneficial CO_2 re-use.

CONCLUSIONS

Today, nearly three out of every four coal-burning powerplants in this country are equipped with technologies that can trace their roots back to DOE's advanced coal technology program. These efforts helped accelerate production of cost-effective compliance options to address legacy environmental issues associated with coal use. Advanced CCS technologies will undoubtedly play a key role in mitigating CO_2 emissions under potential, future carbon stabilization scenarios. CO_2 re-use technologies with salable byproducts are logical "first market entry" candidates for greenhouse gas mitigation due to their ability to produce revenue from the use of CO_2. These re-use technologies, along with large-scale geologic sequestration, will contribute to the suite of options for reduction of anthropogenic CO_2 emissions.

DOE's research programs are helping develop these enabling technologies. The United States must continue to show leadership in technology development and future deployment to bring economic rewards and new business opportunities both here and abroad.

I applaud the efforts of this subcommittee and its members for taking a leadership role in addressing these timely and significant issues.

Senator DORGAN. Mr. Klara, thank you very much.

Next, we will go to Mr. Jeff Muhs, who is with Utah State University, executive director of the Center for Biofuels at USU's Energy Laboratory.

Mr. Muhs, welcome.

STATEMENT OF JEFF D. MUHS, EXECUTIVE DIRECTOR, CENTER FOR BIOFUELS, USU ENERGY LABORATORY, UTAH STATE UNIVERSITY

Mr. MUHS. Thank you, Mr. Chairman and members of the subcommittee.

It is a pleasure to speak to you today on the beneficial reuse of carbon dioxide. I will be summarizing findings from a report that Utah State University is jointly issuing with a number of other entities on the opportunities, challenges, and research to each of our algae biofuels, particularly emphasizing systems design for carbon recycling from point source CO_2 emitters.

America faces five interdependent challenges that threaten our prosperity and quality of life—energy price spikes, climate change, depletion of natural resources, high food prices, and an addiction to foreign oil. Although there is no single answer, algae energy systems represent a possible partial solution to all five of these challenges.

Growing algae, the most productive of all photosynthetic life on Earth, and converting it into fuels could help mitigate carbon emissions, reduce oil imports and price shocks, reclaim wastewater, and lower food prices. Fundamentally, algae use solar energy and nutrients to transform CO_2 into organic matter. Due to their simple biological structure, they capture carbon more rapidly than terrestrial plants and store it in a form that can be processed into fuel such as biodiesel.

Some algae strains are capable of doubling their mass several times a day, and unlike terrestrial plants, algae can be cultivated on marginal desert land and using saline, brackish, or wastewater. Since some species have a high affinity for CO_2, siting these algae systems near point source CO_2 emitters is a very attractive option. Research has demonstrated that the yields can be dramatically improved by enhanced concentrations of CO_2.

Because of its high lipid or oil content and growth rate, algae can produce between 10 and 50 times more biodiesel per acre than, for example, soybeans. To compare the two feedstocks, if all the soybeans harvested in the United States were converted into biodiesel, the resulting fuel supply would accommodate less than 10 percent of our annual diesel fuel needs.

Conversely, if an area roughly the size of one-tenth of North Dakota or Utah were to be converted into algae systems, it could provide all of our diesel fuel needs. So because of that enhanced yield opportunity, there is a big opportunity.

The fundamentals of algae energy systems are sound. As a recent article in National Geographic noted, there is no magic bullet fuel crop that can solve our energy woes without harming the environment says virtually every scientist studying the issue, but most say that algae comes closer than any other plant.

But many challenges lie ahead, and our analysis indicates that the overall lifecycle cost of algae energy systems must be reduced by at least a factor of two and probably much more. Unlike traditional crops, the technology needed to grow and harvest algae using industrial or agricultural processes is still pre-commercial. In the field of plant biology, algae is one of the least explored fields.

Recycling carbon is a new concept, and there are challenges related to separating, compressing, and delivering CO_2 into these algae cultivation systems. To cultivate algae in open ponds, land and water, which must be replenished because of evaporative losses, are required. Energy is needed to keep the algae stable, healthy, and growing. Invasive species, which can kill algae, must be controlled.

In enclosed growth systems, capital costs for equipment used to enclose, mix, and maintain cultures must be reduced. In both scenarios, surface shading limits the amount of sunlight that can be used constructively to produce biomass.

After cultivation, algae must be dewatered and dried prior to oil extraction and fuel production, and each step along the way, energy and other resources are required. But by harnessing the same biology, chemistry, and genetics that led to the doubling of yields in traditional crops, we should be able to do the same with algae. And advances in optics, mechanical engineering, and other disciplines are leading to scalable cultivation systems that better utilize sunlight and have the potential to meet cost targets.

Indeed, algae has the unique potential to produce renewable fuels and recycle carbon sustainably without interfering with food supplies. To succeed, however, private and public cooperation is critical. Without it, the algae industry will struggle to reduce cost and integrate subsystems. Without regulations limiting carbon emissions, utilities and, in particular, small CO_2 emitters will have little motivation to explore these reuse options.

Therefore, a robust and well-integrated RD&D program will only occur with Government involvement, both in sponsorship of research and development and enactment of policies in future energy and climate change legislation that help to accelerate commercial deployment.

We recommend that Congress authorize and appropriate funds for an algae-related RD&D program at the Department of Energy. It should include research on lifecycle analysis, leverage strengths of existing Department programs, and be coordinated at a systems level. It should take advantage of new program to management tools and include a portfolio of activities from foundational research to integrated demonstration.

PREPARED STATEMENT

And deployment projects should demonstrate the viability of technologies at a scale large enough to overcome infrastructure challenges and include regional partnerships similar to the Department's programs in geologic sequestration.

Thank you very much.

[The statement follows:]

PREPARED STATEMENT OF JEFF D. MUHS

Chairman Dorgan, Ranking Member Bennett and other members of the subcommittee, it is a pleasure to speak to you today on the subject of beneficial reuse of carbon dioxide. I will be summarizing findings from a report Utah State University is jointly issuing with a number of other entities on opportunities, challenges, and research needs for algae biofuel production—emphasizing systems designed for carbon recycling from point-source CO_2 emitters.

America faces five interdependent challenges that threaten our prosperity and quality of life:

—energy price spikes;
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Although there is no single answer, algae energy systems represent a possible partial solution to all five challenges. Growing algae, the most productive of all photosynthetic life on earth, and converting it into fuels could help mitigate carbon emissions, reduce oil imports and price shocks, reclaim wastewater, and lower food prices.

Fundamentally, algae use solar energy and nutrients to transform CO_2 into organic material. Due to their simple biological structure, they capture carbon more rapidly than terrestrial plants and store it in a form that can be processed into fuels such as biodiesel. Some algal strains are capable of doubling their mass several times a day, and unlike terrestrial plants, algae can be cultivated on marginal or desert land using saltwater, brackish-water, or wastewater. Since some species have a high affinity for CO_2, siting algae energy systems near point-source CO_2 emitters is an attractive option. Research has demonstrated that algal yields can be improved dramatically using enhanced concentrations of CO_2.

Because of its high lipid (or oil) content and growth rate, algae can produce 10 to 50 times more biodiesel per acre than, for example, soybeans. To compare the two feedstocks, if all the soybeans harvested in the United States were converted into biodiesel, the resultant fuel supply would accommodate less than 10 percent of our annual diesel fuel needs. Conversely, if an area roughly equating to one-tenth the area of either North Dakota or Utah were developed into algae energy systems, it would supply all of America's diesel fuel needs.

There is growing consensus that the fundamentals of algae energy systems are sound. As a recent article in National Geographic noted: "there is no magic bullet fuel crop that can solve our energy woes without harming the environment, says virtually every scientist studying the issue. But most say that algae . . . comes closer than any other plant."

But many challenges lie ahead and our analysis indicates that the overall lifecycle cost of algae energy systems must be reduced by at least a factor of two and probably more.

Unlike traditional crops, the technology needed to grow and harvest algae using industrial or agricultural processes is in its infancy. In the field of plant biotechnology, algae is one of the least explored areas. Recycling carbon is a new concept and there are challenges related to separating, compressing, and delivering CO_2 into algae cultivation systems.

To cultivate algae in open ponds, land and water (which must be replenished because of evaporative losses) are required. Energy is needed to keep algae cultures stable, healthy and growing. Invasive species, which can kill oil-rich algae, must be controlled. In enclosed growth systems, capital costs for equipment used to enclose, mix, and maintain cultures must fall. In both scenarios, surface shading limits the amount of sunlight that can be used constructively to produce biomass. After cultivation, algae must be dewatered and dried prior to oil extraction and fuel production. In each step along the way, energy and other resources are required.

But by harnessing the same biology, chemistry, and genetics that led to a doubling of yields in traditional crops, we should be able to do the same with algae. And advances in optics, mechanical engineering, and other disciplines are leading to scalable cultivation systems that better utilize sunlight and have the potential to reach cost targets.

Algae has the unique potential to produce renewable fuels and recycle carbon sustainably and without interfering with food supplies. To succeed, however, private and public cooperation is critical. Without it, the algae industry will struggle to reduce costs and integrate subsystems. Without regulations limiting carbon emissions, utilities, and in particular, small CO_2 emitters will have little motivation to explore reuse options.

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We recommend that Congress authorize and appropriate funds for an algae-related RD&D program at the Department of Energy. It should include research on lifecycle analyses, leverage strengths of existing Department programs, and be coordinated from a Department-wide perspective. The program should take advantage of new program management tools and include a portfolio of activities ranging from foundational research to integrated demonstrations. Deployment projects should demonstrate the viability of technologies at a scale large enough to overcome infrastructure challenges and include regional partnerships similar to the Department's programs for geologic sequestration.

Thank you. I look forward to answering any questions.

Senator DORGAN. Mr. Muhs, thank you very much. We appreciate your testimony.

Next, we are going to hear from Dr. Brent Constantz, chief executive officer and founder of Calera. And from his biography, specializes in high-performance and novel cements. Is that the case, Mr. Constantz?

Dr. CONSTANTZ. Yes.

Senator DORGAN. And is the inventor on over 60 issued U.S. patents on the subject.

You may proceed. Thank you for being with us.

STATEMENT OF BRENT R. CONSTANTZ, Ph.D., CHIEF EXECUTIVE OFFICER, CALERA CORPORATION

Dr. CONSTANTZ. Thanks. We really admire the Senate's vision in appreciating the beneficial reuse of CO_2 and turning it into a profit center for a CO_2 emitter instead of a huge liability for them.

Just looking at the mass balance of carbon on Earth, if we look at the Kyoto Protocol, we are calling for 5 billion tons of mitigation. And to put that in perspective, powerplants and cement plants put out about 11 billion tons of CO_2 a year into the Earth's atmosphere.

We could put 16 billion tons of CO_2 a year into cement and aggregate. So we could more than triple the Kyoto requirement putting CO_2 into cement and aggregate.

Calera has developed breakthrough technology that allows us to handle the flue gas streams such as from coal, which are only about 15 percent CO_2, which is a major challenge. Otherwise, it needs to be separated via very expensive techniques. It can also be taken from natural gas in cement plants, which are also dilute streams of CO_2, unlike what has been used in EOR.

This technology also has multi-pollutant control features, especially with SO_2 and NO as well as mercury and other toxics. The absorption technology is an absolute breakthrough and has allowed us to have very high absorption of the raw flue gas with no separation step.

We have developed a revolutionary low-voltage base technology, which allows us to produce base at one-fifth the voltage of traditional base generation and have accelerated mineral dissolution technologies to produce. Then we utilize the waste heat from the power plant to dry the powders to make cement.

Our chief operating officer joined us from NRG, the largest non-regulated power company, where he held the same role. Our head of emissions came from 30 years' experience with General Electric. His Ph.D. was on the burning of coal. Our head of process technology came from Exxon, where he spent 20 years building their process plants.

We are producing green building materials. Our first product, which we launched already, is a replacement for portland cement, a supplementary cementitious material that has been tested against ASTM C1157, and we have a 15,000 square foot lab where we do concrete and cement testing. It was launched at the World of Concrete, which is an 80,000-person convention. It has been well addressed by the entire portland cement industry and the ready-mixed industry as well as the asphalt industry.

In addition, we are producing aggregate. I have an example of the aggregate. At Stanford, I teach carbonate sedimentology. And if I were to put this piece of aggregate on my final exam, unless they had a microscope, none of the students could tell you that this wasn't natural limestone, which is what two-thirds of all natural aggregates are.

These mix designs are carbon negative. So they are not just carbon neutral, but we are actually sequestering CO_2 from the powerplant into the solid material. And we can sequester, as I said, 16 billion tons of CO_2 a year this way on an ongoing basis for centuries to come. This is a profitable option, both for a cement plant that has to deal with their CO_2, as well as a coal plant.

The aggregates provide the possibility of specialty products such as lightweight aggregates, which are very important, or aggregate for pervious concrete.

One byproduct of our process is fresher water because we take all of the hardness out of the water to combine with the carbonate, and this fresher water can be desalinated via reverse osmosis for less than 50 percent the regular energy intensivity. So the water aspect of the profit is important. In fact, in Moss Landing, where we have 200-acre pilot plant, we already have a contract with the local water district to produce fresh water in addition to everything else we are producing.

Other revenue sources are the carbon tipping fees and allocations where we are working in Victoria, Australia, already doing this. We have the ability to use off-peak electricity consumption. So this can be done with almost no energy footprint.

And the important point I would like to point out is this is the permanent removal of CO_2. It is not temporary. We convert the CO_2 to carbonate. Just like the white cliffs of Dover, it is going to stay there for millions of years. It is never coming back.

I would like to urge the Senate to consider leveling the playing field because there is currently a monomaniacal focus on geologic sequestration in all of the language. We believe a more inclusive approach to look at all of the ways of dealing with carbon would be better for everybody and focus on the outcome of sequestering CO_2 as opposed to one specific method, which is geologic sequestration.

PREPARED STATEMENT

And I think the United States needs to provide international leadership in this area, showing the broad variety of solutions for removal of CO_2.

Thank you.

[The statement follows:]

PREPARED STATEMENT OF BRENT R. CONSTANTZ

INTRODUCTION

Chairman Dorgan and members of the subcommittee, first, I would like to thank this subcommittee for their important work in advancing solutions to climate change. I would also like to thank you for inviting me to testify on a carbon-mitigation sector that I believe holds tremendous promise: the conversion of carbon dioxide (CO_2) to mineral form for beneficial reuse.

This hearing comes at a critical time: Congress is debating climate change legislation; the President has promised a green energy policy that helps not hurts our economy; and almost 200 countries are preparing for the Copenhagen international climate discussions. As these and other political decisions unfold against the backdrop of a global economic crisis, we must develop a broad array of cost-effective methods to mitigate the release of CO_2 into the atmosphere.

My name is Brent Constantz, and I am the CEO of Calera Corporation, based in Los Gatos, California. Over the past 20 years, I have built three successful Silicon Valley companies based on innovative specialty-cement technologies, covered by approximately 70 issued U.S. patents I hold in this area. Additionally, I am a professor at Stanford University where my teaching and research are focused on carbonate mineral formation and oceanic carbon balance.

My goal today is to urge Congress to think broadly in terms of the carbon capture and sequestration (CCS) technologies it supports, and the current budget language that needs to be carefully crafted to take full advantage of the opportunities these technologies can offer. Additionally, my testimony will give you an overview of our CO_2-conversion technology; how it is possible to beneficially reuse CO_2 when it is converted to a mineral form; how our technology compares with other CO_2-capture options; and the commercial potential of beneficial CO_2 reuse.

Finally, I will conclude with recommendations that not only align with this subcommittee's demonstrated commitment to CCS, but also help move beneficial CO_2-reuse technologies such as Calera's from pilot-scale to global innovation, thereby fostering other technologies that may be alternative or complementary to CO_2 separation and geologic sequestration.

Calera has developed a transformational technology that converts CO_2 into green building materials. The process captures CO_2 emissions from power-plant flue gas and cement manufacturing, and chemically combines it with a variety of natural minerals, water and solid waste materials to produce cementitious materials, aggregate and other related building materials. Thus the process is more than CO_2 sequestration—it represents permanent CO_2 conversion.

Calera is backed by Khosla Ventures, a well-regarded venture capital firm specializing in "green" technology. With Mr. Vinod Khosla as a partner in this effort, Calera has been able to engage a formidable team of scientists and engineers to move beyond the laboratory and bench-scale research. We currently operate a pilot facility adjacent to a 1,000 MW powerplant in Moss Landing, California that allows us to test our technology with a goal of scaling the process up to full production levels. In less than a year Calera has grown from 12 to more than 70 employees, including 18 PhDs and senior executives with more than 200 years of combined experience in power, water and concrete.

But we have many milestones ahead to reach commercial scale, particularly in this difficult economic climate. Government support is necessary at this stage of development for demonstration facilities and early deployment in commercial plants. Government support, along with commercial partner investment will make the financial hurdle of financing these first scaled plants possible. Government policies that are directed toward mitigating carbon and stimulating the economy by the best available approaches will enable substantial progress for the profitable, beneficial reuse of CO_2.

LEVEL THE PLAYING FIELD FOR NEW TECHNOLOGIES

I would like to underscore that CO_2 mitigation technologies are evolving rapidly. Calera is one of several companies focused on CO_2 conversion technologies with the potential for beneficial reuse. Yet, despite the promise of these technologies, carbon mitigation funding has been narrowly focused on CO_2 separation and purification for geologic sequestration. This focus is proscriptive to one method, assuring that carbon reduction dollars will be directed only towards this method's narrowly defined pool of projects in hopes of making geologic CO_2-sequestration a viable option. This is especially vexing, considering that the Calera process and comparable CO_2-capture technologies largely avoid the economic burden, carbon balance, risk and permitting constraints that accompany geologic CO_2-sequestration.

We submit that taxpayer support and funding should be based on carbon reduction outcomes and seek to advance the most effective technologies. While CO_2 separation and purification for geologic sequestration is one important potential method in the carbon-capture toolbox, we need to consider all of the potential solutions to address the volume of CO_2 at issue. Broad statutory language is needed that encourages innovation and rewards breakthrough technologies consistent with our goals as a free-market nation. The methods we implement should be selected by how we best arrive at the desired outcome, and not constrained to any one particular method for CO_2 mitigation.

I will come back to the crucial point of how the Federal Government can level the playing field for other technologies after providing you with an overview of Calera's CO_2-conversion technology.

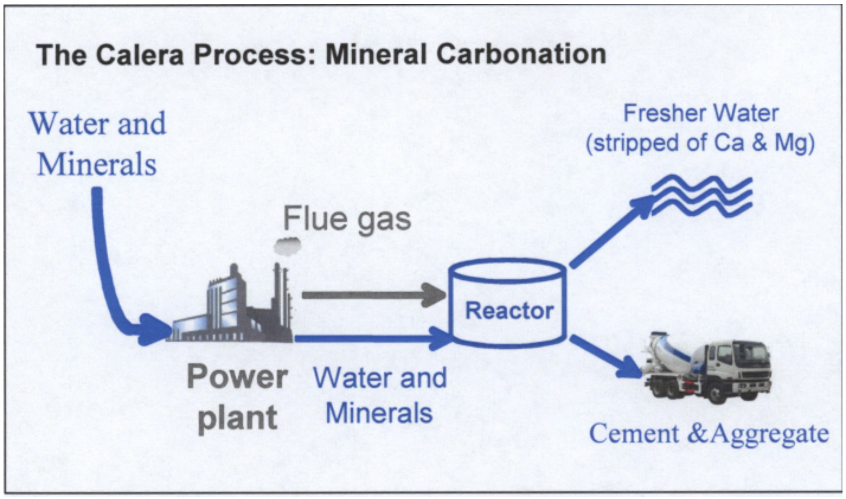
THE CALERA PROCESS—CMAP TECHNOLOGY AND LOW-VOLTAGE BASE PRODUCTION

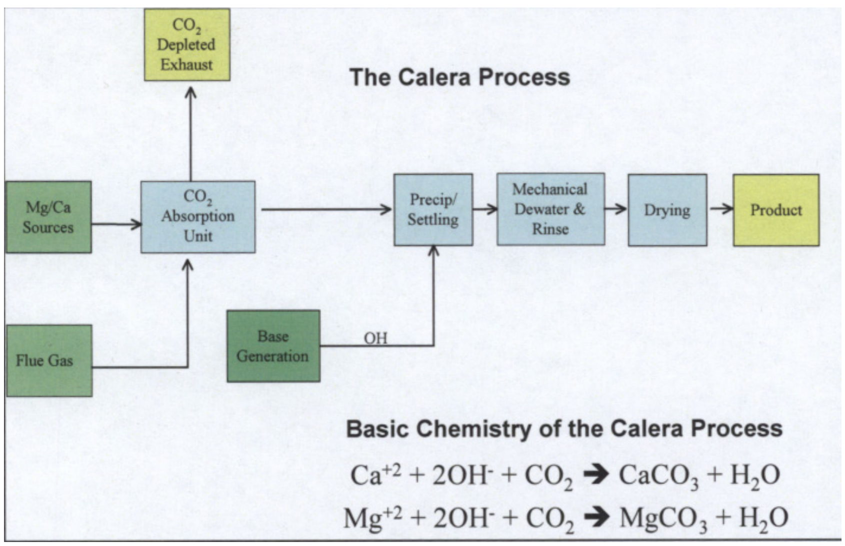
Calera's technology is called Carbonate Mineralization by Aqueous Precipitation (CMAP). The Calera process is unique in how it essentially mimics the natural carbonate mineralization of corals when making their external skeleton. This technology captures CO_2 emissions by converting CO_2 to CO_3 (carbonate) and effectively storing it in a stable mineral form. This mineral can then be used to replace or supplement traditional portland cement, offsetting emissions that would otherwise result from the CO_2-intensive manufacture of conventional cement.

The biggest hurdle to the mineralization concepts studied has been high-energy demand or extremely slow rates of reaction occurring over geologic timeframes. Calera's CMAP bypasses the limitations of previous mineralization approaches, but it has not been broadly pursued in the past due to the requirement for sustainable, unlimited chemical-base sources. Amongst the many technologies now possible are novel base-production methods that are low in cost, energy, and carbon footprint. These Calera innovations—fully described in USPTO patent applications—revolutionize the technical feasibility, carbon-mass balance and economics of carbonate mineralization for CO_2 capture and conversion via aqueous mineralization.

Calera's mineralization process utilizes break-through, low-voltage chemical base-production technology that makes the conversion from CO_2 to carbonate cost-effective and sustainable. Using approximately one-fifth the voltage of conventional base-production processes, Calera's base production has a very low carbon-footprint and is an alternative to natural or waste sources of chemical base. Therefore, the process can occur irrespective of any specific site location.

The technology uses aqueous minerals and CO_2 from power plant flue gas. The CO_2 in the flue gas is dissolved in a reactor, where it becomes carbonic acid converted to carbonate ions that forms a slurry containing the suspended mineral carbonates. A solid-liquid separation and dewatering step results in a pumpable suspension. Calera employs spray dryers that utilize the heat in the flue gas to dry the pumpable suspension. Once dried, the Calera cement looks like white chalk and can be blended with rock and other material to make concrete. A graphic illustration of this process is attached.





Once it is hydrated, Calera's carbonate mineral cement behaves like traditional portland cement, and it can be used as a supplementary cementitious material to replace portland cement at various levels. A 20 percent-50 percent replacement has been tested extensively against ASTM C 1157 concrete specifications. Based on worldwide production estimates, approximately 1.5 billion tons of portland cement could be substituted with carbonate cement, and another 30 billion tons of aggregate used in concrete, asphalt, and road base could be substituted—each ton of carbonate aggregate and cement containing one-half ton of CO_2. Thus, some 16 billion tons of CO_2 could be permanently converted to CO_3 per year on an ongoing basis at a profit. This product would be stable for centuries.

The Department of Energy, the National Energy Technology Labs, and several academic institutions in the United States and other countries have evaluated several methods for accelerating the natural chemical weathering of minerals to produce carbonate minerals. Research has focused both on aboveground conversion of CO_2 to carbonate minerals, and the potential for carbonate conversion below-ground in brine reservoirs, or at geologic sequestration injection sites. These investigations began in the mid-1980s with Reddy's investigation of techniques to accelerate the natural mineral carbonation process.

Since then, there have been many well known scientists working in this study area: Herzog at MIT, Halevy and Schrag at Harvard, O'Connor, researchers at the National Energy Technology Laboratory in Albany, and others, active in mineralization research. The focus of this research was testing of various base materials, reducing the massive energy consumption in the processing of these materials, and acceleration of the reaction rates. Current research has moved toward carbonation of coal-combustion fly ash and accelerated dissolution techniques of magnesium- and iron-rich silicates (so-called mafic minerals) used in carbonation processes.

COST-EFFICIENCY

Every carbon-capture technology struggles with the issue of cost. The economic viability of our carbonate mineralization business model is significantly enhanced by the ability to sell captured-and-converted-CO_2 building materials into large end-markets. For each ton of CO_2 captured, about two tons of building material can be produced. This process provides the opportunity to transform an environmental liability into a profit center. The market for these newly created materials can be significant. Based on USGS data showing worldwide annual cement consumption of 2.9 billion tons, approximately 12.5 billion tons of concrete are used yearly. Additional aggregate usage for asphalt and road base almost triples the potential for storing this captured CO_2.

Test data has shown that we can capture and convert CO_2 at 70 percent to 90 percent + efficiency with our current absorption configuration on flue gas typical of coal fired utility boilers (about 10 percent-15 percent CO_2). We have higher capture efficiencies for other industrial combustion sources, with higher concentrations of CO_2 such as cement kilns (about 20 percent-40 percent CO_2) and refinery operations (about 95 percent-100 percent CO_2). In addition to our high-capture efficiencies, we produce materials that offset other products that have large carbon emissions such as cement. When we include the "avoided" CO_2 of our capture and conversion into materials, this results in CO_2 efficiency greater than 100 percent.

We believe our CMAP technology can be cost-competitive. Particularly advantageous as compared to traditional CCS methods, our conversion technology does not require CO_2 separation, which can be more energy, cost and carbon-intensive as the CO_2 gas becomes more dilute or compressed. Separating CO_2 emission from dilute streams, such as a coal-fired plant or a cement plant, is far more difficult than from a refinery that is almost pure CO_2. In addition, our process does not require transportation, injection, storage or monitoring. Finally, it is important to keep in mind that as our plants grow and scale, we believe our costs will be lower than revenues, enabling a more rapid and extensive scale-up to address large-scale CO_2 mitigation.

POLLUTANT REMOVAL

Unlike other carbon-mitigation technologies, CMAP removes sulfur compounds and other pollutants. We are developing a multi-pollutant control option using the same basic absorption and conversion techniques we are using for CO_2. The basis of our process for SO_2 (sulphur dioxide) control is similar to seawater scrubbers that have been used in the world's largest power plants. We are still in the process of generating data, but our initial analysis indicates that we will be able to readily achieve SO_2 capture efficiencies greater than 90 percent.

We are also working on new systems that will control NO_X compounds by converting NO (nitrogen monoxide) to NO_2 (nitrous oxide), serious greenhouse gases that are water-soluble and can be stabilized in our mineral product. A significant advantage of our carbonate mineralization technology is that scrubbing SO_2, NO_X, particulate matter and other regulated air pollutants is not required in order for the process to capture CO_2. This robust feature is in sharp contrast to other CO_2-capture technologies such as those based on amine (MEA) and chilled ammonia, which require stringent control of SO_2 because it interferes with the absorption process. Therefore, to adequately compare carbonate mineral CO_2-reduction to conventional CO_2-reduction methods would require that the cost and energy consumption of the additional SO_2 control be included with the conventional method for comparison sake.

DEMONSTRATION PLANTS

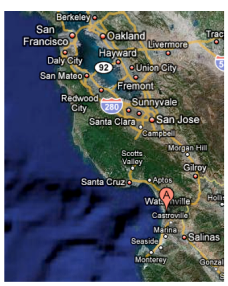
Calera's business model is focused on the global potential of our technology with a milestone-driven plan to demonstrate capture rate and scalability. Our plan calls for building one or more demonstration plants that capture and convert flue gas

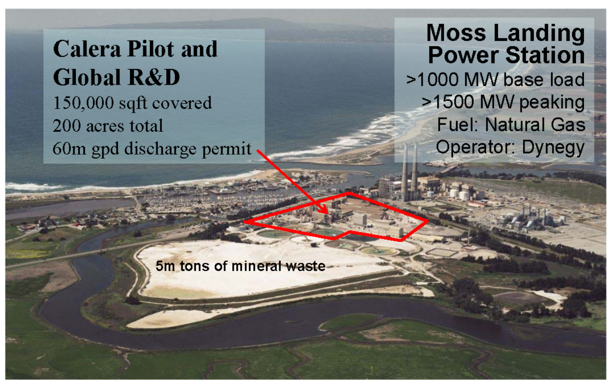
CO_2. These projects will benefit the socioeconomic status of the local communities by creating new jobs and business opportunities. Each plant will create 200–300 construction jobs over a 2-year construction phase. Job types required include pipe fitters, electricians, operators, carpenters, laborers, steel workers, ironworkers, mechanics, bookkeepers, and clerical staff, among others. The completed facility will also provide new permanent jobs.

We have completed a substantial amount of laboratory and scaled batch-process development and have recently commissioned a continuous pilot plant at Moss Landing, California, producing an average of one ton of material per day (a photo of this site is attached). From there we can quickly scale up the process to 20–80 MW for demonstration at coal-fired, electricity-generating units and cement manufacturing plants. Though the capital expenditures on these demonstration facilities are lower than many other CO_2 mitigation technologies, they require investments in the tens to hundreds of millions of dollars—hence, my testimony today in support of a more balanced legislative language to foster the commercial development and scale-up of innovative technologies such as ours.

CA pilots validate process, product and environmental feasibility

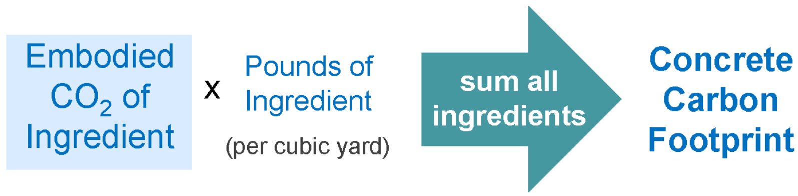
- Pilot plants running large scale batch and continuous processes
- Flue gas simulator – Ability to test any type of coal and flue gas composition
- Producing material for product development and testing
- Demonstration of waste mineral utilization
- Monterey Bay Marine Sanctuary requires highest level of environmental performance





Our process converts CO_2 into carbonate minerals, thus permanently converting CO_2 into a stable mineral form. When compared to traditional CCS methods, this conversion technology does not require costly CO_2 separation or compression. Like any other manufacturer, energy is required to produce this product. Unlike other processes, our technology has the flexibility to capture CO_2 and produce products continuously, while shifting a large fraction of the electrical power consumption to off-peak hours. The shifting of power consumption is accomplished through energy storage in chemical intermediates specific to the mineral sequestration chemistry. By producing and storing these intermediates during periods of low power demand, this process not only avoids straining the grid, but also better utilizes off-peak sources of power such as solar and wind.

Carbon Footprint Basic Calculation



First Carbonate Mineral concrete – July 2008

Calera's technology also reduces energy consumption and carbon footprint by utilizing power plant waste-heat for product processing. The use of waste heat is enabled by the process chemistry, which requires only low temperatures—in contrast to the very high temperature processes employed in the manufacture of other building materials. As a further means of reducing environmental impact, advanced versions of the process employ recirculation of process water. Although recirculation of process water may be desirable in arid regions, other process options under development may exploit synergies between the mineralization process and desalination technologies, resulting in improved economics for freshwater production.

Another key breakthrough of our technology is the capacity to incorporate solid waste normally bound for landfills into useful products. Waste (such as fly ash) or aluminum smelter by-products (such as red mud and other waste products) can be incorporated into this process.

BEYOND CEMENT

Calera will be important and valuable to States producing and/or consuming coal as they attempt to meet future carbon capture and trading requirements. Calera projects will bring long-term benefits to the coal industry by allowing existing coal plants to continue their operations under new air compliance regulations and avoid shutting down plants producing electricity at the lowest cost. This will save jobs at coal plants, mining sites and in transportation. The low cost of implementing Calera's technology compared to other CCS technologies reduces the impact of new CO_2 regulations on the cost of energy and avoids leakage of U.S. operations oversees to countries that don't have CO_2 regulations.

By shifting the treatment of CO_2 from a pollutant that needs to be disposed at a high price, to a potential raw material for clean manufacturing, our process enables a sustainable and cost-effective capture of a significant portion of the anthropogenic CO_2. In fact, when factoring the long-term potential revenues, revenues from building materials, carbon incentives and water treatment using a carbonate mineral process will be offset by the cost of capturing a ton of CO_2.

Based on our current estimates for construction and operating costs, and our forecasts for the building material markets, we expect a payback period of less than 10 years. Furthermore, based on our experience we believe our costs will go down as we learn to build and operate our plants, to the extent that our payback period could be reduced to 7 years. In our 2 years of operation we have made significant progress in understanding the scientific and engineering tasks of building a full-scale plant. From a small one-liter batch process to a 1-ton per day continuous pilot plant, we have learned how to optimize our capture rates and reduce our footprint and costs. Our progress is supported enthusiastically by the scientific community, environmental groups, potential business partners and the public. However, as for any industrial large-scale process, the next step requires a large investment to build a full-scale plant confirming our commercial scalability. Furthermore, the urgency of the climate challenge calls for an accelerated development path that demands special investments and support.

RECOMMENDATIONS

Congress is working hard to address CCS and to rethink product manufacturing. We commend the Committee for acknowledging the importance of CCS and funding innovations in this area. However, current legislative language and Government funding consistently targets geological sequestration, which disadvantages other CCS options. While we acknowledge the potential value of geologic CO_2 sequestration, we recommend placing other viable CO_2-sequestering technologies on an equal playing field with geological sequestration.

It is our hope that your subcommittee will also consider supporting an independent assessment by the National Academy of Sciences that reviews the opportunities and challenges of beneficial reuse and carbon conversion as part of the larger national CO_2-reduction strategy.

Calera is one of many breakthrough clean technologies that are evolving rapidly. Companies like ours need Government funding to help move this process towards commercialization. It is in the best economic interest of our country to advance the most effective technologies over time by providing grants, loan guarantees, tax incentives and other sources of financial support. For this reason, I urge Congress to preserve our ability to move beyond existing carbon-sequestration technologies through broad statutory language that encourages innovation and rewards breakthrough technologies that are not yet, but may soon be, household names.

Finally, we seek Federal Government support because—despite the promise of technologies such as ours, the capital requirements are high in an extremely challenging macroeconomic environment and the risk of any new business venture is significant. The market for CO_2-reduction solutions such as ours is tremendous, but our product will take time and considerable capital to develop sufficiently in order to offset our development costs. Thus we need to scale up rapidly.

On behalf of Calera Corp. and our stakeholders, I respectfully thank Chairman Dorgan, Ranking Member Bennett, and subcommittee members for your time and consideration. We see an important new option with the recovery funding, and we thank the Energy and Water Subcommittee for providing us with this opportunity to explore with you the beneficial reuse of CO_2. The funding we seek could be both stimulating and transformative to energy policy, climate change, and the future of our economy. We look forward to working with the U.S. Congress and the appropriate subcommittees of jurisdiction (i.e., Senate Energy, Senate Finance, and others) to ensure equitable policies are in place that provide Federal support of CO_2-beneficial reuse technology.

Senator DORGAN. Dr. Constantz, thank you very much.

And finally, we will hear from Ms. Tatro. Marjorie Tatro is the director of fuel and water systems at the Sandia National Laboratories.

So, Ms. Tatro, thank you for being with us. You may proceed.

STATEMENT OF MARJORIE L. TATRO, DIRECTOR OF FUEL AND WATER SYSTEMS, SANDIA NATIONAL LABORATORIES

Ms. TATRO. Great. Thank you, Mr. Chairman, Senator Bennett, and distinguished members of the subcommittee.

As you know, we are faced as a Nation with two challenges that actually inspire us as well to think about the reuse of carbon dioxide not only to enable this use of the coal reserves that we have, but we believe that carbon dioxide as a fabulous feedstock for creating liquid fuels that could be inserted into our existing infrastructure is really a fabulous and innovative idea.

You mentioned algae-based biofuels, which do have tremendous promise, and we agree that those need to be developed in a way that allow us to scale them up to the kind of quantities to make them commercially and technically viable. And I wanted to talk to you about another technology today that offers some of the same benefits.

We have done a little work at Sandia National Laboratories in taking concentrated sunlight, high-temperature solar energy, and putting it into a heat engine. This heat engine takes carbon dioxide in one side, takes water in the other side, and splits those molecules apart to then thermochemically recombining those together to create a liquid fuel. In this case, it is methanol. And there are commercial processes that can convert methanol into gasoline, jet fuel, and diesel.

This is another way to use carbon dioxide as a feedstock. Just like it is a nutrient for algae, it is a feedstock for a liquid fuel that can be compatible with our existing transportation infrastructure.

Another area I wanted to mention that we ultimately have to look at is being able to extract carbon dioxide from the air. Because if we are going to have progress in reducing the overall emissions from our energy enterprise into the atmosphere, it is important that we think about scalable, affordable technologies that can capture that CO_2 ultimately from the air and reintroduce it or recycle it into some of these fuel feedstock options.

I agree that our first steps are using carbon dioxide from our coal enterprise as a fabulous feedstock for these transportation fuels, and ultimately, we need to make progress in pulling carbon dioxide from the atmosphere as well.

These are just a few ideas that are out there. We believe that this Nation is ready to step up to this innovative area of recycling and reuse of carbon dioxide. And I believe there are many ideas out there that none of us have even thought of, and it is worth an investment by this country to stimulate those ideas and bring them forward.

I think the United States has a chance to be a leader in these areas, but right now, let me tell you other countries are also investing in these areas. And my fear is not only that we might be left behind in this area, but perhaps we could end up importing both these technologies or the fuels they create from foreign sources, which would not help our energy security situation.

So we have talked about algae. We have talked about synthetic fuels that could come from renewable sources like solar energy. We have talked about the idea of extracting CO_2 from the air, and there are many more details in my written testimony that I believe you have been provided.

PREPARED STATEMENT

But we are excited. We think this is a great innovative area for the country. We appreciate and applaud the subcommittee's leadership in looking at this area, and we stand ready to support this area with innovation from a number of different collaborative teams all across the country.

With that, I would like to conclude and look forward to your questions.

[The statement follows:]

Prepared Statement of Marjorie L. Tatro

INTRODUCTION

Mr. Chairman, Senator Bennett, and distinguished members of the subcommittee, thank you for the opportunity to testify this morning. I am Margie Tatro, Director of Fuel and Water Systems at Sandia National Laboratories. Sandia is a multi-program national security laboratory owned by the United States Government and operated by Sandia Corporation [1] for the National Nuclear Security Administration (NNSA). I am a Mechanical Engineer by training and I have worked in energy technologies for over 20 years.

Sandia has roles in the design, development, qualification, and certification of non-nuclear subsystems of nuclear warheads, nuclear nonproliferation, energy security, intelligence, defense, and homeland security. Sandia is proud of the considerable expertise it has achieved in the area of energy security, especially in understanding the relationship between national security and the energy enterprise.

Sandia is widely published in the energy and fuels research category. In fact, according to Science Watch,[2] among institutions ranked by total citations of papers published between 1998 and 2008, none surpasses Sandia National Laboratories, with more than 4,100 citations to its 395 papers. In addition, Sandia ranks in the top 10 institutions when measured by citation impact. The area most widely cited during this 10-year period was combustion science followed by strong contributions in battery science and solar energy. Sandia is fortunate to have a talented multidisciplinary team of scientists and engineers who are dedicated to delivering "exceptional service in the national interest."

SUMMARY OF KEY POINTS

My statement today is summarized in four key points:

—The U.S. economy and environment would benefit from investments in scalable technologies and processes for recycling of carbon dioxide (CO_2) as one option for addressing two critical, yet interrelated, challenges facing our Nation and the world—stabilizing the concentration of CO_2 in our atmosphere and producing new supplies of liquid hydrocarbon fuels that help reduce our dependence on petroleum. Though I will describe efforts at Sandia focused on CO_2 recycling to address these challenges, an organized and focused national effort including the establishment of a number of collaborative teams to explore these and other approaches would be prudent investments in the long-term interest of the Nation.

—Algae-based biofuels and synthetic fuels from solar energy are attractive because of the possibility of converting solar energy into liquid hydrocarbon fuels which are compatible with the existing infrastructure and at scales and efficiencies sufficient to meet large demands. Lifecycle efficiencies are important because they are indicators of the relative "size of the enterprise" necessary for large volume production. As important as efficiency, both options can recycle CO_2 back into fuel at rates faster than the biosphere takes up CO_2. Lastly, if CO_2 is extracted directly from the atmosphere, then we can produce high-efficiency, carbon-neutral fuels.

—With the support of the Department of Energy (DOE) and others, Sandia is developing and applying science-based algae growth models and techno-economic tools to examine the best options for scaling up the production of algal biofuels. Sandia has also built a prototype "chemical heat engine" to split water and CO_2 using concentrating solar energy. This prototype is a critical step towards demonstrating the feasibility of making solar-based fuels without first making electricity. We are equally excited about a number of ideas for extracting CO_2 from the atmosphere. As excited as we are, we know of many others with similar enthusiasm and ready to make major contributions.

—Other countries are exploring reuse and recycling of CO_2 and it would be unfortunate if the United States became dependent on imported technology in this critical area. This "grand challenge" has excited our team; indeed, I believe this, and sustainable energy research in general, is exciting to the next generation of engineers and scientists all across the Nation.

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[1] Sandia Corporation is a subsidiary of the Lockheed Martin Corporation under Department of Energy prime contract number DE–AC04–94AL85000.

[2] Science Watch (2008), Nov/Dec Featured Analysis, http://sciencewatch.com/ana/fea/08novdecFea/ (Note that citation impact is measured by average number of citations per published paper.)

THINKING DIFFERENTLY ABOUT ENERGY, CARBON AND SECURITY

Taking today's energy system in the United States as a whole, there are six major problems: (1) over 50 percent of primary energy resources are lost as waste heat and emissions during energy transformations and transport; (2) diverse and intermittent resources, such as wind, solar, and distributed generation, are difficult to accommodate; (3) the system relies on nature to close the cycle on waste by-products such as used nuclear fuel, CO_2, and heat; (4) the infrastructure is limited in capacity, flexibility, reliability, and resiliency; (5) increased competition for finite petroleum and natural gas resources limits our foreign policy options and puts pressure on our economic and military resources; and (6) unpredictable energy prices create uncertainty and risk for all stakeholders (producers, suppliers, end-users, and policy makers).

As we strive to transition today's energy system to one that alleviates the problems mentioned above, we should keep the following requirements in mind:

—*Safety*.—Safely supplies energy services to the end user;

—*Security*.—Resists malevolently caused and weather or aging infrastructure-related disruptions and recovers quickly from any disruptions;

—Reliability.—Maintains delivery of energy services when and where needed;

—Sustainability.—Matches resources and delivery with needs for energy services for the entire duration of those needs with minimal waste; and

—*Affordability*.—Delivers energy services at the lowest predictable cost.

To meet the needs of future generations—and assuming a desire to stabilize CO_2 concentrations in the atmosphere and a continued demand for portable energy for transportation—the transformed energy system will be one that likely has five key elements: (1) its primary energy supply comes from persistent (preferably domestic) low-net-carbon energy resources; (2) its energy carrier conversion, as well as distribution and use, involves processes that are as efficient as practical; (3) it reuses or recycles resources in waste streams, particularly ones that have some inherent value such as residual energy or useful mass; (4) it uses liquid hydrocarbons [3] made from abundant and accessible carbon and hydrogen resources; and finally, (5) it has inherent storage to accommodate disruptions and makes maximum use of the existing energy infrastructure. The current national dialog focuses mostly on the first element and, unfortunately, very little on the other four.

We find making liquid hydrocarbon fuels from "recycled" CO_2 an intriguing prospect for enabling the above envisioned energy system as it would preserve the positive attributes of petroleum while eliminating most of the negatives, and at the same time using an abundant waste stream. Indeed, developing solar, wind, geothermal (and maybe nuclear) driven processes that can efficiently, cost-effectively, and sustainably take the products of combustion, CO_2 and water, and recreate liquid hydrocarbon fuels would be an unparalleled achievement. Surmounting this challenge would go a long way toward solving the problem of finding domestic substitutes for petroleum which do not add more carbon to the atmosphere. Later in my statement, I will talk more about our ultimate vision of "recycling" CO_2 by extracting it directly from the atmosphere, thereby slowing the increases in the concentration of CO_2 in the atmosphere. We envision using the atmosphere as an efficient means for transporting the CO_2 from any source to the "recycle sink." But before doing this, a summary of the CO_2 "situation" is in order.

Carbon Management Options

Carbon dioxide is a by-product of energy conversion processes; it is emitted when fuel is combusted. In 2006, worldwide CO_2 emissions were 29.2 $GtCO_2$ (metric Gigatons of CO_2) with the U.S. being one of the largest contributors, adding 5.9 Gt in 2006.[4] The United States consumed 20.7 million barrels of oil per day in 2007. Note that a typical barrel of crude oil will produce 0.42 metric tons of CO_2 if combusted.[5] Of petroleum use in the United States, 69 percent goes to transportation. The transportation sector in the United States contributed almost 2 Gt of CO_2 emissions to the atmosphere in 2006.[6] Since pre-industrial times the concentration of

[3] Liquid hydrocarbons are easily distributed and used in the existing infrastructure, including the hundreds of millions of vehicles currently on the road with mean age of 8–9 years and median lifetimes of >17 years. Hydrocarbons can also provide inherent portable storage for intermittent sources such as solar and wind, especially in circumstances when those resources are not readily connected to the grid.

[4] DOE Energy Information Administration (2006).

[5] NETL (2008), "Storing CO_2 with Enhanced Oil Recovery," DOE/NETL–402/1312/02–07–08, 35.

[6] DOE Energy Information Administration (2006).

CO_2 has increased from roughly 280 parts per million by volume (ppmv) to approximately 385 ppmv.[7]

We now explore how recycling of CO_2 fits into carbon management options with the goal of reducing the growth of atmospheric CO_2 concentrations more broadly. We think of carbon management in terms of rebalancing the sources and sinks to and from the atmosphere—currently sources exceed sinks and this is why the concentration of CO_2 in the atmosphere is increasing. There are five elements in a carbon management tool box: (1) reduce; (2) extract; (3) reuse; (4) recycle; or (5) bury. There are three avenues to reduce: (i) reduce the demand for energy services (e.g., drive fewer miles); (ii) increase the efficiency in the energy conversion and transport processes; and (iii) reduce the carbon intensity or CO_2 emitted per unit of primary energy. Extract comes into play as we begin to seriously think about active carbon management by capturing at the source, usually large stationary sources, such as coal-burning power plants. However, we can also conceive of extracting directly from the atmosphere, surface waters, or heavily distributed emitters. The reuse category presents several options, including enhanced oil recovery (EOR) as well as using the CO_2 as a "green" solvent in chemical processing, for dry ice in food processing, and for carbonation. The recycle category has received very little attention to date except indirectly through the production of bio-energy from biomass. Recycle is the category that is the principle focus of my statement today. The bury category is equivalent to sequestration—or the storage part of carbon capture and storage.

At present, industry has a variety of uses for CO_2, but the quantities are small. Some example uses are: neutralizing alkaline effluents in the chemical sector; making salicylic acid and aspirin in the pharmaceutical sector; chilling and carbonation in the food and beverage sector; balancing the pH in the pulp and paper sector; cooling and cleaning in the electronics sector; and as the fire suppression material in fire extinguishers.[8] [9] The annual use of CO_2 for EOR in the United States is estimated at 0.04 Gt.[10] While "recycling" CO_2 as a feedstock for chemical production is an important use, the United States only consumed on the order of 0.11 Gt[11] of CO_2 in the 2003 timeframe; the largest use was to make urea. Furthermore, even if the top three U.S. produced chemicals (ethylene, propylene, and ethylene di-chloride) used CO_2 as the carbon source, they would only consume another 0.14 Gt.[12] The one "chemical" product that does scale to large quantities is fuels. If we were to use CO_2 as the carbon source to generate the equivalent of our petroleum consumption, 3.0 Gt of CO_2 would be consumed or recycled.[13]

Technologies that can recycle CO_2 into liquid hydrocarbons are attractive propositions. Liquid hydrocarbon fuels are ideal energy carriers and exceptionally convenient to store, transport, and transfer due to their liquid form and high energy-density by mass and volume. While greater electrification of the transportation fleet will almost certainly be an important element of a transformed energy system, routes to creating liquid hydrocarbons which have properties equivalent to gasoline, diesel, and jet fuel should not be ignored.

Efficiency Matters

We are reminded that petroleum, coal, natural gas, and unconventional oil are in fact "stored sunlight" and "sequestered carbon".[14] We tend to categorize fossil fuels as primary energy resources when, in fact, they are energy carriers, which are the result of an inefficient set of conversions of energy and mass fluxes integrated over a very long time. The process began many millions of years ago with a biological organism capturing sunlight (solar flux) and storing the sun's energy by using it to drive chemical reactions of CO_2 and H_2O to higher energy hydrocarbons and oxygen (photosynthesis). A small fraction of the plant matter was then converted over time by heat and pressure to coal, oil, and natural gas. The overall efficiency in this naturally occurring process was quite low.

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[7] http://www.noaanews.noaa.gov/stories2008/20080423__methane.html.

[8] Gobina, E. (2004), "Carbon Dioxide Utilization and Recovery," BCC Report E–131, Business Communications Co., Norwalk, CT.

[9] "Carbon Management: Implications for R&D in the Chemical Sciences and Technology" (A Workshop Report to the Chemical Sciences Roundtable), http://www.nap.edu/catalog/10153.html.

[10] DOE/NETL–402/1312/02–07–08, "Storing CO_2 with Enhanced Oil Recovery," February 2008, pp 45.

[11] Beckman, E.J. (2003), "Green Chemical Processing Using CO_2," Ind. Eng. Chem. Res., 42 (8), pp 1598–1602.

[12] Chemical & Engineering News, July 2, 2007.

[13] For this conversion, we assumed 20.7 million barrels/day, 136 kg/barrel, and 83 percent carbon in petroleum by weight.

[14] Dukes, J.S. (2003), "Burning Buried Sunshine: Human Consumption of Ancient Solar Energy." Climatic Change, 61, 31.

Efficiencies are important because they provide an indicator of the "scale of the enterprise" needed to convert solar energy into fuels, and are therefore one indicator of relative costs. For oil, the sunlight-to-stored energy can be estimated [14] to be only about 0.0002 percent efficient, with large error bars on that estimate. Another way to look at this efficiency is to estimate energy and carbon fluxes. This estimate reveals possible efficiencies of algal biofuels of nearly 3 percent and solar synthetic fuels of 5 percent-10 percent (though large uncertainties exist because neither technology has been proven at large scale). Assuming an average lifecycle efficiency of 5 percent (and average solar energy of 200 watts per square meter), producing the equivalent of the U.S. petroleum usage of 20.7 million barrels of oil equivalent per day using solar energy would require approximately 28 million acres of land. In contrast, total U.S. land is roughly 2 billion acres and paved highways in the United States cover approximately 19 million acres.

Bio-energy from biomass or biofuels can be thought of as a modern-day approach to improve upon nature's inefficient process to create petroleum. As with fossil fuels, the starting point is the photosynthetic conversion of CO_2 and H_2O to hydrocarbons in the form of carbohydrates and lipids. The efficiency of this process is significantly better than that for petroleum and is estimated in our energy flux analysis to be approximately 3 percent. Additional chemical or biological steps are then undertaken to produce a liquid hydrocarbon fuel. Algae are attractive as a fuel feedstock because their production can potentially avoid competition with agricultural lands for food and feed production and can use nonfresh water resources. CO_2 is added to the water as a nutrient to achieve high productivity from algae.

Taking another step further towards increasing the efficiency and directly recycling CO_2 into synthetic fuels can be thought of as emulating the effectiveness of nature's choice to store solar energy by converting CO_2 and H_2O into high energy-density hydrocarbons.[15] Synthetic processes bypass the biological steps that lead to low energy and carbon fluxes and low efficiencies. A worthy target for synthetic routes would be to achieve lifecycle efficiencies of approximately 10 percent.

A known option would be to assemble a system based on solar photovoltaics using electrolysis of water to make hydrogen (H_2), then reacting the H_2 with CO_2. Such a system could be assembled from commercially available components (though none is currently economically viable) and could achieve approximately 5 percent efficiency, with a limiting factor being the initial step of converting solar energy to electricity.

It is these relatively high efficiencies and minimal land requirements that generate our excitement about the prospects for recycling CO_2 into algae-based fuels and solar-based fuels. Creating technologies that are capable of extracting CO_2 from the atmosphere is also important to make these fuels "carbon neutral." In the remainder of this document, we delve more deeply into the three types of technologies that are key enablers for the recycling of CO_2: (1) algae-based fuels; (2) direct synthesis of fuels from CO_2 and water including "Sunshine-to-Petrol"; and (3) extraction of CO_2 from the air. For each technology, we will present a few activities both domestically and abroad, efforts at Sandia that that indicate the promise of such options, and current technological and economic challenges with possible timelines.

ALGAL BIOFUELS

Current Activities

From 1978 to 1996, the Department of Energy's (DOE) Aquatic Species Program represented the most comprehensive research effort to date on fuels from algae. Headed by National Renewable Energy Laboratory (NREL), the program also supported fundamental research at many academic institutions.[16] Since 2007, Sandia has partnered with NREL to develop an algal technology roadmap for DOE's Office of Energy Efficiency and Renewable Energy and Office of Biomass Program. The roadmap will identify and prioritize key biological and engineering hurdles that must be overcome to achieve cost-effective production of algal-based biofuels and coproducts. It will also suggest research strategies to address these barriers. The DOE's National Energy Technology Laboratory has partnerships in place with coal-fired power plant operators to explore the option of growing algae in cooling-water ponds.

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[15] Nature's preferred energy storage means is fat or oil, both which have an energy density of approximately 39 MJ/kg, fairly close to that of gasoline, diesel, and jet fuels at approximately 45 MJ/kg.

[16] Sheehan, J., T. Dunahay, J. Benemann and P. Roessler (1998), "A look back at the U.S. Department of Energy's Aquatic Species Program-Biodiesel from Algae," https://www.nrel.gov/docs/legosti/fy98/24190.pdf.

The prospective value of biofuels from algae has been recognized internationally not only by the global research community, but also a range of commercial sectors including transportation energy, agriculture, and biotechnology, and the venture capital community. A large cadre of venture-backed start-ups working on algal biofuels has emerged over the last few years and larger companies are also getting involved in algae. Meanwhile, the global research community has moved quickly to embrace the challenges presented by producing algal biofuels at scale as witnessed by the dramatic acceleration in conferences on algal biofuels and the formation of public-private partnerships and consortia. This is occurring in the United States, Israel, China, India, France, the Netherlands, and Denmark.

It is estimated that the production of 2.4 million barrels of gasoline with algal oil would consume 1.5 billion tons of CO_2, or 43 percent of total 2008 U.S. emissions from stationary sources.[17]

Sandia's Efforts

The algal biofuels program at Sandia National Laboratories leverages technical strengths in analytical chemistry and applied biology, computational fluid dynamics, and integrated systems analysis—including developing and applying biofuels supply chain models aimed at identifying barriers to cost-effective production of algal biofuels. Sandia's efforts include developing and applying analytical tools to characterize algae gene and protein networks and to monitor algae health. In applied biology, Sandia develops fundamental understanding of algal physiology through genetic engineering, enzyme engineering, and identifying biomarkers and strategies for monitoring biomarkers relevant to biomass cultivation and fuel production.

In the area of computational fluid dynamics, Sandia has developed an algae growth kinetic model in a computational fluid mechanics framework as an engineering tool to develop cultivation strategies for algae—both open ponds as well as photobioreactors.[18] Sandia also owns and operates a facility with algal growth tanks that are equipped with sensors that can be used for validating production models. Systems dynamics models also help us understand the relationship between water supplies, evaporation, and algae production.

In related efforts, Sandia is an active member of the Joint Bioenergy Institute and contributes towards biomass deconstruction and pretreatment for cellulosic biofuels. Our world-class Combustion Research Facility and Center for Integrated Nanotechnologies provide fundamental science understanding in areas of alternative transportation fuels.

Techno-Economic Challenges

Scientific discovery must be complemented by engineering and techno-economic evaluations to enable affordable, scalable algal biofuels. Open literature has reported algal-derived crude oil at a cost spanning over three orders of magnitude ($1 to $1,000 per gallon of triglyceride), with the greatest uncertainties in estimates of facility and operating costs.[19] Investment in every step of the supply chain, from understanding algal biology, strain selection and optimization, cultivation at scale, harvesting, dewatering, and extraction of the hydrocarbons from the algal biomass is needed. As such, both the DOE and the U.S. Department of Agriculture have called for algal biomass funding opportunities to accelerate the R&D cycle.

The DOE has commissioned Sandia and NREL to jointly create a systems dynamics model for carrying out techno-economic analyses of algal fuel development strategies. To be cost competitive, the process must be able to tolerate solar energy variability and energy and water consumption must be lowered. In evaluating resource constraints, it is clear that the availability of water and CO_2 use will limit the locality of sustainable algal biofuel production.[20]

While algal biofuels present an opportunity that will require some time (roughly 10 years) to realize, they are a key component in the U.S. biofuels strategy. Transportation fuels produced from algal biomass are compatible with our existing transportation fuel infrastructure, can recycle CO_2 waste streams, and can be produced on nonarable land with impaired water sources.

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[17] National Carbon Explorer 2008 CO_2 Stationary Source Atlas, http://www.natcarb.org.

[18] Boriah, V. and S.C. James, "Optimizing Algae Growth in an Open-Channel Raceway," Algae Biomass Summit, 2008.

[19] Pienkos, P., "Historical Overview of Algal Biofuel Technoeconomic Analyses," National Algal Biofuels Technology Roadmap, December 9–10, 2008.

[20] Pate, R., "Algal Biofuels Techno-Economic Modeling & Assessment: Taking a Broad Systems Perspective," National Algal Biofuels Technology Roadmap, December 9–10, 2008.

SYNTHETIC FUELS FROM CO_2 AND WATER

Current Activities

Work on alternative fuels has been ongoing for much of the last century; the chemistry and technology for converting fossil-energy resources such as coal is well established and has been practiced commercially in parts of the world for many decades. In contrast, the science and technology for producing hydrocarbon fuels from persistent energy sources (e.g., solar, wind, geothermal, and nuclear power) in a sustainable fashion, is relatively immature. Investments and advances in biofuels and H_2 are ongoing. Because H_2 is a critical feedstock for making liquid fuels, research efforts aimed at the renewable production of H_2 also further the vision of recycling CO_2 into fuels.

Work on CO_2 reuse and recycling has been less visible, but nonetheless efforts are underway around the world. Many of these efforts have been directed towards applications that could consume only a very small fraction of the CO_2 produced through the combustion of fossil fuels, for example supercritical solvents and production of higher-value chemicals.

The primary challenge to recycling CO_2 as a chemical feedstock for either fuels or chemicals and pharmaceuticals is the energy cost and efficiency for splitting (activating) the very stable, CO_2 molecule; furthermore, that energy source must itself have a very low carbon intensity. Achieving such a technology would open the door to using CO_2 as a feedstock for liquid fuels as well as for polymers, plastics, carbonates, and numerous other valuable chemicals and materials (i.e., light-weight carbon composites and carbon-nanotube-based materials).

One basic approach for re-energizing the CO_2 molecule into a useful product has been to react it with another energetic molecule such as H_2. Both Korea and Japan have sponsored work in this area. For example, Japan's Mitsui Chemicals recently announced their intent to make methanol from captured CO_2 and H_2. Additionally, efforts have been initiated in Iceland to commercialize the production of methanol from CO_2 and H_2 from geothermal-powered electrolysis of water.

An alternative means is to use electricity to directly re-energize CO_2. This is analogous to splitting water by electrolysis to make H_2. Hybrid biological and electrical approaches are showing progress. Examples include work at Princeton and announcements from the private sector, such as Carbon Sciences. However, we emphasize that unlike splitting water and making H_2, there are no commercialized technologies that have been developed to directly activate CO_2 and only few research efforts around the world are underway.

Finally the greatest amount of work has been carried out on approaches that can broadly be categorized as artificial photosynthesis. These most closely emulate the process of photosynthesis in harvesting the energy from sunlight to generate electrons and protons to reduce the CO_2. The work ranges from efforts to engineer new devices using the tools of nanotechnology to efforts to replicate natural systems removed from a living organism. Genetic engineering of living organisms is a related approach.

Sandia's Efforts

At Sandia, we have assembled a multi-disciplinary team of scientists and engineers, including a number of university partners to explore a promising new approach to directly activating CO_2 using concentrated solar energy. A novel new "heat engine" concept [21] breaks a carbon-oxygen bond in the CO_2 to form carbon monoxide and oxygen in two distinct steps at two different temperatures. Energy for the high-temperature step comes from the sun. This thermochemical approach appears suited to the production of both H_2 from water and carbon monoxide from CO_2. This process, which we call "Sunshine-to-Petrol," avoids converting the principal energy source (e.g., solar energy) to electricity thereby providing an avenue to potentially higher efficiency than the alternatives. The Sandia team built a thermochemical "heat engine" and named it the Counter-Rotating Ring Receiver Reactor Recuperator or "CR5." The CR5 is a solar receiver which converts concentrated solar energy into thermal energy. The rings counter-rotate. It is a reactor, actually two reactors—thermal reduction and oxygen extracting. Lastly, it is a recuperator—to minimize heat losses and maximize efficiency. If suitable materials can be developed and the design challenges can be met, the CR5 heat engine concept appears to pro-

[21] Diver, R.B., J.E. Miller, M.E. Allendorf, N.P. Siegel, R.E. Hogan (2008), "Solar Thermochemical Water-Splitting Ferrite-Cycle Heat Engines," Journal of Solar Energy Engineering, November 2008, vol. 130, issue 4041001.

vide an integrated approach for potentially efficient and affordable solar-activated CO_2 and water. However, this system imposes unique requirements on materials.

Techno-Economic Challenges (for "Sunshine-to-Petrol")

The CR5 involves numerous design issues and tradeoffs. It places extraordinary demands on materials and involves high-temperature moving parts. Ensuring we have suitable materials will require a substantial degree of fundamental understanding of the chemical and cycle thermodynamics. To establish the practicality of the CR5 concept, we are experimentally evaluating materials, exploring the thermodynamics and kinetics of the materials, evaluating heat and mass flows within the device, and assessing a number of integrated system designs. We expect a focused effort to have a reasonable probability of success. We envision a series of improved engine and system designs. Successful progress would consist of continuously improved generations of prototypes and Sunshine-to-Petrol systems resulting in a new generation every 3 years with significant improvements in performance, durability, and cost. The system would produce gasoline or diesel or jet fuel as the end product. Our targets are efficiency: 10 percent system and lifecycle efficiency,[22] durability: 5 years of operation for the reactive rings and 20 years for the mirrors and the rest of the engine, and of course cost: competitive with all low-carbon alternatives to petroleum, but perhaps no more than $5.00/gallon of gasoline. With that schedule of improvements, the technology should be market-ready in less than two decades. For a concept as new as the CR5 and Sunshine-to-Petrol, we believe that this would be an aggressive schedule.

EXTRACTING CO_2 FROM AIR

Current Activities

To achieve the promise of recycling CO_2 into renewable and sustainable liquid hydrocarbons through either algae-based or solar-based fuels requires extraction of CO_2 directly from the air. The extraction of CO_2 from air has received relatively little attention. However, with the announcement of the Earth Challenge Prize,[23] by Richard Branson of Virgin Atlantic, a number of small start-up companies are taking on this challenge. Small-scale CO_2 capture within submarines and spacecraft is well known. In these applications however, the CO_2 was generally not used for further purposes and release from the capture agent had not been a deliberate design parameter. Klaus Lackner of Columbia University authored several studies on CO_2 capture, with many compelling arguments and has been awarded a patent, with Allen Wright from Global Research Technologies for their novel concept. A project initiated at Carnegie Melon[24] demonstrated the general feasibility of CO_2 capture from air using an aqueous NaOH spray. Lab-scale units have been built by teams at the University of Calgary in Alberta, Canada and at the Swiss Federal Institute of Technology in Zurich. "Green Freedom" efforts at Los Alamos National Laboratory are addressing the capture of CO_2 from air flows of cooling towers, such as those at nuclear power plants.

While conversion of atmospheric CO_2 into a pure feedstock for hydrocarbon fuels synthesis is unquestionably feasible at the bench scale, estimations suggest prohibitively high costs and very low efficiencies relative to what is theoretically possible. Hence, proven methods needed to concentrate large amounts of CO_2 at affordable costs and high efficiency do not exist. CO_2 capture in a specially designed material is analogous to H_2 storage, where the design consideration is to be able to grab it tight enough, but not so tight that it cannot be released at the appropriate time. Most materials identified have a large energetic cost penalty to remove the CO_2 or very slow kinetics at the uptake. What is needed is fast kinetics at the uptake and low energy for release, but not too low. Industrial-scale capture will also entail the processing of large volumes of air through the capture media.

Sandia's Efforts

At Sandia, we have explored the plausibility of large-scale capture from air and a number of new solid sorbents. Our investigations indicate, among other things, that at 4.5 meters/second wind speeds, the cross-sectional area needed to collect

[22] Lifecycle efficiency includes solar energy to gasoline conversion and takes into account the energy required to manufacture the components of the system. Some refer to this as "rays-to-tank" efficiency.

[23] Sponsors are seeking method that will remove at least one billion tons of CO_2 per year from the atmosphere, and the winner will receive $25 million.

[24] Stolaroff, J.K., D.W. Kieth, and G.V. Lowry (2008), "Carbon Dioxide Capture from Atmospheric Air Using Sodium Hydroxide Spray," Environmental Science and Technology, 42, 2728–2735.

enough CO_2 to produce 20.7 millions barrels of oil is between 14,000–36,000 acres, corresponding to capture efficiencies[25] of 50 percent and 20 percent, respectively. Sandia has been collaborating with researchers at the National Energy Technology Laboratory to explore the feasibility of a number of ideas for capturing CO_2 from the atmosphere.

Techno-Economic Challenges

Our analysis suggests the following technical challenges must be met before capture of atmospheric CO_2 for conversion to hydrocarbon fuels or for other re-use options can be considered plausible at the industrial scale: (1) low-energy air processing approaches to assure effective air flows through CO_2 sorbent media to ensure high production rates; (2) durable and easily manufactured materials that readily capture as well as release CO_2 from air at industrial scales; (3) less expensive solid or liquid CO_2 sorbents that have high capacities and are stable over very many catch-and-release cycles; and (4) bench-scale testing and later, pilot-scale demonstrations of atmospheric CO_2 capture approaches.

We expect a focused effort for a decade would have a good probability for success, depending on what cost the market can bear. Note that a capture cost of $50–$75 per metric ton of CO_2 would add only $0.44–$0.66 to the cost of a gallon of gasoline. This seems achievable.

CONCLUSION

The possibility of making liquid fuels from domestic resources that are compatible with our existing transportation energy infrastructure while recycling CO_2 is exciting and real. Because so much of today's CO_2 emissions come from the burning of fossil fuels, it seems natural for us to use this waste stream to produce alternative fuels for future generations. Ideas including those described in this document—algal-based biofuels, solar or other renewable-based fuels, and extraction of CO_2 from air—require investments to prove their technical and economic viability at large scale.

Collaborative teams from across the Nation, and the world, are already developing ideas worth pursuing, but the efforts are currently splintered; we must act now to stimulate this area of research and development. Other countries are exploring the re-use and recycling of CO_2 and it would be unfortunate if the United States became dependent on imported technology or imported alternative fuels in this critical area.

Let me conclude by noting a caution from the technology-policy interface perspective. Carbon management policies that might inadvertently create disincentives for those who pursue the idea of CO_2 recycling could be detrimental to innovation and commercialization of technologies in this area. Policy experts may want to explore the implications of currently proposed actions from this perspective.

Senator DORGAN. Ms. Tatro, thank you very much.

First, we are working on this issue of carbon capture, and most people say carbon capture and sequestration, CCS, they call it. And the sequestration side of it really describes a mindset. "Here is what we have to do. We have to figure out a way to grab the carbon, separate it, and put it someplace deep underground forever." I mean, that is kind of the mindset of what CCS means.

The purpose of this hearing is to say I think there is another mindset out there that I am much more interested in. It is not that I am not interested in sequestration. I am much more interested in finding is there a way to take this carbon and provide from it beneficial use, which might well allow us to cap carbon emissions and actually have very little cost if you could find the right kind of beneficial use.

So the question for all of you is as you watch the Federal Government invest in all these things, do you think there is largely a bias in favor of sequestration or in geologic issues as opposed to other alternatives?

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[25] Capture efficiency is the percent of CO_2 extracted. For example, 50 percent at 400 ppmv in the air stream would leave 200 ppmv in the air stream after passing through the collection media.

Because, Ms. Tatro, you just suggested that we are moving along here, but other countries are moving perhaps, in some cases, faster. Is there a circumstance where you have more difficulty in this whole collegiate discussion about carbon capture with your approach as opposed to sequestration, Ms. Tatro?

Ms. TATRO. Well, I believe there is a lot of activity being looked at now for carbon capture and sequestration, and it is a step forward we need to take. I don't believe that the country has organized around this idea of recycling carbon dioxide. There has been no organized, concerted effort to bring innovation, ideas to the table beyond the capture and sequestration.

But I think the science and technology and innovation community and the industry and universities have ideas in their mind and have talked about them. There is just no concentrated way for those ideas to come forward at this point.

Senator DORGAN. But with the new Secretary of Energy coming from a science lab, one would think that this is the time.

So tell me, Mr. Muhs, what do you think of Dr. Constantz's testimony? You are working on a range of things at Utah, but you heard Dr. Constantz testify on something I thought was very novel and unique.

Mr. MUHS. My assessment is there is no silver bullet and that we should look at biologic approaches as well as chemical approaches to sort of, in his case, reuse for in the use of cementitious material. So, in my mind, we have to look at all of those things. And sort of to follow on with what Ms. Tatro said, I think the whole idea of recycling is a mindset, and it is one that sort of requires a certain level of osmosis into one's mind.

Obviously, you think about recycling in a very general sense, the European countries have done a lot on that in the past and just in general sense in things like recycling aluminum, things of that nature. So I believe that it takes a little time, but I do think we are to that point, and I think you are right.

Senator DORGAN. Mr. Klara, my understanding about algae is that some strains of algae—there are many, many, many different strains of algae.

Mr. KLARA. Right.

Senator DORGAN. And so, some would be very productive with respect to this and some not. Tell me how we go about identifying which would be the productive candidates.

Mr. KLARA. Well, absolutely that is a correct statement. And a lot of the algae work that is ongoing right now is looking at literally dozens and dozens of different strains to find the most robust strain that could have the optimum performance under flue gas conditions where they are getting the CO_2.

And there are also a lot of nifty approaches coming forward with algae as well. One of the issues you have is there is so much algae produced, you have to cultivate and remove it to keep the algae growing. And so, there is all kind of schemes being looked at right now to try to get past that issue so that you can have the truly continuous process.

Senator DORGAN. Where do you think the most successful work is going on in algae at the moment on a trial basis? I am talking about growing algae and then harvesting the diesel fuel and so on.

Mr. KLARA. Well, I think, by far, relative to using carbon dioxide from an energy facility and a coal plant, Arizona Public Service is showing themselves to be a true leader in this area.

Senator DORGAN. Yes, and I have been out to take a look at that. We need to do a lot of everything to find out what works and what scales up.

But Dr. Constantz—yours sounds like a silver bullet. But you can take the carbon and with your process turn it into concrete, and you have captured all of the carbon, which probably has a significant value. You are talking about how much you could produce worldwide and so on. When will you be able to scale up your process so we understand if this works at scale?

Mr. Muhs says there is no silver bullet, but is yours close to a silver bullet?

Dr. CONSTANTZ. Where we are at is we have a 200-acre facility next to a 1,000-megawatt powerplant in Moss Landing, California. We also have a coal-fired boiler simulator there. So we are burning both coal and gas, and we are making cement every day. In a batch process, we have been making 5 tons a day for several months.

We have just commissioned a plant, which is a continuous process, which runs 24–7 solely on coal, which is producing 1 ton a day. The large EPC firms working with us say the parameters that they are getting from this continuous plant will allow them to design and construct a plant of any size.

Senator DORGAN. And you think this approach is going to demonstrate at scale your capability?

Dr. CONSTANTZ. Yes, I mean, I think we are doing that right now. And all the——

Senator DORGAN. Well, if that——

Dr. CONSTANTZ [continuing]. Energy balances look very good.

Senator DORGAN. I don't mean to interrupt you, but if you are doing it right now and it was demonstrated at scale that you can produce a product of substantial value and sequester virtually all of the CO_2 at the same time, it seems to me there would be a traffic jam leading right to your office of everybody in the world that says, "You know what? You found the silver bullet. We need to do that."

Dr. CONSTANTZ. In fact, the materials I am pointing out to you are highly sought after by the entire construction industry, and they are beating a path to our door. I mean, we are talking to every major producer of portland cement and aggregate in the world.

And we are talking about the whole fabric of the infrastructure here. It is not just a power problem. If you are a hammer, everything looks like a nail. And just what you said, the goal is not to purify CO_2 so you can inject into the ground. The goal is to lower the amount of carbon in the atmosphere.

And you need to understand the whole construction industry has a huge problem, too. The cement industry, for every ton of cement produced, produces a ton of CO_2. They are under the same problem that the power guys are under. And so, they are looking for ways to mitigate their CO_2, and they see the opportunity to turn this liability into a profit.

Sixty percent of the aggregate used in northern California is imported from British Columbia on barges, and it is all limestone. It looks just like this. We can produce it locally with the carbon. We are producing in a profitable way.

And it links in with the water. At our plant in Monterey, we have a contract with the local water district because they have big problems, and we can lower the energy intensivity of their reverse osmosis by 50 percent. So we are actually doing it.

Senator DORGAN. Ms. Tatro, what do you think? I mean, you are looking at a lot of different things. Give me your assessment of Dr. Constantz's presentation.

Ms. TATRO. Sir, I think there is tremendous merit to taking CO_2 and permanently sequestering it in these construction materials. I think that is a fabulous idea. I think it can be complemented nicely by using CO_2 to create liquid transportation fuels.

This is my point in my testimony. I think there are a lot of good ideas out there that have not come to the forefront because there has not been an organized effort to call for these ideas. I think it is a fabulous idea. It would complement making transportation fuels very nicely.

Senator DORGAN. Now you have worked since 1985 for Sandia, and you have got a couple hundred people working with you. You lead a couple hundred people working on these issues. So you have spent a lot of time and a lot of public funding working on these issues. Let us fast forward 5 and 10 years.

Ms. TATRO. Okay.

Senator DORGAN. And let us say that we really begin to focus on all the aspects of carbon capture and also start to emphasize beneficial use. Do you think in 5 to 10 years we would make significant progress on the beneficial use side?

Ms. TATRO. I believe we can. I think the 10-year timeframe—to answer your question earlier about when the maturity of these technologies is going to vary. But a 10-year timeframe is a very reasonable timeframe for a target of doing some of these concepts in a way that is both affordable and technologically feasible.

I will offer this one caution. Those who are expert in this area of policy, such as yourselves ought to be looking at the current policies that are being discussed to make sure they do not disincentivize the recycling of carbon dioxide as an option. That will significantly affect the timeframe in which these technologies can be viable.

Senator DORGAN. Well, this subcommittee is going to try to have an impact on that, and we tried to have an impact on that in the stimulus bill as well to make sure that most of these things tend to move toward the geologic side of things because of CCS. So we intend to try to have a significant impact on that.

Senator Bennett?

Senator BENNETT. Thank you very much, Mr. Chairman. And thank you for the hearing.

Thank you to all the witnesses, and a special welcome to my fellow alumnus from Utah State University. I became a graduate as of last Saturday. They gave me an honorary degree.

Senator DORGAN. How were your grades?

Senator BENNETT. I, what is the—you pencil-whipped them through.

I would ask that the algae report be part of the record, if that has not been done already.

Senator DORGAN. Without objection.

[The information follows:]

ALGAE BIOFUELS AND CARBON RECYCLING—A SUMMARY OF OPPORTUNITIES, CHALLENGES, AND RESEARCH NEEDS

SUMMARY OF RECOMMENDATIONS

Congress should support and strengthen policies inclusive of algae energy system development in future energy and climate change legislation and loan guarantees for commercial demonstrations (EPACT 2005; title 17).

Congress should authorize and appropriate funds for a comprehensive research, development, and demonstration program administered by the U.S. Department of Energy specifically focused on algae energy systems.

—The program should include a balanced and distributed portfolio of foundational, translational, and transformational research, development, and scalable demonstrations.

—Fundamental research should provide new knowledge discovery in several areas.

—Applied R&D should involve laboratory and pilot-scale R&D on all three subsystems (upstream, cultivation and downstream systems) and interdisciplinary activities that bridge between them.

—Crosscutting R&D should be included on topics such as advanced materials, instrumentation and controls, systems engineering, and economic modeling.

—Demonstration and deployment elements of the program should be designed to demonstrate the viability of algae energy system technologies at a scale large enough to overcome real and perceived infrastructure challenges.

—The largest component of the demonstration and deployment program should be regional partnerships similar to the Department's Fossil Energy ongoing regional programs for geologic sequestration.

—The program should include initial supporting research on lifecycle analyses.

—The program should leverage strengths from existing Department programs, establish programmatic roles, and coordinate from a Department-wide perspective.

—The program should include development of education programs.

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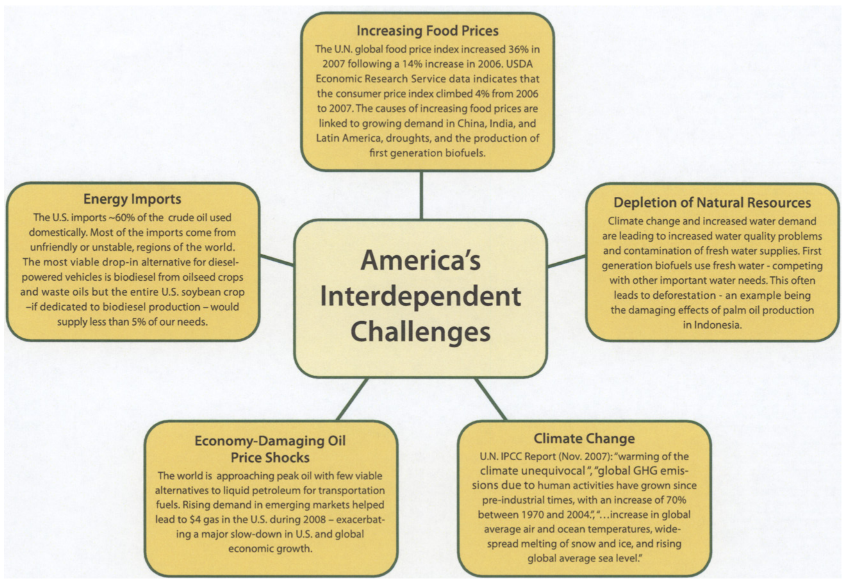
EXECUTIVE SUMMARY

The United States of America faces five interdependent challenges (described below) that threaten the prosperity and quality of life of its citizens. Central to these challenges is the need for domestically-produced renewable transportation fuels and carbon mitigation strategies that are affordable, environmentally-sustainable, and avoid interfering with food supplies. This report summarizes opportunities, challenges, and research needs for sustainable algae-based biofuel production with an emphasis on systems designed for carbon recycling from point-source CO_2 emitters. It reviews the limitations of other biofuel and carbon mitigation options and summarizes how algae energy systems can fill a unique niche in both cases. Recommendations for a national-scale RD&D program and critical steps leading to robust pilot demonstrations by 2015 and integrated systems demonstrations by 2020 are also provided.



INTRODUCTION

In response to increasing pressure to reduce carbon emissions, fossil-fired utilities are pursuing deep geological sequestration as the preferred option for handling the enormous quantities of CO_2 being introduced to the atmosphere (Figure 1). Recent analyses indicate that additional options for risk mitigation may be necessary, as liability issues for deep sequestration are unknown and potentially significant. Industries and utilities face increasing difficulty in financing new fossil-fired boilers and electric power generators because of uncertainty over CO_2 abatement.

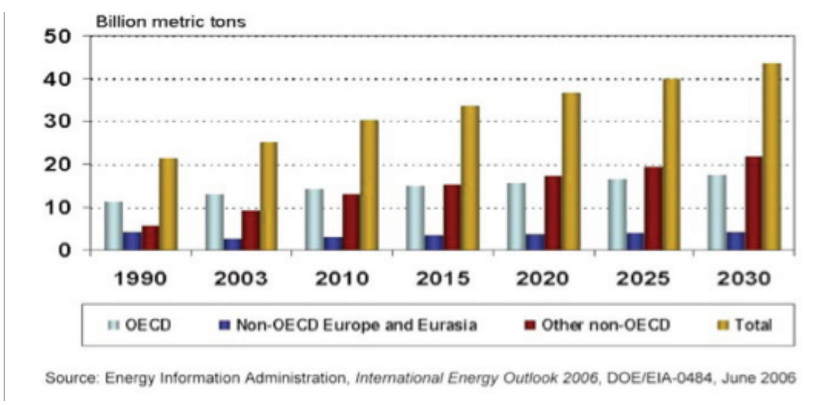


FIGURE 1.—*World CO_2 Emission by Region as Published in the DOE Carbon Sequestration Technology Roadmap and Program Plan 2007*

Industrial operations, in particular, face serious risk with respect to CO_2 control. Flue gas separation is expensive and access to geological sequestration for smaller emitters is limited and costly. Given EPA's new rules for assuring ground water quality, the long-term risk to small operations is even more stifling. The lack of other options has driven these operations toward natural gas, with little possibility of future CO_2 control. Natural gas boilers emit less CO_2 than coal per Btu, but without control, long-term CO_2 release will continue unabated. Natural gas, which has higher value uses in the production of fertilizer and in home heating, will continue to rise in price as demands increase, resulting in higher food, home heating and electricity prices. Without options to mitigate CO_2 emissions, the ultimate loser will be the consumer.

Compounding the climate change challenge is the worldwide dependence on fossil fuels for transportation and home heating. Unlike concentrated CO_2 sources, homes and vehicles are highly dispersed, and it is difficult to visualize viable ways to collect, separate, and sequester carbon dioxide from such locations. Instead, options that are more viable are sought including replacement of fossil fuels with biofuels.

The U.S. biofuel producers, however, are in the process of shifting to new feedstocks because of increasing concerns over the environmental and economical impacts of 1st-generation biofuels. Corn and soy-based biofuel industries experienced rapid growth from 2002 to 2007, but rising corn and soybean prices, volatile petroleum markets, and new studies on their carbon footprints have slowed investments. The cultivation and harvesting of traditional biofuel crops, long viewed as part of the solution to climate change, may actually increase greenhouse gas emissions.[1] Further, the energy density of both corn- and cellulosic-based ethanol is considerably lower than gasoline and diesel making their widespread use in ground freight and air-transportation markets highly unlikely.

Thus, we are entering an era where several factors are aligning to promote the use of algae for photosynthetic mitigation of greenhouse gas emissions and production of next-generation biofuels. Algae and cyanobacteria offer an alternative and sustainable solution via two fundamental routes: (1) value-added sequestration of CO_2 through conversion to stable biopolymers; and (2) displacement of fossil fuel use by producing renewable fuels (biodiesel and/or biogas) in areas with little plant life. Reported values of algal growth-rates and yields indicate a near-term potential for using algal energy systems for biodiesel production and carbon recycling from smaller CO_2 generators such as industrial boilers or fuel-ethanol plants.

Algae energy systems will likely be part of a national/global energy security portfolio, resulting in distributed energy systems not disadvantaged by CO_2 transportation costs to distant geological locations, an option not likely viable for smaller-scale producers.

Fundamentally, algae and cyanobacteria use solar energy to transform atmospheric CO_2 to organic cellular material via photosynthesis. Due to their simple biological structure, they convert and capture carbon more rapidly than terrestrial plants and store a significant amount of carbon as material that can be converted into biodiesel, bioplastics, feedstock for gasification, or numerous other products. Some algal strains are capable of doubling their mass several times a day. Algae can be cultivated on marginal land (and on ocean surfaces) using low-quality and or saline waters. In contrast, terrestrial sequestration and biofuel production requires fresh water, is slower and restricted by the availability of fertile land; eventually reaching steady state, with no additional sequestration or biofuel production possible.

While algal products offer the potential to provide sustainable solutions for both liquid transportation fuels and CO_2 mitigation, important challenges must be overcome to make them cost-effective. Unlike terrestrial crops that have been cultivated and harvested for centuries, the infrastructure and knowledge needed to cultivate and harvest algae using industrial processes is in a pre-commercial stage of development. For example, within the field of plant biotechnology, algal research is one of the least explored fields and industrial-scale algal energy systems will benefit greatly from intense R&D efforts.

For these reasons, clearly-defined goals and significant, well-managed and coordinated Federal investments are needed in areas such as CO_2 delivery and conditioning; integration and systems engineering; energy and water use; algal areal and volumetric productivity; cultivation system design; strain optimization; synthetic biology; downstream processing; value-added co-product development; and carbon lifecycle analysis.

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[1] Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu T. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. Science AAAS [Internet]. 2008 [cited April 2009]. Available from: http://www.sciencemag.org/cgi/content/abstract/1151861. 2008;319(5867):1238–1240.

LIMITATIONS OF OTHER CARBON SEQUESTRATION PATHWAYS

Figure 2 illustrates the three primary pathways to carbon sequestration. Though significant investments and progress in developing geologic and chemical carbon mitigation pathways has been made, significant hurdles remain.

FIGURE 2.—*Primary Pathways to Carbon Sequestration*

Challenges of Underground Geologic Sequestration

The problems associated with geological sequestration of supercritical CO_2 are well documented and reasonably well understood; however, there is a significant difference between sequestration of CO_2 as a gas phase compared a supercritical fluid. Gas phase CO_2 can be stored in geological formations. Large natural CO_2 deposits can be found worldwide, much like there are large natural gas formations. Gaseous CO_2 has been successfully used over decades for enhanced oil and gas recovery by injection into gas and oil reservoirs, and there is strong evidence supporting the ability to store gas phase CO_2 for significant lengths of time.[2–9]

There are two concerns with gas phase storage of CO_2: First, at low gas pressures, the capacity of all geologic storage is estimated to be only decades of fossil fuel use; Second, CO_2 will remain in the gas phase and ready for release should an accidental penetration occur in the formation or a cap rock be compromised. While intense management of geological formations should limit this, accidental release is a non-trivial possibility.[10] [11]

Supercritical CO_2, or storage of CO_2 at pressures exceeding the critical point (7.38 MPa), is highly favored over gas phase storage because the higher pressure significantly increases the holding capacity of the geological formation. Gas pressures as high as 80 MPa are being considered for sequestration.[12] Further, supercritical CO_2 is more reactive than gas phase CO_2 and has the ability to chemically join with metals in the aquifer (e.g., calcium and magnesium) to form solid carbonates, which

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[2] Marchetti C. On Geoengineering and the CO_2 Problem. Climatic Change, 1977;1: 59–68.

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[8] Bachu S, Gunter WD, Perkins EH. Aquifer disposal of CO_2: hydrodynamic and mineral trapping, Energy Conversion and Management. 1994;35(4):269–279.

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[10] Gunter WD, Bachu S, Benson S. The role of hydrogeological and geochemical trapping in sedimentary basins for secure geological storage for carbon dioxide. In: S. Baines and R.H. Worden editors. Geological Storage of Carbon Dioxide. Technology. Special Publication of Geological Society, London, UK. Special Publication; 2004. 233: p. 129–145.

[11] Kaarstad O. Geological storage including costs and risks, in saline aquifers, Proceedings of workshop on Carbon Dioxide Capture and Storage: Regina Canada; 2002.

[12] Benson S, Cook P. Underground Geological Storage. In: Metz B, Davidson O, de Coninck, Loos HM, Meyer L, editors. Carbon Dioxide Capture and Storage (Intergovernmental Panel on Climate Change): Washington, DC; 2005. p. 197–278.

would be permanently sequestered within the Earth with no chance of accidental release.[13] [14]

Unfortunately, supercritical CO_2 is far more problematic for storage than gas-phase CO_2. Supercritical CO_2 is an extreme solvent and attacks concrete, which is the material of choice for capping wells: And, while the time-scales for dissolution of the concrete seals may be decades, the supercritical CO_2 will be present for time-scales of centuries to millennia because geochemical reactions that form carbonates are very slow. As a result, the possibility of leakage through capped wells is potentially high, and given the hundreds of thousands of wells that must be drilled, it is very likely that leaks will occur.[11] [15]

Whether the leaks are slow and manageable or rapid and catastrophic are key questions. A scenario where a sudden and major leak occurs in an area of high population could be catastrophic because CO_2 has a higher molecular weight than air and presents a significant risk of asphyxia at very high release rates. Therefore, deep geological sequestration will require widespread monitoring over entire formations, leading to significant cost.[12] Further, liability issues (should a significant leak occur) must be resolved by legislation, because few companies will risk exposure to expensive lawsuits in the event of a catastrophe.

Aquifer poisoning is another significant concern. Supercritical CO_2 is mobile, and should an underground fissure lead to migration of the CO_2 from its proposed storage formation to a potable aquifer, the potential exists for formation of significant quantities of carbonic acid in potable water sources.[12] [16] This could make the contaminated aquifer unusable until suitable treatment technology was applied to neutralize the acid. Neutralizing technology is non-trivial, would be very costly, and would take months to implement. Populations dependent on that aquifer could be without drinkable water for the duration; businesses and organizations that are equally dependent on the aquifer for their operation and livelihood could be faced with significant revenue losses.

Another significant issue for supercritical CO_2 storage in deep geological formations is corrosion. By injecting supercritical CO_2 in a saline aquifer, a mixture of corrosive carbonic acid and salts would be present in the region of down-hole well pipes.[12] When the supply of injected CO_2 is stopped, high pressures in the region of the aquifer near the pipe could force that corrosive mixture back, which would create the possibility of rapid pipe failure. What exactly would happen when a down-hole well pipe fails is unknown, but it could range from having to replace more than a mile of down-hole well piping to a catastrophic failure of the entire injection system.[17]

Unfortunately, today's carbon capture and sequestration methods are also expensive. The Intergovernmental Panel on Climate Change's report, Carbon Dioxide Capture and Storage, reports that CO_2 capture is expected to increase the cost of electricity production by 35–70 percent for a Natural Gas Combined Cycle (NGCC) plant, 40–80 percent for a supercritical PC plant, and 20–55 percent for an NGCC plant. The costs of retrofitting existing power plants may be even more expensive and carbon dioxide transportation and storage further add to costs.[18] [19]

As much as we must make deep geological sequestration work, the potential problems, liabilities, and costs are not minor and it is clear that other alternatives must be pursued to mitigate risk.

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[14] Van der meer LGH. Computer modeling of underground CO_2 storage. Energy Conversion and Management. 1996;37:6–8(1155–1160). 14.

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[18] iEA GHG, Leading options for the capture of CO_2 emissions at power stations, report PH3/14, IEA Greenhouse Gas R&D Programme. Available From: Cheltenham, UK, Feb. 2000.

[19] Thambimuthu K, Soltanieh M, Abanades J, Capture of CO_2. In: Metz B, Davidson O, de Coninck, Loos HM, Meyer L, editors. Carbon Dioxide Capture and Storage (Intergovernmental Panel on Climate Change). Washington, DC. 107-p. 178.

Challenges of CO_2 Transport & Sequestration in Oceans

Several concepts have also been proposed for CO_2 storage in oceans. One option considered is injecting CO_2 by ship or pipeline into the water column at depths of 1,000 meters or more so that the CO_2 subsequently dissolves. Another option is to create underwater lakes where CO_2 is piped directly onto the sea floor at depths greater than 3,000 meters where CO_2 is denser than water (and forms a natural lake). In both cases, no one is quite sure how to cost-effectively collect, transport, or inject CO_2, or if the injected CO_2 will actually remain sequestered. Deep saline aquifer storage depends on supercritical CO_2 staying in the aquifer for enough time to form stable mineral species. Unfortunately, the timescale for that transformation is hundreds or thousands of years, and the chance that supercritical CO_2 will not find a way out without converting to carbonates is probably less than is optimistically predicted.

Other environmental effects of oceanic storage are generally negative and poorly understood. Concentrated CO_2 kills ocean organisms. As CO_2 reacts with the water to form carbonic acid, H_2CO_3, the acidity of the ocean water increases, which will dissolve the shells of shellfish and corals and cause reproductive problems for sea creatures. Consequently, ocean storage of CO_2 is likely to have several unintended consequences.

Challenges of Chemical CO_2 Separation and Sequestrations

Before CO_2 can be sequestered in geological or other storage sites, it must be purified or enriched beyond the 5–15 percent concentration typically found in the products of combustion. The concentration of CO_2 in combustion gases is relatively low because the high concentration of nitrogen in the air used to burn the fuel (typically coal or natural gas) remains relatively unchanged during the combustion process. Because there is limited space for CO_2 sequestration and the cost of compression and storage is significant, it is not desirable to sequester large volumes of other gases with CO_2.[12]

The two primary approaches to purify CO_2 for sequestration are absorption-desorption separation and oxygen-based combustion. Absorption-desorption separation removes CO_2 from the nitrogen and water (the other major constituents in the combustion gases). Oxygen-based combustion removes the nitrogen from the combustion air before reacting with the coal or natural gas, leaving mostly CO_2 and water in the combustion products and eliminating the need to remove nitrogen, which is not reactive and difficult to separate from CO_2.[20]

Absorption-desorption based separation of CO_2 is a well-known process. The most commonly employed method in industry uses monoethylamine (MEA or amine) to absorb the CO_2 from combustion gases and, in a separated and heated chamber, strip CO_2 from the amine as a relatively pure gas. While numerous amines have been developed, the energy requirement (primarily for stripping) is enormous: DOE has estimated that about one-third of the output of a power plant would be necessary to run an amine scrubbing system for CO_2 separation. This would not only lead to significant increase in the cost of electricity, but also of the amount of coal needed to produce an equivalent amount of electrical power.[21]

Oxygen-based combustion is also being considered for implementation to produce a sequestration ready CO_2 stream.[22] Theoretically, it is much easier to remove water vapor (the other major constituent found in combustion gases) than nitrogen. However, even in the most optimistic evaluations of implementing oxy-fuel combustion, there will be significant amounts of nitrogen found in the combustion gases. Unfortunately, power plants are difficult to seal completely from air infiltration (need for oxy-fuel combustion) and the retrofit costs of such a system, especially the air separation unit required to remove the nitrogen from the air, will be non-trivial.[23]

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[20] Kohl, A.O, Nielsen RB. Gas purification, Gulf. Houston: TX; 1997.

[21] Alstom Power Inc., ABB Lummus Global Inc. Alstom Power Environmental Systems and American Electric Power. Engineering feasibility and economics of CO_2 capture on an existing coal-fired power plant. Report no. PPL–01–CT–09 to Ohio Department of Development, Columbus, OH and U.S. Department of Energy/NETL, Pittsburgh, PA. 2001.

[22] Babcock Energy Ltd, Air Products Ltd, University of Naples and University of Ulster. Pulverized coal combustion system for CO_2 capture. Final report 2.1.1. Available from: European Commission JOULE II Clean Coal Technology Programme—Powdered Coal Combustion Project. 1995.

[23] Wilkinson MB, Simmonds M, Allam RJ, and White V. 2003a: Oxy-fuel conversion of heaters and boilers for CO_2 capture, 2nd Annual Conf on Carbon Sequestration, Virginia (USA), May 2003.

Challenges of Other Biological Sequestration Pathways

Figure 3 illustrates the three primary pathways for biological sequestration. Though there has been much discussion and limited research on terrestrial and ocean algal carbon sequestration, significant hurdles remain.

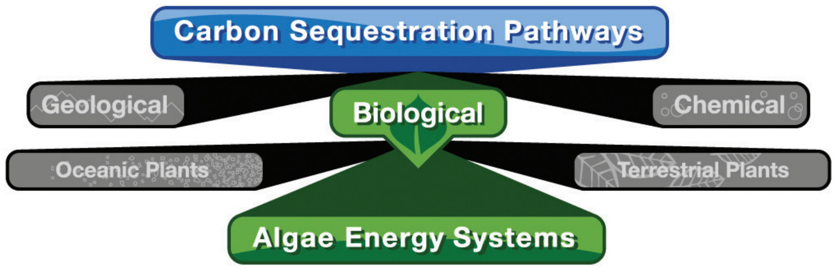

FIGURE 3.—*Primary Pathways to Biological Carbon Sequestration*

Carbon Capture by Forests

Forests are natural carbon dioxide sinks and sequester carbon in the cellulosic structure of trees and humus soil. In 2004, forests sequestered 10.6 percent (637 teragrams or 637 megatons) of the carbon dioxide released in the United States by the combustion of fossil fuels (coal, oil and natural gas; 5,657 teragrams or 5.6 gigatons) while urban trees sequestered another 1.5 percent (88 teragrams) EPA 2008.[24]

An average coal-fired power plant produces about 4 million tons of CO_2 annually (there are about 600 plants in the United States): It would require planting 161 million trees to offset each plant.[25] The land, cost and energy required to plant trees to sequester significant amounts of CO_2 make the approach infeasible.

Typically, carbon stored in soils oxidizes rapidly and reenters the atmosphere or water. Carbon captured by forests is typically temporary (decades in duration) because many forests burn or are harvested and release their stored carbon. Other forests are uprooted by fierce storms and the carbon oxidizes. In 2004, Hurricane Katrina killed or severely damaged 320 million large trees in Gulf Coast forests.[26] Tropical forests are also poor at retaining carbon long term because they tend to have very thin organic mulch on the forest floor; heavy rains leach out the carbon and carry it to waterways. Conversely, carbon stored in soils as humic acids can sequester carbon for long periods and increase the carbon uptake vitality of all types of vascular plants.[27]

Regenerative Agriculture Carbon Capture

The Rodale Institute reported that regenerative (organic) agriculture may sequester up to 40 percent of current CO_2 emissions by plowing organic carbon in green manure (plant biomass) back into the soil.[28] The authors believe that agricultural carbon sequestration has the potential to mitigate climate change. They believe that organic farming practices can be accomplished with no decrease in yields or farmer profits and that organically managed soils can convert carbon dioxide from a greenhouse gas into a food-producing asset.

Some midwestern soils that, in the 1950s, were composed of up to 20 percent carbon are now between 1 and 2 percent carbon. This carbon loss contributes to soil erosion by degrading soil structure, increasing vulnerability to drought, by greatly reducing the level of water-holding carbon in the soil, and by the loss of soil's native nutrient value. Organic farming builds carbon back into the soil, which improves the soil as it sequesters the carbon.

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[24] Malhi Y, Meir P, Brown S, Forests, carbon and global climate. Philos Transact A Math Phys Eng Sci. 2002 Aug 15;360(1797):156.

[25] Union of Concerned Scientists, Clean energy [Internet]. 2008 [cited April 2009]. Available from: http://www.ucsusa.org/clean__energy/coalvswind/c01.html.

[26] NASA, Forests Damaged by Hurricane Katrina Become Major Carbon Source [Internet]. 15 Nov 07 [cited April 2009]. Available from: http://www.nasa.gov/mission__pages/hurricanes/archives/2007/katrina__carbon.html.

[27] Wigley TML, Schimel DS. The Carbon Cycle. Cambridge University Press: Cambridge; 2000.

[28] LaSalle T, Hepperly P. Regenerative 21st Century Farming: solution to global warming. Rodale Institute, 2008.

In 2006, U.S. carbon dioxide emissions from fossil fuel combustion were estimated at nearly 6.5 billion tons. If a 2,000 lb/ac/year sequestration rate was achieved on all 434 million acres of cropland in the United States, nearly 1.6 billion tons of carbon dioxide would be sequestered per year. This would mitigate about one-quarter of U.S. fossil fuel emissions.

Critics note that the cropland required to grow enough green manure for organic fertilizer would take 10 times more cropland than is available in North America; which makes large-scale organic farming impractical unless an organic fertilizer source can be found that requires no cropland and minimal fresh water and fossil fuels. Farmers would have to use no-till farming, which is currently used by less than 5 percent of farmers, in order to ensure the soil is not disturbed and the carbon is not oxidized and released as CO_2.

Marine Algae Sequestration

Even though algae represent only 0.5 percent of total global biomass by weight, algae produce about 60 percent of the net global production of oxygen, which is more than all the forests and fields combined.[29] Algae's ability to sequester CO_2 and produce massive amounts of O_2 has prompted scientists to theorize that propagating algae in large ocean dead zones may be a way of sequestering millions of tons of CO_2 and adding to atmospheric oxygen.

English biologist Joseph Hart theorized in the 1930s that the ocean's great desolate zones were rich in nutrients but lacking in plankton activity or other sea life because they were iron deficient.[30] Decades later, a series of studies proved the iron thesis.

Ocean iron fertilization (OIF) seeds iron in open oceans with micrometer-sized iron particles in the form of either hematite (iron oxide) or melanterite (iron sulfate). The iron feeds phytoplanktons that are in iron deficient blue ocean water. Phytoplanktons grow quickly in algae blooms and consume massive amounts of CO_2 that they convert into plant biomass that sinks to the ocean floor.

Since 1993, 10 international research teams have completed small-scale ocean trials demonstrating the capability of ocean iron fertilization. Ken Buesseler, a scientist of marine geochemistry at Woods Hole Oceanographic Institution in Massachusetts, along with other scientists, is trying to get approvals and funding for more research.[31]

The Southern Ocean test in 2002 near Antarctica reported that between 10,000 and 100,000 carbon atoms are sequestered for each iron atom added to the water. Recent work suggests that biomass carbon in the oceans, whether exported to depth or recycled in the euphotic zone (depth with sufficient sunlight for photosynthesis), results in long-term carbon storage. Therefore, the application of iron nutrients in select parts of the oceans, at appropriate scales, could have the combined effect of restoring ocean productivity while concurrently mitigating the effects of human caused emissions of CO_2 to the atmosphere.

Support for the iron deficiency theory occurred with the 1991 eruption of Mount Pinatubo in the Philippines. Andrew Watson analyzed global data from that eruption and calculated that the eruption deposited approximately 40,000 tons of iron dust in the oceans. This ocean fertilization event generated a significant global decline in atmospheric CO_2 and a parallel increase in oxygen levels.[32]

Critics worry that seeding the ocean with large volumes of iron might have unintended consequences. In a special report, the Intergovernmental Panel on Climate Change called ocean iron fertilization "speculative and unproven and with the risk of unknown side effects".

LIMITATIONS OF OTHER BIOFUEL FEEDSTOCKS

Biofuels have been identified as one of the key pathways for transforming our energy supply away from fossil fuels. The recent cultivation of large quantities of biomass for biofuels has led to a growing debate over the feasibility and sustainability of biofuels as a renewable energy source. Figure 4 shows three primary feedstock options for producing renewable liquid transportation fuels. Significant investment and technological progress in both food/feed and cellulosic-based bio-feedstocks have

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[29] Hall J. Earthworks & Systems: the most important organism?. Ecology Global Network [Internet]. 2008 [cited April 2009]. Available from: http://www.ecology.com/dr-jacks-natural-world/most-important-organism/index.html.

[30] Jones ISF, Young HE. Engineering a large sustainable world, fishery. Environmental Conservation 1997;24: 99–104.

[31] Buesseler, Ken. et. al. Ocean Iron Fertilization—Moving Forward in a Sea of Uncertainty, Science. 2008;319(5860):162.

[32] Watson AJ. Volcanic iron, CO_2, ocean productivity and climate. Nature. 1997;385: 587–588.

occurred in recent years; however, substantial hurdles in certain niche markets remain.

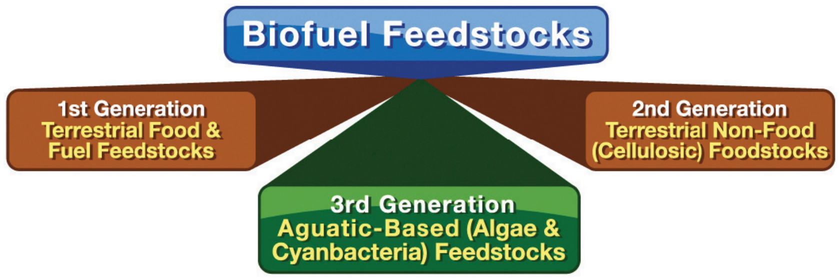

FIGURE 4.—*Primary Feedstock Options for Producing Renewable Liquid Transportation Fuels*

Traditional sources of biomass are abundant and include field crops such as soybeans and corn; perennial grasses such as switchgrass; woody crops such as trees; and other agricultural and forestry residuals. Corn and soybeans are examples of so-called first-generation terrestrial biofuels because of their use in both food and fuel production. Clean-burning ethanol is derived from corn and most biodiesel from soybeans. In 2006, close to 5 billion gallons of ethanol were produced in the United States, which is 3.6 percent of our annual gasoline demand (per volume) and 2.4 percent (per energy).[33]

Limitations of corn ethanol include a considerably lower energy density compared to petroleum both on a per volume and per weight basis. Thus, ethanol requires more fuel to propel vehicles comparable distances. Further, though the growth of corn and soybeans for biofuels absorbs as much carbon as biofuel-powered vehicles emit, it does not absorb the significant carbon emissions associated with planting, fertilizing, harvesting, transporting, processing, and converting biomass into fuel. One analysis concluded that it would take over 150 years for such crops to achieve carbon neutrality.[1]

These challenges are compounded by our need to both feed and fuel a growing global population (projected to be 9 billion by 2050). In comparison to less-complex organisms, food crops like corn and soybeans grow much slower, and thus, require large quantities of fertile land and water, which, in turn, increases food, and water prices. For example, the food price index of the Food and Agriculture organization of the United Nations rose 36 percent in 2007 after a 14 percent increase in 2006 because of—among other things—biofuel production.

Because of these and other concerns, interest in producing cellulosic ethanol from fibrous residue from plants (forestation byproducts, corn stalks, wheat straw, and grasses) has grown in recent years. The production of cellulosic ethanol, considered a second-generation terrestrial biofuel because it uses only nonfood feedstocks, is still a maturing industry. Though technologies for breaking down fibrous material into fuel are still under development, the United States could produce 60 billion gallons of ethanol per year by 2030 through a combination of grain and cellulosic feedstocks, which is enough to replace 30 percent of projected U.S. gasoline demand.[34] Further, perennial crops such as switchgrass would hold soil and nutrients in place and require lower fertilizer and pesticide inputs, thus reducing water quality impacts compared to first-generation biofuels.

There are, however, limitations and uncertainties that accompany the production of cellulosic ethanol. Anticipated cellulosic crops also grow relatively slow in comparison to less complex plants (such as algae) and have little history of use in large-scale cultivation. Like first-generation biofuels, considerable land, water, and energy is required to plant, harvest, transport, process, and convert cellulosic biomass into usable fuels. Data on water, nitrogen and other nutrient needs, herbicide use, soil erosion, and overall yields are still being collected and synthesized. As second-gen-

[33] Yacobucci BD, Ethanol Imports and the Caribbean Basin Initiative. Available from: United States CRS Report for Congress (Order Code RS21930); 2007. Available from: http://www.docstoc.com/docs/779532/CRS-Report-on-Ethanol-Imports.

[34] Sheehan J. A look back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae. National Renewable Energy Laboratory, 1998, Golden, CO.

eration biofuels expand into regions that do not support high agriculture yields, they could dramatically affect water use and damage irrigation introductions.

Many believe ethanol will become the bridge from petroleum to electric-based commuter surface transportation in the coming decades. However, because of its relatively low-energy density (compared to diesel and jet fuel), ethanol is not likely to emerge as the preferred energy carrier in air transportation, ocean shipping or long-haul freight movement. For these markets, biofuels derived from oilseeds such as soybeans are the preferred alternative because their energy densities are comparable to petroleum fuels. Unfortunately, even if all of the U.S.'s soybean crop were diverted to the production of biodiesel, less than 10 percent of the U.S. diesel fuel needs would be met. Clearly, new feedstocks that efficiently produce biofuels that have energy densities rivaling petroleum-based products are needed and current pathways are falling short.

THE PROMISE OF ALGAE ENERGY SYSTEMS

Aquatic (algae) energy systems have the unique potential to address all five of the interdependent challenges facing the United States today. They can domestically-produce renewable transportation fuels and recycle carbon and do so in a way that is potentially affordable, environmentally-sustainable, and does not interfere with food supplies.

Although there is no single answer to reduce atmospheric carbon levels or end our dependence on foreign oil, aquatic-based algal energy systems represent a possible partial solution to both challenges. Growing algae, the most productive of all photosynthetic life, and converting it into plastics, fuels and or secondary feedstocks, could significantly help mitigate greenhouse gas emissions, reduce energy price shocks, reclaim wastewater, conserve fresh water (in some scenarios), lower food prices, reduce the transfer of U.S. wealth to other nations, and spur regional economic development (Figure 5).

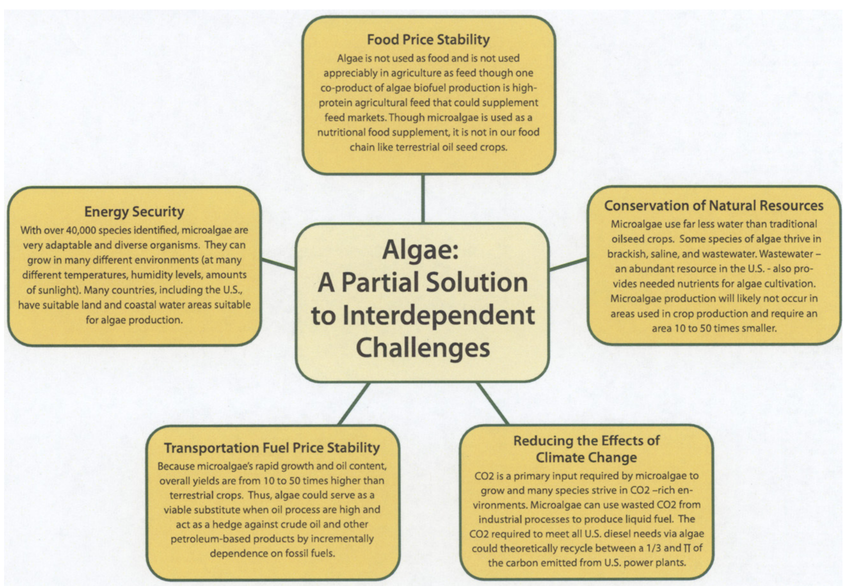

FIGURE 5.—*Algae: A Partial Solution to Interdependent Challenges*

Because of its high lipid (i.e., oil) content, affinity for and tolerance of high concentrations of CO_2, and photosynthetic efficiency, algae cultivation results in higher areal yields and liquid fuels with a higher energy density than alternatives, see Table 1 and Figure 6, respectively.

TABLE 1.—COMPARISON OF OIL YIELDS FROM VARIOUS FEEDSTOCKS

Crop	Oil yield Gallons/Acre
Corn	18
Cotton	35
Soybean	48
Mustard Seed	61
Sunflower	102
Rapeseed/Canola	127
Jatropha	202
Oil Palm	635
Algae (10g/m ^{2}/day at 15 percent TAG)	1,200
Algae (50g/m ^{2}/day at 50 percent TAG)	10,000

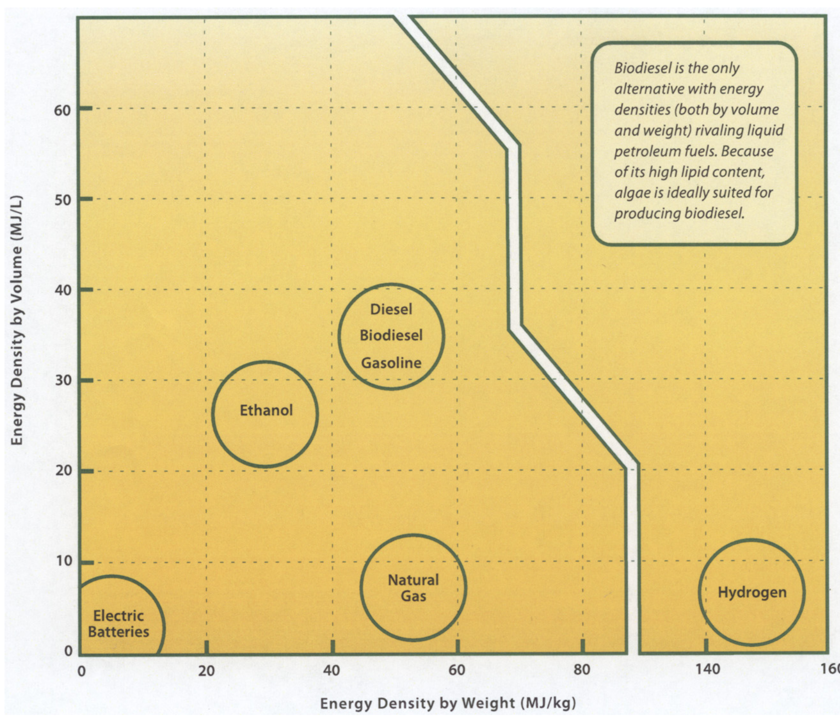

FIGURE 6.—*Energy Density of Current and Future Transportation Fuels*

For example, Figure 7 shows the extent to which soybeans are planted each year across the United States. If all the soybeans grown and harvested in the United States each year were converted into biodiesel, the resultant fuel supply would accommodate less than 10 percent of our annual diesel fuel consumption. Conversely, if an area roughly equating to one-tenth the land area of Utah were developed into algal energy systems, algae could supply all of America's diesel fuel needs. Thus, algae are an ideal feedstock for replacing petroleum-based diesel and jet-fuel, which have a combined U.S. market approaching 100 billion gallons per year.

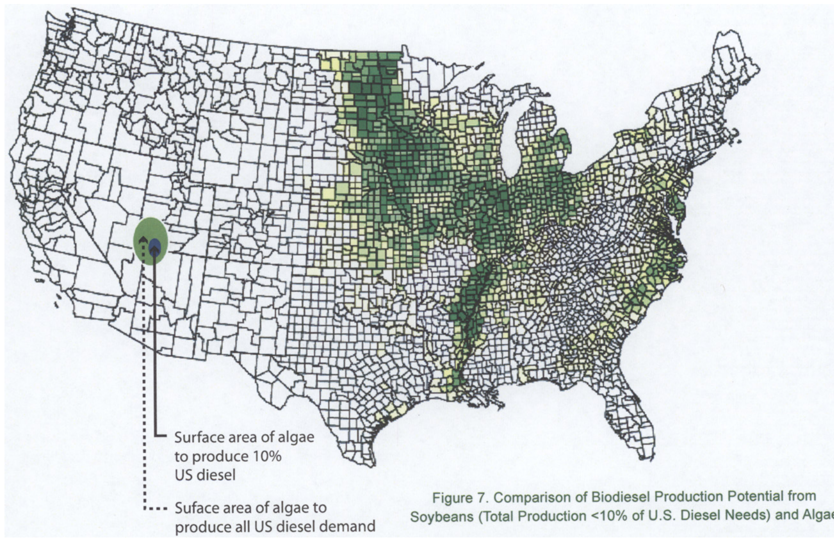

Figure 7. Comparison of Biodiesel Production Potential from Soybeans (Total Production <10% of U.S. Diesel Needs) and Algae

Likewise, because algal cultivation systems do not need fertile soil or rainfall, they can be sited virtually anywhere that five fundamental inputs (Figure 8) are present or can be transported. Since some algae and cyanobacteria species have a high affinity for CO_2, siting algal energy systems near centralized CO_2 emitters is a very attractive option. Research has demonstrated that algal yields can be improved dramatically using enhanced concentrations of CO_2.

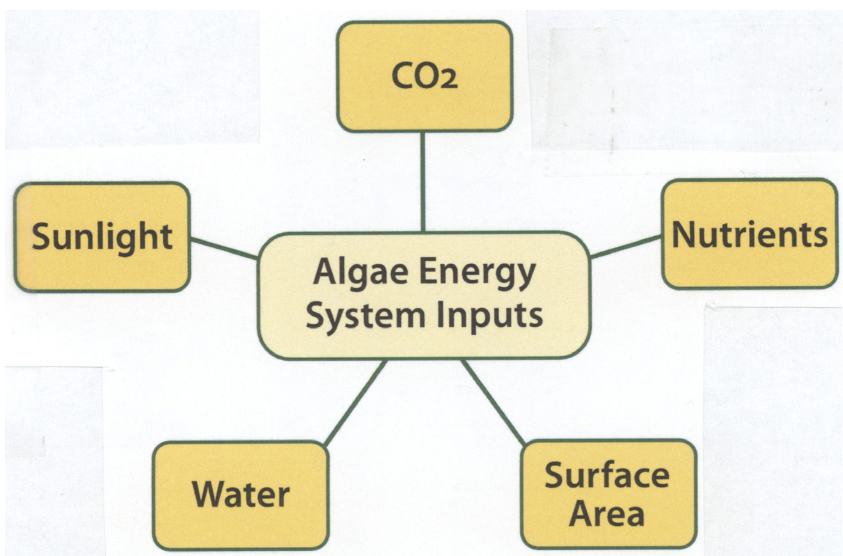

FIGURE 8.—*Algae Energy System Inputs*

Prior Research

Algal energy systems is not a new research topic. In the 1940s and 1950s, SRI International and MIT conducted some of the first research on algae mass culture, cultivation, and biofuel production. Soon after, research at U.C. Berkeley targeted the use of algae for wastewater treatment and methane production. In the 1980s, researchers in the Soviet Union developed large photobioreactors to grow algae for animal feed.

From 1991–1998, the U.S. Department of Energy supported a comprehensive study of algae as a potential biodiesel feedstock through its Aquatic Species Program (ASP).[34] Though the chemistry of algal oils was adequate for biodiesel production at the time [34] [35] [36] major problems remained with growing and harvesting algal biomass.[34] ASP feasibility studies of large-scale algae production proved the concept of long-term, sustainable production of algae, together with the twin environmental benefits of (1) extremely efficient utilization of CO_2 [34] [36] and (2) efficient wastewater treatment.[36]

The ASP studied a specific aspect of algae: their ability to produce natural oils or triglycerides. Researchers not only concerned themselves with finding algae that produced a lot of oil, but also species that could grow under severe conditions (i.e., extremes of temperature, pH and salinity). At the outset of the program, no collections existed that either emphasized or characterized algae in terms of these constraints. ASP researchers set out to build such a collection. Algae were collected from sites in the west, the northwest and the southeastern regions of the continental United States, as well as Hawaii. At its peak, the collection contained over 3,000 strains of organisms that were screened using the Nile Red method.[37]

After screening, isolation and characterization, the collection was reduced to approximately 300 species (mostly green algae and diatoms) based on algal yield and Nile Red response. The collection, housed at the University of Hawaii, is still available to researchers and remains an untapped resource, both in terms of the unique organisms available and the genetic resources they represent.

Prior to the ASP, minimal research had been performed to improve oil production in algal organisms. Much of the program's research focused on finding the elusive "lipid trigger". This trigger refers to the observation that, under environmental stress, many microalgae appeared to "flip a switch" to turn on production of triacylglycerol compounds (algal oil or TAG). Nutrient deficiency was the major factor studied (along with studies of silicon deficiency in diatoms) but the work did not expose overwhelming evidence in support of this trigger theory. In fact, some of the ASP research suggested that the trigger did not exist.

The common thread among ASP studies was a trend showing increased oil production under stress concurrent with the cessation or slowing of cell division. One study reported that preventing cell division by inhibiting the tricarboxylic acid cycle increased TAG yield ten-fold.[38] [39] [40] This led to the hypothesis that TAG accumulation was the result of synthesis minus utilization. Algae with a nutrient starvation controlled cell-cycle did not show an increase in overall production of oil. In fact, overall rates of oil production were shown to be lower during periods of nutrient deficiency.

Another focus of the ASP included initial breakthroughs in molecular biology and genetics engineering.[34]

The program was the first to isolate the enzyme Acetyl CoA Carboxylase (ACCase) from a diatom. This enzyme catalyzes a key metabolic step in the synthesis of oils in algae. The gene that encodes for the production of ACCase was eventually isolated and cloned. This was the first report of the cloning of the full sequence of the ACCase gene in any photosynthetic organism. Researchers went on to develop and patent the first successful transformation system for diatoms—the tools and genetic components for expressing a foreign gene.[34]

In later years, ASP researchers initiated the first experiments in metabolic engineering as a means of increasing oil production. They demonstrated an ability to make algae over-express the ACCase gene with the hope that increasing the level of ACCase activity in the cells would lead to higher oil production. These early experiments, however, did not demonstrate increased oil production.[34]

Efforts were also made to demonstrate feasibility of large-scale algae production in open ponds. In studies conducted in California, Hawaii and New Mexico, the ASP

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[35] Chisti Y. Biodiesel from microalgae. Biotechnol Adv 2007;25:294–306.

[36] Benemann JR. Biofixation of CO_2 and greenhouse gas abatement with microalgae—technology roadmap. NREL Subcontract report 701000426. 2003.

[37] Cooksey KE, Guckert JB, Williams SA, Callis PR. Fluorometric determination of the neutral lipid content of microalgal cells using Nile Red. J.Microbiological Methods. 1987; 6:333–345.

[38] Thomas RM, Triglyceride accumulation and the cell cycle in Chlorella [Thesis]. Montana State University; 1990.

[39] Guckert JB, Cooksey KE, Jackson LL. Lipid solvent Systems are not equivalent for analysis of lipid classes in the microeukaryotic green alga, Chlorella. J. of Microbiological Methods. 1989;8:139–149.

[40] Cooksey, KE. Acetae metabolism by whole cells of Phaeodactylum tricornutum Bohlin. J. Phucol. 1974;10:253–257.

demonstrated the long term, reliable production of algae.[33] Based on results from 6 years of tests run in parallel in California and Hawaii, 1,000-m^2 pond systems were built and tested in Roswell, New Mexico. The Roswell tests proved that outdoor ponds could operate with extremely high efficacy of CO_2 utilization. Careful control of pH and other physical conditions for introducing CO_2 into the ponds allowed greater than 90 percent utilization of injected CO_2. The Roswell test site successfully completed a full year of operation with reasonable control of the algae species grown. Single day productivities reported over the course of 1 year were as high as 50 g/m^2/day. Attempts to achieve consistently high productivities were hampered by low temperatures encountered at the site. Desert conditions of New Mexico provided ample sunlight, but temperatures regularly reached low levels at night. If such locations will be considered, some form of temperature control with enclosure of the ponds may be required.

In Japan, a nation-wide algae-based carbon sequestration R&D effort was also launched during the 1990s. The program was organized by Research for Innovative Technologies of the Earth (RITE) under the Ministry of Economy, Trade and Industry (METI). It involved more than 30 major industrial partners and several major public universities with a total funding of over $250 million. The RITE program partially addressed a number of R&D challenges including: (1) algae strain selection and characterization, (2) photobioreactor design and optimization, (3) mass cultivation of algae supplied with CO_2-rich synthetic or real flue gases from power plants, and (4) the development of value-added co-by-products from the algal carbon recycling processes. Unfortunately, the research focused heavily on one particular photobioreactor design that ultimately proved infeasible.

Recent Research

In the United States, algae-based research related to carbon recycling restarted in 2000 when Ohio University researchers developed a technique to control the emissions of CO_2 from fossil-fired power plants by growing organisms on reactor-enclosed biofilms: A thermophilic mesophilic organism was examined with respect to its ability to recycle CO_2 from scrubbed stack gases and cyanobacteria was grown on fixed surfaces to facilitate algal stability and improve light distribution.[41] Growth-rates of 50 g/m^2/day were reported, but the lipid content was lower than the rates reported by eukaryote algae grown in aqueous solutions.

In 2003, a roadmap outlining short- and mid-term R&D needs for carbon dioxide abatement using microalgae was prepared and issued by John Benemann on behalf of the International Network for Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae, a group formed under the auspices of the International Energy Agency (IEA).[42]

The roadmap emphasized the use of open pond algae production in combination with municipal- and agricultural-waste treatment facilities. In such combined systems, algae would be used to accomplish wastewater treatment to help subsidize the cost of carbon utilization and algae growth. It also emphasized the need for generation of co-products including fuel, fertilizer and animal feed to add value to algal energy systems and provide outlets that could partially displace use of fossil sources for these commodities. The use of enclosed photobioreactors was considered as a viable option only for small-scale growth (e.g., for the production of inoculum for larger-scale open systems).

More recently, research and development has begun at several dozen universities and private companies with total Federal, State, and private investments in excess of $300 million in 2008–2009. In industry, for example, Arizona Public Service began a DOE/NETL-funded project to demonstrate CO_2 capture by algae using a scalable bioreactor integrated with a power plant.

APS's planned an algal biofuel production system that will use modular photobioreactors, algae harvesting systems for dewatering and oil extraction, inoculation systems, water/nutrient management, flue gas/CO_2 management, and instrumentation and controls.

In academia, for example, the State of Utah is investing over $6.5 million over 5 years in research at Utah State University on algal energy systems.

[41] Bayless DJ, Kremer G, Vis M, Stuart B, Prudich M, Cooksey K, Muhs J. Enhanced Practical Photosynthetic CO_2 Mitigation. Third Annual Conf on Carbon Capture & Sequestration. 2004:173. Available from: http://www.netl.doe.gov/publications/proceedings/04/carbon-seq/173.pdf.

[42] Benemann J, Pedroni PM, Davison J, Beckert H, Bergman P. Technology Roadmap for Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae. Second Annual Conf on Carbon Capture & Sequestration. 2003. Available from: http://www.netl.doe.gov/publications/proceedings/03/carbon-seq/PDFs/017.pdf.

Likewise, the Department of Defense has accelerated investment in algal RD&D. The Defense Advanced Research Projects Agency (DARPA) recently awarded two large contracts aimed at developing and fielding large-scale production facilities with aggressive biofuel production price targets by 2011. The Defense Energy Support Center recently certified an algal oil-based biodiesel and demonstrated a Ford F450 driven solely from algal feedstock. Boeing Corporation has teamed with multiple engine suppliers on similar lab and flight tests using algae-derived jet fuel.

Clearly, the promise of algal energy systems is becoming evident with growing energy, land, water, and carbon concerns over first- and second-generation biofuels; aggressive renewable fuel standards; growing acceptance of peak oil; and the oil price shocks of 2008. These factors have moved algae energy systems to the forefront of energy research.

Nevertheless, as noted by National Geographic: "[T]here is no magic bullet fuel crop that can solve our energy woes without harming the environment, says virtually every scientist studying the issue. But most say that algae . . . comes closer than any other plant . . .".[43]

ALGAE ENERGY SYSTEMS—CHALLENGES AND R&D NEEDS

Though intermittent investments and progress has been made in recent decades, the potential of algal energy systems has yet to be fully realized. Unlike terrestrial crops cultivated and harvested for centuries, recycling carbon through industrial or agricultural algal energy systems that simultaneously produce biofuels is a relatively new concept.

In open algal cultivation systems, a large quantity of land and a large volume of water (that must be replenished) are required. Energy from outside sources is needed to keep algae cultures stable, healthy and suspended in their solution and invasive species, which often infiltrate cultivation raceways and lower or destroy the desired cultures, must be controlled.

In most enclosed cultivation topologies, capital costs for materials and equipment associated with containing, mixing, controlling, and maintaining cultures are prohibitive. In both open and closed systems, nutrients and CO_2 must be delivered and introduced into the growth environment. Likewise, photosynthetic saturation and surface shading limit the amount of sunlight that can be used constructively to produce biomass.

After cultivation, the algae must be dewatered and dried prior to oil extraction and fuel production. In each step along the way, significant energy is required for processing. There are also remaining questions regarding the emission of certain criteria pollutants and the compatibility of resultant fuels with existing energy distribution/storage infrastructure, engine systems, and extreme operating environments. Generally, the challenges and R&D pathways associated with algal energy systems can be divided into three subsystems each having a number of issues that must be addressed before commercial-viability is realized (Figure 9).

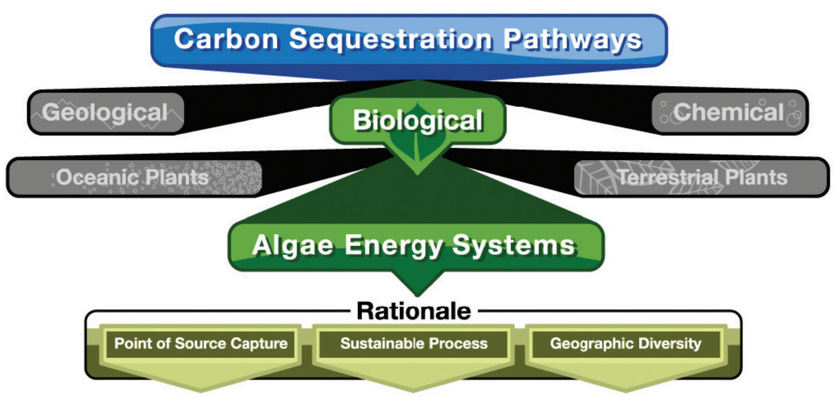

FIGURE 9.—*Three Rationales for Algae Energy Systems*

[43] Feature Article: Biofuels. National Geographic. April 2009. Available from: http://ngm.nationalgeographic.com/2007/10/biofuels/biofuels-text/6.

Upstream Challenges & R&D Needs

To overcome upstream challenges, there are a number of CO_2 and nutrient-related issues that must be addressed.

CO_2 Quality and Delivery

For microalgal processes to be considered as practical methods for CO_2 mitigation, the costs of separating, compressing, treating and delivering the CO_2 must be reduced. Ideally, CO_2 could be used directly from an emissions source. Unfortunately, that may be impractical. CO_2 from a combustion source is usually delivered at extremely low pressures and cannot be sparged through any depth of water without compression. Further, combustion flue gas contains numerous pollutants that would not be permitted for wide-spread direct contact and dispersion at ground level, including but not limited to mercury, particulate, sulfur dioxide, nitrogen-oxides, and heavy metals (notably arsenic and selenium).

The vast majority of CO_2 in enhanced gas streams (typically >4 percent by volume) is found in combustion sources. It is also potentially the lowest cost source of CO_2, even lower than air, as future carbon restrictions may give non-trivial value to removing CO_2 from combustion gases. However, unless low-pressure drop bioreactors are used that can return the remaining flue gas and products of photosynthesis to the stack for atmospheric dispersion; the options for using direct flue gas become limited. Such options include using separated enhanced mass transfer reactors in the flue gas train to put carbon species in the aqueous phase for transport to a microalgal growth facility.

Separated and pressurized CO_2 from combustion sources may or may not be available at low-cost in the distant future, as plans are being considered for a supercritical CO_2 pipeline network. This pipeline is being proposed to facilitate large-scale geological sequestration of CO_2 though such a network would not be ready for operation until 2020. We envision the same CO_2 piping and distribution schemes could assist the deployment of distributed rural algae farms far from urban sources of CO_2.

Further, the current cost of CO_2 liquefaction would make its use cost prohibitive under almost any circumstance. Making such sources viable for interfacing with microalgal growth facilities will require new research focused on gas cleanup, enhanced aqueous phase mass transfer, and/or development of low-pressure drop growth chambers where CO_2 gases could be easily recovered and dispersed from stacks.

CO_2 Sources

Since CO_2 is a major contributor to the cost of algal mass cultivation, the CO_2 from flue gas is being explored as a viable option to reduce cost and achieve economic-viability. In addition to CO_2 utilization, algae can utilize NO_X and SO_X, reducing overall plant costs by bypassing scrubber requirements. A syngas-fed open pond can result in a 4- to 10-fold increase of algal biomass yields.

Though commercially-viable biofuels can be produced while recycling CO_2, NO_X and SO_X from flue gas, several research challenges remain. For example, pipelines have been negatively influenced by the interaction of SO_X with industrial-grade steel joints and pipes. Further, a mismatch of volumes and rates of CO_2 exhaust exists between large industrial coal-powered operations and gas fixation through slower, lower throughput processes involving algae. To address flue gas integration issues, R&D is needed to address mass transfer limitations (balancing CO_2 supply with algae growth at minimum system pH disruption), CO_2 purity requirements for algae growth, and analysis of the viability (technical and regulatory) of ground-level sparging of CO_2 or flue gas into the algal growth media (whether for pond-raceway or bioreactor application).

Another source of CO_2 is biorefineries used to convert sugars into ethanol and other commodity products: A process made less cost-effective because of the release of fixed carbon in form of CO_2 (e.g., for C6 sugar, carbon losses are 30 percent). Thus, recycling and utilizing carbon released via CO_2 will increase process efficacy. Capturing and recycling of the CO_2 off-gas has been discussed in scientific literature, but practical solutions are still applied on a limited scale and often involve collection of CO_2 by chemical absorption for pulp and paper, and food and beverage manufacturing (e.g., low-value product).

Fortunately, the volumes and rates of CO_2 production by the biological process of fermentation at biorefineries are more closely matched to the rates of biomass production by algae. But integrating algae energy systems with biorefineries is limited by site-specific spatial and climate constraints. For example, past use of circular ponds resulted in adequate biomass productivity and captured up to 90 percent of the CO_2, but required more space and was susceptible to contamination and loss of productivity due to overgrowth and harvesting problems. Closed bioreactors required less space, were well suited for the growth of uncontaminated cultures, and allowed easier harvesting; however, light limitations and temperature fluctuations effected their productivity.

Analysis of these data and application of conventional agricultural practices to biotechnological processes led the ASP to believe that cultivation productivity could be optimized regionally through rotation of cultures because algae differ in their illumination and temperature requirements. For example, cyanobacterial productivity is higher at 2000–3000 lux and 30° C, whereas productivity of green algae are optimal at 200–300 lux and 26° C. Therefore, R&D on proper selection of cultivation system design and optimal crop rotation schemes are needed to optimize the productivity of each system.

Nutrient Sources

Algae, like any other living organism, require nutrients to sustain, grow and thrive. They require the same nutrients as terrestrial plants (e.g., nitrogen, phosphorus, potassium and trace amounts of iron and other metals, and other fertilizers). In nature, these nutrients are readily available via biomass decomposition and are stored in aqueous form in bodies of water. However, large-scale, land- or ocean-surface based algal production facilities will likely need to replenish these nutrients at rates exceeding the naturally occurring levels. As man-made fertilizers are increasingly used for large-scale algal production, the need for low-cost nutrient supplies will drive further research.

Agricultural wastes provide a readily available source for low-cost nutrients. By processing nutrient-rich retention ponds and waste lagoons at concentrated animal feed operations, algae can be grown at rates needed to achieve economic viability with the benefit of significantly reducing water contamination from animal waste. Similarly, other agricultural and lawn-based fertilizer runoff into wetlands and streams also provides a source for algal nutrients, which, if used, could minimize the uncontrolled algal blooms that have damaged ecosystems in such places as the Gulf of Mexico and the Chesapeake Bay. Therefore, significant research must be conducted to provide stable, conditioned, and low-cost nutrient supplies to future algal production facilities. Site-specific controls must be developed and implemented to monitor and control key inputs to cultivation systems. Establishing reliable nutrient sources for mass-algae production will require R&D for the development and production of other lower-value phototrophs as a feed source, which supports wastewater treatment, and the cultivation of strains requiring lower nutrient input.

Cultivation Challenges & R&D Needs

In addition to overcoming upstream subsystem challenges, there are a number of biological, geographical, environmental, and site-specific issues that influence algae cultivation.

Organism Selection

With over 40,000 species, algae and cyanobacteria exist in many forms that can be optimized to grow under specific conditions to yield desired products. These organisms evolve naturally and can be engineered to meet specific goals. Harnessing the power of these organisms to convert CO_2 into useful products is commercially practiced for the production of neutraceuticals and other valuable goods. The production of transportation fuel, which is a relatively high-volume, low-value product, will require additional research and development to identify or create robust organisms that grow and accumulate lipids rapidly under diverse environmental conditions. It is unlikely that the ideal production organism has been identitified, thus bioprospecting is still a valuable approach.

The creation of modified microorganisms that produce valuable commercial products previously derived from petroleum is well established. For example, Genencor and DuPont received the U.S. Environmental Protection Agency's 2003 Presidential Green Chemistry Award for the development of a process to make 1,3 propanediol (PDO) from renewable resources instead of petrochemicals. The process uses a strain of Escherichia coli that was engineered to produce (PDO) from glucose.

Despite some commercial successes, basic research is still needed to improve the process of creating synthetic microorganisms. Genetic modifications are inherently unstable due to the metabolic costs and toxicities associated with the products produced as a result of the modifications. Many engineered microbes lose their ability to generate product within 1 day of growth unless the modifications are maintained with expensive antibiotics. Research to develop general methods and principles for stabilizing genetic modifications is critical to advancing the practice of metabolic engineering and using this tool to capture carbon more effectively. Further, the production of materials by microbial biotechnology requires a deeper understanding of the biochemistry involved at both the physiological and/or genetic levels. It is most important to understand the associated regulatory constraints.

The production of triacylglycerides (TAG) as a precursor of biodiesel or biojet fuel will be no different. There is a paucity of information on algae in general and almost none on algae poised to be considered as production organisms. Thus, further research is needed to strengthen our understanding of algae.

Growth Systems

Although a discussion of all algae cultivation techniques is beyond the scope of this document, two primary architectures for cultivating algae exist: open ponds and enclosed reactors.

Open ponds most closely resemble microalgae's natural environment and are relatively inexpensive to build and operate (Figure 10). These ponds, however, possess significant drawbacks, including low algae production on surface areas, inability to strictly control the algae environment, water evaporation, low volumetric cell densities, and the risk of contamination by predator strains.

FIGURE 10.—*Open Algal Cultivation System*

In open raceways, algae are typically suspended at cell densities of less than 2 grams per liter of aqueous solution. Unfortunately, low-cell density cultures require extensive energy to keep algae properly suspended, healthy, and well-mixed. Some estimates report that over one-half of the energy needed during the cultivation process in open ponds can be attributed to mixing and maintaining algae in suspension.[37]

For these reasons, considerable research is now aimed at devising low-cost enclosed systems (Figure 11). Relative to open ponds, photobioreactors possess a lower risk of contamination, the ability to better control and regulate nearly all of the important process parameters, a reduced risk of losing CO_2 or water to evaporation, higher reproducibility, greater productivity (which reduces land requirement), and reduced harvesting costs (due to the higher cell densities achieved).

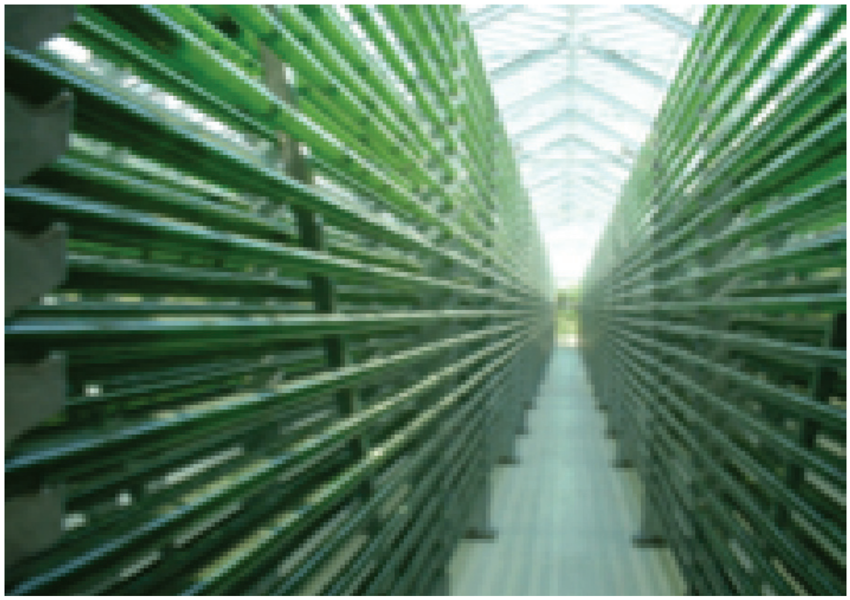

FIGURE 11.—*Closed Algal Cultivation System*

Conversely, the capital and operating costs associated with photobioreactor-based cultivation systems are significantly greater than those for open ponds. When operating at higher cell densities, costs associated with the following become issues: thermal management requirements, oxygen accumulation, mixing, and CO_2 management. Biofouling and deterioration of optical materials occur over time. Moreover, cell damage due to shear stress from rigorous mixing remains a concern.

Regardless of the cultivation system approach, there are 10 published essential operational imperatives for successful deployment of algae energy systems (Table 2).

TABLE 2.—THE TEN ESSENTIALS FOR ALGAE ENERGY SYSTEMS—A2BC CARBON CAPTURE

ALGAE ENERGY SYSTEMS HAVE THE POTENTIAL TO BECOME ONE OF THE PLANET'S LARGEST INDUSTRIES. FOR THIS INDUSTRY TO BE SUCCESSFUL, CORE TECHNOLOGIES MUST FULFILL 10 ESSENTIAL REQUIREMENTS

Flexibility in Cultivation and Harvesting.—High algal product value requires precise control of cultivation parameters to support diverse crop species and varying harvesting protocols. Advanced algae variety development will be paralleled by the evolution of process pathogens and consumptive invaders. Control and flexibility in the growth environment and harvesting is critical.

Long Term Biologic Stability.—High productivity, profitability, and industrial relevance require uninterrupted PBR operation over periods of 1 year or more. Threats of bacteriological infection, virus infection, weed algae invasion, and rotifer population explosions must be sustainably managed in order to provide industrial reliability energy and food source technology.

Efficient Temperature Control.—Broad global deployment requires high efficiency utilization of water and energy to control algae farm temperatures. Algal photosynthesis captures at most only 5 percent to 10 percent of the solar energy spectrum. Accordingly, all energy and water expended in heating or cooling PBRs will greatly impact the overall energy and water balance.

Functionally Unlimited Scalability.—Algae industry infrastructure construction and operations must be viable at any scale using only sustainable and abundant global resources. Once the algae industry is set in motion via the engine of commerce it will be difficult to stop, making it essential that this growth expansion occurs in a planet-healthy and sustainable fashion.

High Areal Light Productivity.—High algal biomass productivity per square meter of sunlight is required to minimize land area thereby controlling high technology infrastructure costs. High technology infrastructure elements are required to maximize the productive growing season, crop value, and industrial reliability that will be required for algae farms to propagate.

Frequent Cellular Re-Suspension.—During cultivation the entire algal cell population must be kept in fluid suspension to provide each cell sufficient access to nutrients and light so that a state of generalized maximum productive health is maintained. Periodic re-suspension of settled pockets of stranded cells is required to prevent cell death, bacterial growth and PBR crashes.

Frequent Biofilm Management.—Biofilms are readily deposited on the light transmission and containment surfaces of all PBRs. Sustainable management of biofilms is required to maximize light transmission efficiency and minimize deleterious bacteriological infections. Biofilms can provide synergistic benefits and extra biomass productivity when well managed.

Efficient Gas and Nutrient Management.—Every kg of algal biomass produced will require more than two kg of CO_2 and plant nutrients to be fed into the algae PBRs. Energy consumption must be minimized in handling these quantities of CO_2; and especially using flue gas. Sustainable sources and process recycling strategies for the vast quantities of nutrients are mandatory.

Industrial Reliability.—The algae industry must work in tandem with upstream and downstream industry partners to convert constant process flows of CO_2 into feedstocks, refine them into products and distribute them to waiting markets. There is no room for unreliability or disruption due to weather, infection, regulation, terrorism, or scalability challenges.

Politically Deployable.—There is no more fundamental requirement for an algae technology than to be politically deployable on a massive industrial scale providing broad local benefits. Deployment and operational plans must withstand the muster of planning boards, regulatory agencies, funding agencies, lending banks, and environmental interests.

Water Use Issues During Cultivation

Of all the issues facing aquatic algae cultivation, adequately addressing water issues may represent the biggest challenge of all in open cultivation systems. Simply put, aquatic species need water to grow. While the consumption of water by phototropic organisms is essential for growth, it is usually less than the amount of water lost through evaporation in open raceway cultivation systems.

This problem is exacerbated by the fact that phototrophic organisms need sunlight for photosynthesis. Generally speaking, the more sunlight available, the more algae produced. However, as the average solar insolation increases, so does evaporative losses in open systems. Unfortunately, areas with high solar insolation (e.g., southwestern United States) are typically plagued by a shortage of fresh water.

The lack of fresh water can be overcome by growing algae which is native to salt water, brackish, or wastewater. For example, transported ocean water could provide the basis for large-scale algal ponds in the American West. However, because the rates of water evaporation are significant, a supply of fresh (or very low salinity) water remains critical. Because salt remains in the ponds as water evaporates, addition of more saline water would lead to an increase in salinity levels, endangering algae, or reducing their productivity. Further, salt-water intrusion could lead to adverse effects on the quality of surface and ground water. While these problems are surmountable, they represent an engineering and biological challenge for future large-scale algal production. Solutions could come from development of algae strains capable of living in hyper saline waters (note, research has already begun) or through the development of low-cost partial desalination processes (e.g., membrane filtration).

Most experts also believe that early algal production facilities will depend heavily on wastewater reuse both for nutrients and to conserve/reclaim fresh water (discussed earlier). Regions with less solar insolation and more fresh water could find economically competitive niches in algae production alongside regions with abundant sunlight and limited fresh water. Ultimately, the issue of water will force developers to evaluate trade-offs between:

—The cost of supplying of suitable water vs. the availability of other cultivation inputs (e.g., nutrients, CO_2, and sunlight); and

—Low-cost open cultivation systems that rely on passive thermal management through evaporative cooling vs. more expensive closed bioreactors that conserve water but require, for example, active thermal management.

While no one knows how these issues will be resolved, the development of regional strategies leading to a national network of distributed algal production facilities seems likely. To reduce water consumption, it is also imperative that research continue on pathways to improve volumetric yield (i.e., grams of algae harvested per liter of aqueous solution). As volumetric yield increases, the amount of water needed to produce the same amount of biomass decreases. Unfortunately, surface-shading increases as cell density increases so inexpensive methods to dilute sunlight spatially over a larger surface area also must be developed.

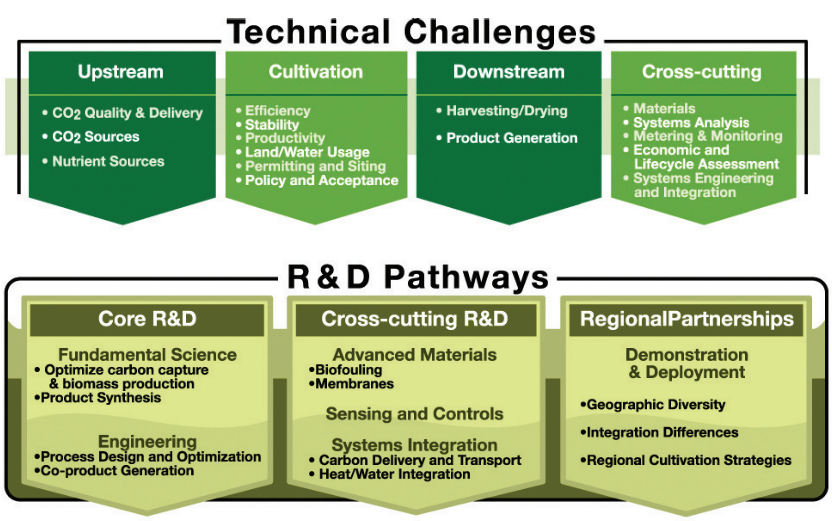

FIGURE 12.—*Technical Challenges on R&D Pathways for Cost-effective Algae Energy Systems*

Land Use Issues

The amount of land available for siting algae energy system projects represents a significant challenge. Though algae grow extremely fast in comparison to higher plants and, therefore, require far less area to grow an equivalent amount of biomass, to overall conversion efficiency of sunlight to biomass remains relatively low (typically less than 4 percent).

Table 3 provides a first-order estimate of the amount of surface area required to recycle carbon from various point source and distributed carbon emitters. The data does not take into consideration externalities such as the area needed for roads and processing equipment and assumes optimistic algae yields of ~40 g/m2/day (dry weight) and ~50 percent of the biomass as carbon.

TABLE 3.—SURFACE AREA EQUIVALENT REQUIRED TO RECYCLE CARBON FROM VARIOUS POINT SOURCE AND DESTRIBUTED CARBON EMITTERS

Carbon Emitter	Approximate Area Required	Rough Area Equivalent
Ethanol plant (50 million gal/yr)	100 acres	⅓ of the National Mall
Typical industry boiler	800 acres	2 National Malls
Power plant (500 MWe)	35,000 acres	Washington, DC
U.S. diesel vehicle fleet	5,000,000 acres	1⁄10 of North Dakota or Utah
U.S. coal power plants	22,000,000 acres	Indiana or Maine (1⁄100 of the U.S.)

From these estimates, it is clear that large-scale algal energy systems, though dramatically less area-intensive than oilseed crops such as soybeans (Figure 7), will require significant amounts of land. When sited near point source emitters (e.g., ethanol plants or industrial boilers), nearby land must be relatively flat (less than a 2 percent slope) to avoid cost-prohibitive site preparation. Large areas covered with open ponds or enclosed photobioreactors will inevitably disrupt the natural habitat of native wildlife (discussed in section V.B.5). For these reasons, significant research is needed to develop both biological and engineering pathways to improve area yield.

In coastal regions of the United States and Europe, land use issues have driven some of the research community to contemplate ocean-deployed enclosed cultivation systems where unused areas of ocean are readily available, seawater is both abundant and provides thermal stability, and natural wave action that can be used to aid in mixing. Though the challenges differ from land-based architectures, ocean-based systems have a host of biological, engineering and environmental challenges that must be addressed (e.g., new problems related to ocean wildlife impacts, cultivation, harvesting, and processing infrastructure, access, shipping, durability, and control).

Wildlife Impact Issues

In recent years, there has been increasing interest in siting large, industrial-scale renewable electric generation facilities similar in size and scope to those envisioned in the western United States for algal energy systems. As a result, the Western Governors' Association (WGA) and U.S. Department of Energy initiated the Western Renewable Energy Zones (WREZ) initiative in 2008. The WREZ initiative is designed to identify areas in the West with significant renewable resources to accelerate the development of renewable energy. One of the renewable technologies included in the study is large-scale solar thermal electric generation systems. Though there are several differences, this technology has many of the same needs as algal energy systems requiring large-tracts of accessible flat land with significant solar insolation.

In parallel to the WREZ process, WGA also established the Western Governors' Wildlife Council (WGWC) to manage the implementation of the WGA Wildlife Corridors report. The mission of the WGWC is to "identify key wildlife corridors and crucial habitats in the West and coordinate implementation of needed policy options and tools to conserve those landscapes."

As the WREZ process unfolds, resolving inherent conflicts between wildlife corridors and renewable energy zones has emerged as arguably the biggest hurdle to Western U.S. renewable energy development. The same series of issues will need to be addressed in early deployment of algal energy systems.

Other Permitting, Policy and Acceptance Issues

Another major obstacle for algal growth systems, especially at large-scales, will be permitting issues. In addition to the environmental impact of the footprint needed for significant CO_2 mitigation and biofuel development, the issues of water quality, gaseous discharge, contamination of regional waterways by salt water, and invasive or genetically altered species, are all non-trivial considerations.

Efforts must be made to work with local, State and Federal officials to develop streamlined environmental impact assessments and permitting reviews. Action will be needed sooner, rather than later, because this is essentially uncharted territory for environmental protection boards and agencies. This suggests the need for aggressive actions to develop new regulatory and policy guidelines.

Efforts are already underway to incentivize development and integrate algae into the U.S. renewable fuels portfolio. For example, the Energy Independence and Security Act of 2007 added algae to the list of feedstocks qualifying as renewable biomass, which qualifies it to help meet Federal Renewable Fuel Standards. In the near future, standards organizations must begin developing certification and qualification processes so end-users can justify switching to algae-based fuels and co-products.

Downstream Challenges and R&D Needs

In addition to overcoming issues related to upstream and cultivation subsystems, there are a number of engineering challenges related to cost-effective downstream processing.

Harvesting/Drying

The isolation of algae from their culture medium is challenging for two main reasons: (1) their small size (typically 3–20 microns); and (2) the low concentrations in which they can be grown (typically less than 2 g algae/L water). A compounding problem is the sensitivity of the cell walls in many species to damage in high shear processes (e.g., centrifuging), which can result in leaching of the cell contents. To date, three main methods have been developed for algal isolation: filtration, centrifuging and flotation. Filtration is normally performed using a cellulose membrane and a vacuum being applied in order to draw the liquid through the filter.[44] Although this method is simple, the membrane tends to become clogged, rendering the process extremely time consuming. Centrifuging, in a continuous or semi-continuous process, appears to be more efficient in this regard; however, it is extremely energy intensive and cannot readily be scaled to very large applications. The third option, flotation, uses a bubble column. Gas is bubbled through the algae suspension, creating a froth of algae that can be skimmed off. Several variants of this process have been published.[45] [46] [47]

The extent to which the water content of the resulting algae paste must be reduced depends largely on the method used for the subsequent oil extraction step. Ideally, drying to ca. 50 percent water content is required in order to produce a solid material that can be easily handled. Given the fact that algae paste, as obtained by centrifuging or filtering, typically consists of ca. 90 percent water, drying algae is an energy intensive proposition. Consequently, solar drying is the main approach that has been considered to date.[48] Solar drying is used commercially for drying grains and timber, and is inherently inexpensive; however, drying large quantities of algae would necessitate the use of a considerable areas of land.

Considering the methods available for algae harvesting, it is clear that more research is needed in order to improve efficiency and to reduce the required energy input. Flocculation appears to be a promising alternative to the technologies described above, providing that the necessary flocculants are either very inexpensive or can be recycled. Rather than using solar energy for subsequent dewatering/drying of the algae, a better approach might be to develop processes that make use of low-grade waste heat from an existing CO_2 source (e.g., power plant).

Oil Extraction and Product Generation

Oil extraction from algae is a highly debated topic: Several methods exist and each has its advantages and drawbacks.[49] The three primary methods applied to date are (1) expeller/press, (2) solvent extraction, and (3) supercritical fluid extraction. The expeller/press method, while simple, requires dried algae and typically re-

[44] Clark WJ, Sigler WF. A method of concentrating phytoplankton samples using membrane filters. Limnol. Oceanogr. 1963;8:127–129.
[45] Guelcher SA, Kanel JS. U.S. Patent 5,776,349. 1998.
[46] Guelcher SA, Kanel JS. U.S. Patent 5,910,254. 1999.
[47] Borodyanski G, Konstantinov I. U.S. Patent 6,524,486. 2003.
[50] Kadam KL. Microalgae Production from Power Plant Flue Gas: Environmental Implications on a Life Cycle Basis. Department of Energy, National Renewable Energy Laboratory. NREL/TP–510–29417, 2001, Golden, CO.
[49] Oilgae Digest [Internet]. Copyright 2006 [cited April 2009]. Available from: http://www.oilgae.com/algae/oil/extract/extract.html.

covers ca. 70–75 percent of the oil. In contrast, solvent extraction is more complex but is able to recover nearly all the oil (>95 percent). If wet algae are used, then a water miscible co-solvent is necessary; this co-solvent is usually required in order to lyse the cells (i.e., open the cells to expose their contents), although other methods are available to do this (e.g., sonication or acidification). Finally, supercritical fluid extraction uses supercritical CO_2 as the extraction solvent. While this method is able to recover almost 100 percent of the oil, it requires high-pressure equipment.

Thus, the recovery of algae oil is an area where there is a pressing need for research. Solvent extraction appears to be the leading approach, given that it is suitable for use with wet algae. However, several of the literature methods use complex solvent mixtures and/or environmentally unfriendly chlorinated solvents, while overall there is a relative paucity of published data.[50] Complicating the situation is the fact that optimization of the extraction process will likely depend on a number of variables, such as the algal water content, and the ease with which the cells can be lysed (which is a function of the species of algae). The development of a generic set of principles that can assist in this optimization process is a pressing need.

As with vegetable oils and animal fats, options exist for the production of biofuels from algae oil: (1) transesterification with methanol to give to fatty acid methyl esters (biodiesel); and (2) conversion to hydrocarbon fuels (e.g., jet fuel or diesel). Transesterification is a well-established technology, while the catalytic conversion of triglycerides to hydrocarbons via hydrotreating has been recently commercialized.

In most scenarios, the solid recovered from the oil extraction process (algae cake) will be used either as animal feed, as a feedstock for fermentation to ethanol, or thermo-chemical conversion into other fuels. The ability to use the cake as feed will depend on its nutritional content and whether there is contamination by heavy metals (e.g., Hg and As). Further, the oil extraction process can effect the nutritional content: If the cells are lysed in the presence of water, there is the risk that a significant fraction of the nutrients in the cell will be leached into the aqueous waste phase and lost.

JP–8 military jet fuel (i.e., the military version of civilian-grade Jet A–1 turbine-engine fuel) can be produced from the algae oil. Algae can also be cultivated to serve many other commercial products including: (1) Animal feed, (2) bioplastics, (3) paints, dyes and colorants, (4) lubricants, (5) cosmetics, (6) neutraceuticals, and (7) pharmaceuticals. Aside from co-products, algal carbon recycling processes will likely find increased use in co-located pollution control applications (e.g., fertilizer runoff reclamation and sewage treatment).

Thus, in the area of algal oil processing to fuels, the main research requirements concern the production of hydrocarbon fuels. Research needs include the optimization of catalysts for hydrotreating algal oil, and the development of processes that do not require hydrogen (e.g., those based on cracking or hydrolysis to fatty acids followed by decarboxylation). These latter processes have the advantage of being amenable to on-site oil processing. Simultaneously, if the algae cake is to be used as animal feed, research will be required in order to ascertain the extent to which algal bio-accumulate heavy metals present in flue gas (e.g., from coal-fired power plants) and, if possible, identify species which show little or no tendency towards bioaccumulation. There are also challenges and research needs related to ensuring compatibility of resultant fuels with existing energy distribution/storage infrastructures, engine systems, and extreme operating environments.

Cross Cutting Technical Challenges & R&D Needs

Materials

As with any large-scale technological development effort, advanced coatings and materials are needed to improve various component- and process-level functions. In certain cultivation systems, new polymers that enable the creation of super-hydrophobic coatings capable of reducing hydrodynamic drag and cleaning requirements are needed, as are low-cost, spectrally selective thin films used to reject infrared and ultraviolet solar radiation. In some cultivating environments, new optical components should be considered (e.g., planar waveguides) to improve areal and volumetric yield through enhanced sunlight distribution and utilization.

In downstream processing systems, new materials and coatings will be necessary to address compatibility issues with energy distribution/storage infrastructures, engine systems, and extreme operating environments.

[50] Guckert JB, Cooksey KE, Jackson LL. Lipid solvent Systems are not equivalent for analysis of lipid classes in the microeukaryotic green alga, Chlorella. J. of Microbiological Methods, 1989;8:139–149.

Process Control and Monitoring

There are a number of complex challenges related to process control and monitoring of subsystems and at the interfaces between each subsystem. Similar to other industries, this will require the development optimization of a wide variety of pumps, mixing apparatus, thermal management systems, new instrumentation, control systems, and process algorithms.

Systems Engineering and Integration

There are two primary-systems integration issues related to algal energy systems. The first is within the algal cultivation facility itself where integration of such elements as sunlight transmission systems, nutrient delivery systems, harvesting systems and pH management systems is needed. This is complicated by higher-level system integration issues (i.e., the cultivation system coupling with a CO_2 source and the integration of the microalgal growth facility with downstream use/processing systems). For example, an algal-based system could be used to recycle the CO_2 emitted from a coal-to-liquids plant that, in turn, uses the residue from the algae as a gasification feedstock (with the coal) to produce liquid transportation fuels. Another example would be to use algal energy systems to recycle CO_2 from bio-digesters, use nutrient-rich digester sludge to fertilize algae, and use the waste matter, after processing high-value products from the algae, as an input to the bio-digester to make additional biogas. These examples point to integration issues of significant scale.

Economic Challenges

Cost estimates for large-scale microalgae production and carbon recycling has evolved considerably since the 1970s and 1980s. A powerful conclusion from these early analyses was that there was little prospect for any alternatives to the open pond designs, given the low cost requirements associated with fuel production and limited knowledge of externalities related to extensive water use and wildlife impacts. At that time, the driving cost factors were considered to be biological, and not engineering- or environmentally-related. The analyses pointed to the need for highly productive organisms capable of near-theoretical levels of conversion of sunlight to biomass. Even with aggressive assumptions about biological productivity, the studies reported that projected costs for biodiesel were much higher than petroleum diesel fuel costs.

Today, the economics of algal energy systems is known to be more complex and evolving rapidly. For example, new inputs to cost models including carbon recycling and environmental reclamation opportunities must be considered.

Regardless of technological and biological breakthroughs or carbon mandates, the fact remains that the commercial marketplace will not have an appetite for funding capital-intensive energy projects unless the risk-return ratio is acceptable to debt and equity financiers. A number of companies and government organizations have recently assessed different input models and production designs and offered estimates of costs for algal systems. The most popular of designs recently analyzed include stand-alone open ponds, open raceways, and closed photobioreactor cultivation systems.

Generally, these assessments have taken a first-order look at capital and operations and maintenance (O&M) costs. The capital costs are usually divided into costs associated with algal biomass growth, harvesting, dewatering, and algal oil extraction systems. In addition, there are more traditional project costs to include (e.g., engineering, permitting, infrastructure preparation, balance of plant, installation and integration, and contractor fees). O&M costs generally include expenses for nutrients (generally N–P–K), CO_2 distribution, water replenishment, utilities, components replacement, and labor costs. In addition to capital and O&M costs, the costs of the land (owned or leased) must be considered.

Publicly released data reveal significant variations in capital and O&M costs. Some entities have reported capital costs as low as $10k/acre, while others have shown costs approaching $300k/acre. These wide variations in costs are also seen in O&M projections. For example, Sandia National Laboratories and National Renewable Energy Laboratory recently conducted an assessment of previously reported, open literature and concluded that average capital costs were roughly $57k/acre (with a 1-sigma standard deviation of $72k/acre) of utilized surface area and corresponding annual O&M costs were $27k/acre (standard deviation of $25k/acre).[51] This data represents over a dozen different types of open and closed archi-

[51] Phillip T, Pienkos. Historical Overview of Algal Biofuel Technoeconomic Analyses. National Algal Biofuels Technology Roadmap Workshop, December 9–10, 2008.

tectures. Some of the data was older and does not reflect the results being achieved today. It is challenging, therefore, to estimate the costs of such systems. This uncertainty has been driven by three fundamental factors: (1) There are no large-scale commercial algal biofuels production systems with which to develop and substantiate the data; (2) the companies developing new technologies and architectures are very protective of their detailed financial data; and (3) because of the immaturity of the market, there are many unknowns coupled with a number of companies making aggressive claims.

Instead of forecasting the likely capital and O&M costs for a given architecture and its reported yield, this report assesses what a project would require in terms of cost to achieve commercial viability. That is, using traditional discounted cash flow analyses, along with justifiable assumptions on yields and revenues from algal biomass; what would the capital and O&M costs need to be to satisfy the demands of those financing an algae biofuels project?

Figure 13 illustrates the results. The vertical axis represents the total installed costs of a project including of the cost of the land, capital equipment, installation, and other traditional project costs as described earlier. The land accounted for here represents the utilized surface footprint of algal biomass growth systems undergoing photosynthesis, not the gross land area. This approach likely underestimates the true land costs as there will be tracts of acreage (sometimes as much as 2X) not directly contributing to photosynthesis, but instead providing for access ways, harvesting, dewatering, oil extraction, piping and plumbing, storage, laboratory space, and other functions.[52] The horizontal axis represents O&M costs as discussed earlier.

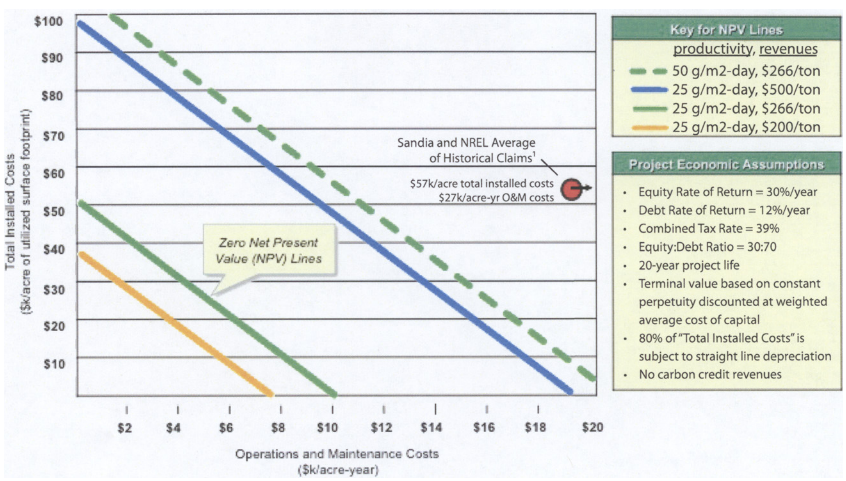

FIGURE 13.—*Project Economic Analyses Used to Assess the Viability of Commercial Algae Systems*

The diagonal lines on the graph depict what are called zero net present value (NPV) curves. These lines represent what a project would need to achieve in total installed and O&M costs to be economically viable from a commercial market perspective. Based on the economic assumptions shown in the figure, projects that achieve costs on or below these NPV lines will provide the required returns. If a project falls on the line, it will return 30 percent (average) per annum to equity providers and 12 percent (average) per annum to debt providers over the 20-year project life. If a project is above the line, it will fail to meet these required returns. If below the line, a project will provide additional profit.

Note that the orange line represents a yield of 25 grams/m^2 per day and a sales price of $200 per dry ton of biomass produced. While yield projections are a subject of major debate and speculation, this productivity level represents what most experts would consider as a reasonable and substantiated expectation using today's

[52] Hassannia J. Diversified Energy Corporation. Simgae™ Algal Biomass Production System. [cited April 2009]. Available from: www.diversified-energy.com/simgae.

technology; one that is plausible for future large-scale algal production systems with sustained operations. Likewise, $200/ton is a metric often quoted and likely represents the low-end of revenue potential by simply assuming $0.10/lb, which can be considered the median for estimates of algal biomass usage as a high antioxidant animal or fish feed (generally quoted as somewhere in the range of $0.07–$0.13/lb).[53]

Thus, the solid orange line illustrates the magnitude of the challenge. Very few organizations have discussed total installed costs of less than $40k/acre. For reference, the Sandia and NREL data point is plotted on the figure as a red circle.

When O&M costs are factored into the analyses, a project must reach the orange line, which lowers total installed cost hurdles. For example, fertilizer such as N–P–K costs approximately $300–$400/ton. It is reasonable to assume that an average algae strain will require 1 ton of fertilizer for every 3 tons of dry algal biomass produced. At a productivity of 25 grams/m^2-day, annual fertilizer costs alone would easily equate to over $4k/acre unless inexpensive nutrient-rich wastewater were used. Very sizeable energy costs also need to be added for pumping and flowing water, capturing and delivering CO_2, and harvesting the algae and extracting the oils. Finally, labor, water composition, and hardware replacement costs need to be considered. It is easy to see how O&M costs alone can derail a project's viability regardless of how low (even to zero) total installed costs become, as evidenced by the Sandia/NREL O&M average being off the graph's scale at $27k/acre-year.

The solid green NPV line represents a more reasonable analysis for algae biomass systems focused on biofuels production. In this case, algae being grown contain 25 percent total lipid content, of which 80 percent is extractable and of the desired characteristics (i.e., non-polar lipids) for biofuels production. Twenty-five percent of total lipid content represents a reasonable and substantiated claim for an alga strain that can be grown abundantly, at large scale, in outdoor systems today. In this scenario, for every ton of algae produced, 400 pounds of oils for biofuels and 1,600 pounds of biomass for animal/fish feed would then be available. Assuming $2/gallon for the oils sold, and $0.10/lb for the remaining biomass, this equates to roughly $266/ton for the algae produced. Based on the earlier discussion of O&M costs, one can quickly see that even at $266/ton the economics appear very challenging given the state of the industry today and for the near-term future.

Also note that the NPV lines such as the solid blue or dashed green line, begin to show an entirely different and much more plausible story for the potential of algal biofuels. The blue line represents achieving almost twice the dollar/ton sales price of algae biomass discussed previously. How might this be possible? Using the same assumptions as earlier, algal oil would have to be sold for prices in excess of $6/gallon, which could be possible should corresponding petroleum prices reach these levels. Alternatively, this could be achieved by focusing on strains and production architectures that extract other, higher-value components from the algae such as nutraceutical products. The dashed green curve represents the same assumptions as the solid green line, but in this case assumes achieving productivity numbers twice that deemed reasonable today (i.e., 50 grams/m^2-day).

The eventual answer will likely be a combination of greater productivity coupled with a focus on co-generation of higher value products from algae and carbon credits. In addition, emphasis needs to be placed on reducing O&M costs across all elements of the algae production value chain.

By assessing the viability of algae projects from a true market perspective, it is apparent that total installed and O&M costs will be a major hurdle to future commercialization. Technologies must be developed to reduce costs and increase yields. This can be accomplished only through a focused, comprehensive, and well-funded R&D program. In parallel, the industry must consider business models that not only look at the bioenergy potential of algae through the transportation fuels market, but also consider carbon recycling, wastewater treatment, and higher-value products in order to achieve economic viability. Finding niche markets that take advantages of these opportunities will be important in the early phases of this promising, yet challenging industry.

Carbon Life-Cycle Assessment

It is critical for the development of algal production technologies that accurate, industry-wide methodologies exist for estimating of carbon lifecycle impacts. Because this industry is in its infancy, these impacts are poorly understood and present significant hurdles for various approaches to the bio-fixation of CO_2 using

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[53] Gieskes TE. Organic Fuels Holdings, Inc., Integrated Biorefineries [Internet]. March 2008 [cited April 2009]. Available from: http://www.organicfuels.com/library/art/Organic%20Fuels%20Presentation%20FO%20Lichts%202008%2004%2023.pdf.

algae. Likewise, there remains a wide array of unanswered issues related to large-scale algae production on human health, wildlife, and the environment. If problems arise during the implementation stage of an algae-based biofuel production process, they may be costly to correct (if, indeed, a correction is even possible). Therefore, future LCA activities should build upon the limited studies that currently exist,[48] [54] [55] but not be dependent on either the fundamental datasets or results presented.

The earlier analyses all suffer from a few fundamental issues that limit their usability for the present and future development of algae based biofuel production. At a fundamental level, none of the available LCAs direct their focus robustly at the production of algae in a manner that would lead to sensible process development activities.

In order to achieve a more robust and useful assessment tool, a base LCA should: (1) Define the metrics to be used for analysis of future LCA activities in the base LCA to ensure an equivalent comparisons; (2) not become fixated on a particular technology or method of production to allow for flexibility as new technologies are developed; and (3) work in tandem with an energy and economic study so that environmental, energy, and economic costs can be directly correlated. Recent energy and economic studies of note include those of Benemann and Oswald[56] and Campbell et al.[57]

Algal Biomass Organization (ABO) Architecture for Green House Gas-Life Cycle Assessment (GHG LCA) Computation.—During 2007–2008, an international effort, primarily facilitated by U.S. industry and academia, culminated in the formation of the non-profit Algae Biomass Organization formed to "promote the development of viable commercial markets for renewable and sustainable commodities and specialty products derived from algae." ABO has taken a leadership role in facilitating public and private interactions, framing the major issues and opportunities related to algae energy systems, educating policy makers, media and others, and serving as an emerging national and international trade association. The following summarizes ABO's Technical Standards Committee work to determine algae's unique role in energy security, climate, and sustainability with a specific focus on GHG LCA computations.

The Committee first defined mechanisms where algal industry based products reduce GHG emissions through three pathways:

—*Substitution.*—Algal fuels, feeds, and chemicals may be substituted for conventional alternatives, with multiple routes to emissions reductions, for example:
  —Algal fuels may directly displace fossil alternatives.
  —Algal fertilizers may reduce conventional, GHG-intensive production.
  —Algal animal feeds may reduce emissions via indirect land use change.
  —Novel algal products may enhance other mitigation strategies. For example, building thermal efficiencies may be substantially enhanced with algal-derived phase changing materials.

—*Sequestration.*—Long-lasting algal products (including plastics, stabilized waxes, and humic acid) may sequester carbon away from the atmosphere for extended periods.

—*Photosynthetic uptake.*—Algal soil amendments may enhance CO_2 uptake and storage by terrestrial plants (e.g., fertilizers, soil tackifier, and char additives).

Second, though greenhouse gas LCA protocols such as ISO 14040:2006 were previously developed (through ABO), the algal industry plans to incorporate process elements that have not yet been fully defined or analyzed. These unique elements generally fall within the industry segments of cultivation, harvest and valorization shown in Figure 14 and highlighted with a red boundary. ABO is recommending development of data and analyses methods for life-cycle analysis that focus on the unique industry-specific details related to inputs, outputs and processes within the denoted architecture boundary.

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[54] Aresta M, Dibenedetto A, Barberio G. Utilization of macro-algae for enhanced CO_2 fixation and biofuels production: Development of a computing software for an LCA study. Fuel Processing Technology. 2005;86:1679–1693.

[55] Life Cycle Assessment: Principles and Practice. Available from: U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Laboratory. EPA/600/R-06/060, 2006, Cincinnati, OH.

[56] Benneman JR, Oswald WJ. Systems and economic analysis of microalgae ponds for conversion of CO_2 to biomass, US DOE [Internet]. 2004 [cited April 2009]. Available from: USDoE.http://govdocs.aquake.org/cgi/reprint/2004/915/91550050.pdf.

[57] Campbell PK, Beer T, and Batten D. Greenhouse gas sequestration by algae-energy and greenhouse gas life cycle studies, CSIRO [Internet]. 2009 [cited April 2009]. Available from: http://www.csiro.au/resources/Greenhouse-Sequestration-Algae.html.

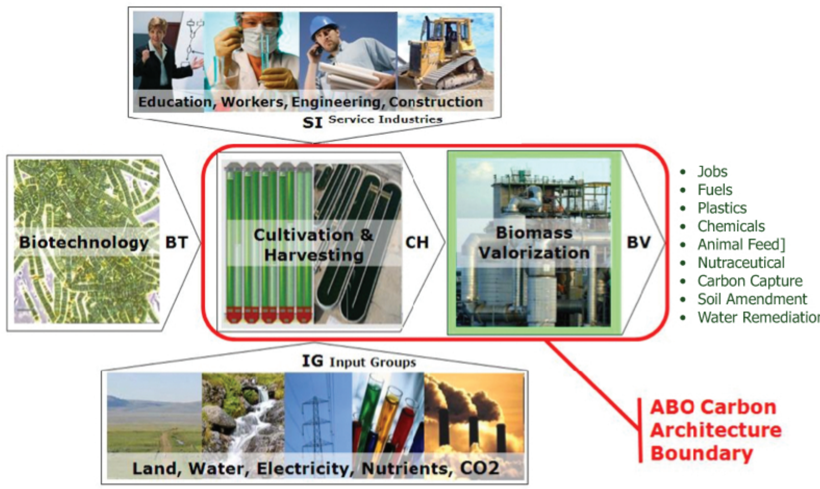

FIGURE 14.—*Algae Biomass Industry—Segment and Products*

Third, ABO is recommending that the parameters shown in Table 4 be quantified to assess the overall GHG lifecycle impact of specific algae cultivation, harvesting, and valorization processes. Different algal process types, output product mixes, and methods of using input resources can only be evaluated consistently and comparatively when the LCA calculations are based on a common set of parameters. The Committee's work continues, as it is assisting in the task of refining the parameter descriptions and recommending appropriate computational methodologies.

TABLE 4.—PARAMETERS TO BE QUANTIFIED

Algal Process CO_2 Credit	CO_2 feedstock flow into the system.
Algal Process GHG Credit <or> Debit	Nitrous oxide & other GHG emissions.
	GHG impact of specific algal products.
	Indirect land use (iLUC) effect.
	Water vapor emissions GHG effect.
Algal Process GHG Debits	Amortized construction emissions.
	Direct land use displacement.
	GHG footprint of all inputs.
	CO_2 leakage into atmosphere.

RECOMMENDATIONS

Earlier sections of this report highlighted opportunities, challenges, and research needs of algal energy systems from both the biofuel production and carbon recycling perspectives. Below are recommendations for a path forward, discussed in broad terms, in anticipation of a national RD&D effort.

Program Goal

Integrated algae energy systems have the potential to offer an effective low-risk alternative to first- and second-generation biofuels and sequestration options that are currently under development. To guide research through early stages of development, we recommend the algae biofuel and carbon recycling community reach consensus on an overarching technology goal drafted as follows:

To develop and deploy by 2020, integrated algal-biofuel and point-source carbon recycling systems that offer 90 percent CO_2 capture with 80 percent recycle at less than a 10 percent increase in the cost of energy goods (fuel) and services (carbon abatement) compared to today's best practices.

R&D Program Scope, Organization and Management

A geographically- and organizationally-diverse, well-managed and results-oriented research, development, and demonstration (RD&D) program built on private and public cooperation is critical to fostering cooperation among carbon emitters and algae energy system developers. Without such a program, the algae biofuels community will struggle to integrate the numerous facets of algal production and processing critical to making this area a successful economic enterprise. Likewise, in the absence of value-added recycling options and regulations limiting carbon emissions, utilities, small CO_2 emitters will have little motivation to consider carbon reuse options. Thus, a robust RD&D program as drafted in Figure 15, will only occur with government involvement both in sponsorship of research and enactment of policy tools that incentivize and accelerate commercial deployment. Specific recommendations include:

Congress and the administration should strengthen policies to incentivize and accelerate commercial deployment of algal energy systems through such vehicles as:

—Loan guarantees (EPA CT 2005—title 17).
—New regulatory and policy guidelines.
—New certification and qualification processes.

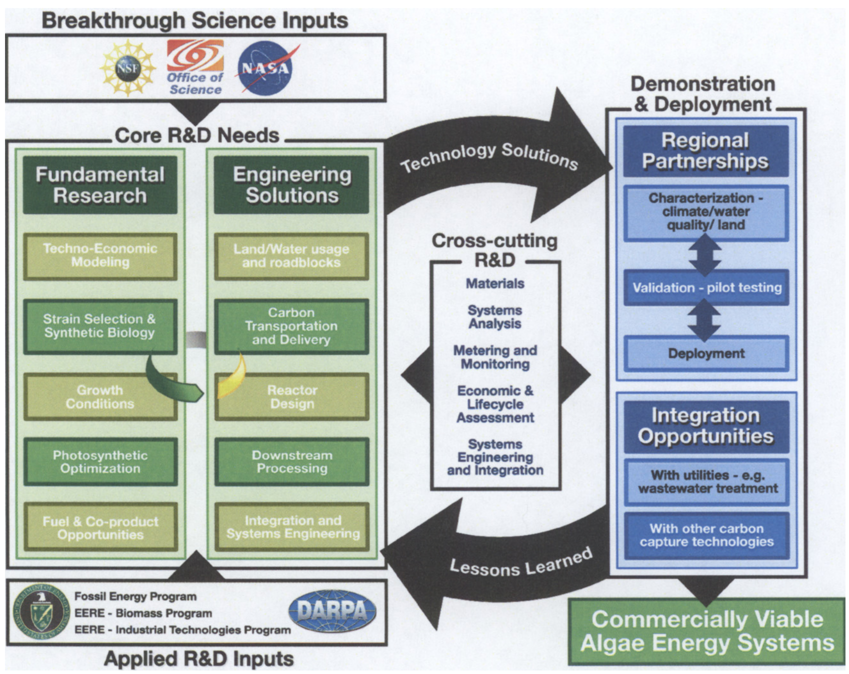

FIGURE 15.—*Suggested Federal RD&D Program Organization and Structure*

Congress should authorize and appropriate funds for a comprehensive research, development, and demonstration program through the U.S. Department of Energy focused on algae energy systems (including both biofuel production and carbon recycling).

The RD&D program should include a balanced and distributed portfolio of foundational, translational, and transformational research, development, and scalable demonstrations executed by regional consortia (Centers of Excellence) consisting of industry, academia, and national laboratories.

Fundamental research should provide new knowledge discovery in several areas such as elucidation of pathways for synthesis of lipids/oils and other desirable products, determination of photosynthetic carbon fluxes and partitioning into desirable products, exploration of metabolic pathway engineering and synthetic biology, examination of novel engineering processes leading to improved CO_2 uptake and areal/

volumetric algae yields, and investigation into alternative approaches to product synthesis.

Applied RD&D should involve laboratory and pilot-scale RD&D for all three subsystems (upstream, cultivation and downstream systems) and the interdisciplinary activities that bridge between them. System integration solutions, developed through public/private partnerships, should lead to integrated demonstrations and deployments in the field. Lessons learned from field tests should be reported to core RD&D elements to guide future activities. A portion of the program should also include research on disruptive technologies, targeting approaches with a high degree of technical risk but also significant potential return on investment.

Crosscutting RD&D should be included on topics such as advanced materials, instrumentation and controls, systems engineering, and economic modeling.

Demonstration and deployment elements of the program should be designed to demonstrate the viability of algae energy system technologies at a scale large enough to overcome real and perceived infrastructure challenges. They should include systems-level demonstrations that include carbon delivery and transport, heat and water integration, and co-siting with wastewater or other nutrient-rich waste streams. Technologies should be tested in the field to identify and eliminate technical and economic barriers to commercialization.

The largest component of the demonstration and deployment program should be regional partnerships similar to the Department's Fossil Energy ongoing regional programs for geologic sequestration. As many as seven regional partnerships should examine regional differences in land and water use, cultivation techniques, ecosystem management practices, and industrial activity that can effect the deployment of algae energy systems. To begin the process, the Department's Fossil Energy Program should build upon algal-related technology roadmapping activities underway within EERE emphasizing and strengthening technology pathways that entail carbon reuse from small point-source emitters (e.g., industrial boilers and ethanol plants). Their goal should be developing pathways to deploy regional "FutureGen" (e.g., algae energy systems) large-scale demonstration of multiple producing and processing platforms with shared technology development.

The program should include initial supporting research on lifecycle analyses of potential new algae energy system processes to identify issues prior to their development. This should include a rigorous upfront lifecycle analyses aimed at quantifying the energy, water, and carbon balance of various technology pathways and system architectures to ensure uniformity of data and overall viability prior to large-scale demonstrations. The program should also participate in cross-cutting studies to model future national energy and water use scenarios incorporating algae energy systems.

The program should include an education component. Over the past two decades applied microalgal research and biotechnology has not been a significant element in educational or research programs. Few students have graduated during this period with sufficient knowledge and practical experience necessary to develop and sustain mass culture of algae and carryout downstream processing of algal biomass. The decline in the supply of scientists and engineers is severe enough to warrant the establishment of an educational initiative toward producing a new generation of scientists and engineers with the multidisciplinary skills needed for emerging algal-based carbon recycling and biofuels industries.

The program should leverage strengths from existing programs, establish programmatic roles, and be coordinated from a Department-wide perspective. Leveraged strengths include: Fossil Energy (upstream systems, carbon capture and recycling); Office of Science (new knowledge discovery & fundamental science); EERE Office of Biomass Programs (cultivations systems); and EERE Industrial Technology Programs (cross-cutting needs and downstream systems).

The Department should seek ways to streamline and strengthen management of the program through use of administrative tools such as experimental personnel authority and other updated contracting and intellectual property management strategies.

Program Timeline

It is premature to assign an exact timeline and estimate of resources required to achieve the program goal described; however, it is reasonable to assume that cost-effective, broad-scale algae energy system solutions will require at least a decade to complete (Figure 16) and Federal investment similar in magnitude to other mainstream sequestration and biofuel pathways.

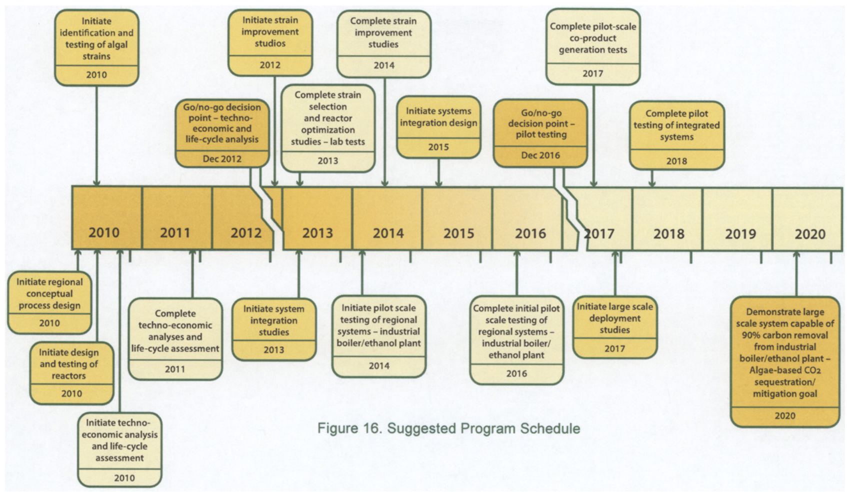

Figure 16. Suggested Program Schedule

Senator BENNETT. Ms. Tatro, I think you hit on it exactly, and words have meaning sometimes that seem innocuous enough. But we have, as a government, as a people, we have come to regard CO_2 as a pollutant, and your testimony here collectively says CO_2 is a resource.

And if you simply make that semantic change in defining it, the whole world changes, so I intend to start talking in those terms. I gather you would be willing to start talking in those terms. And that can be the shift in mindset that can get us in the right direction.

Now, Mr. Klara, will DOE start thinking, okay, how do we organize to take advantage of this resource to generate new energy? Wouldn't that be a significant mind shift at DOE?

Mr. KLARA. Oh, absolutely. But I am not sure that a mind shift is quite needed. We have been investing around $35 million, for example, in fiscal year 2009 in reuse-related concepts. As Senator Dorgan has stated, we are looking at a very aggressive influx of funding, potentially out of the stimulus funding, to this area as well.

I would also caution, also with the approach to having no silver bullet to stabilizing emissions that, at the end of the day, all the analyses continue to show that the emissions are just so large that CCS will likely have to be the backstop.

Senator BENNETT. I realize that, but I am encouraged by what you have just said, the backstop.

Mr. KLARA. Right.

Senator BENNETT. If we think of it as a resource and how can we use this resource? Oh, there is still some left over that we have to deal with. All right, we will use sequestration at the backend rather than the focus which is there now, which is that everything—it is a pollutant. Everything we can do to get rid of it is where we ought to be going. And the testimony here is, no, it is a resource.

Now it may be a resource in overabundance so that that is left over becomes a nuisance. But that significant mind shift I think has to take place, and I realize in the stovepiping of the way we organize our Government, you are focusing entirely on energy. So you can't even talk to Dr. Constantz because he is not producing energy. He is producing concrete.

Let us kind of break down those sorts of stovepipes and realize again this is a resource, and it is a resource that can be used to turn into something very valuable.

Now, Dr. Constantz, how competitive are you with portland cement? Without a Government subsidy, just doing what you are doing, can you under price traditional portland cement in the market today?

Dr. CONSTANTZ. Yes. Well, there are two components. There is the cement and the aggregate, which is composed concrete.

Senator BENNETT. Right.

Dr. CONSTANTZ. And both of them, in our case, half a ton of the material sequesters half a ton of CO_2 within it.

Our price to the gate is competitive with the price to the gate of portland cement. It is much more competitive, though, if you consider the future because, remember, the cement guys are under the same constraints the power guys are under. So they have to put emissions control in place, like in California, we have AB 32. And that is going to drive their cost to the gate up to about $90 a ton, and we will beat that big time.

Senator BENNETT. Sure. I understand that, and that is a political decision rather than an economic decision. I am not saying it is the wrong decision, but it is a political decision to put that extra cost onto the traditional portland cement. And the point I want to discover is even without that extra cost on them, can you compete today?

Dr. CONSTANTZ. On the cement side, we can easily compete, and it is very profitable. On the aggregate side, aggregate is not a very high-value product. It sells for $10 to $20 a ton. So there, by having a carbon credit or like in Australia we have allocations that we get, that can be very profitable.

However, as I mentioned other specialty products like lightweight aggregate sell for as much as $60, $70 a ton or the angular aggregate for pervious concrete, which is used everywhere today, or elongated. See, we can make them any shape we want.

Senator BENNETT. Sure.

Dr. CONSTANTZ. So there are a number of high-value products. The aggregate is easier to get on the market. That is tested with fewer tests than the cement, but we are in testing for both of them. Our vice president of materials research is the past president of the American Concrete Institute, and he chairs the ACI 518 Committee that oversees all the other testing committees. So we are very much in contact with that.

And the cement industry is really thrilled about this because just by, for example, substituting the sand in their mix design with our sand, they can bring a yard of concrete, which is normally 500 pounds of CO_2 net emitted, down to carbon neutral. If they supplant both the sand and the gravel in the concrete, plus only replace 20 percent of the portland cement with our cement, they can bring it to a negative 1,100 pounds per yard of sequestered CO_2.

So we are negotiating with many, many powerplants, but we are also negotiating with many, many cement plants. And at a cement plant, an average cement plant produces a million tons of cement a year. So that is 2 million tons of our product that we can produce.

And because transportation is a large amount of the cost in delivering concrete, which is the commercial product, by having the aggregate produced locally right at the cement plant from their emissions and being able to take that out along with their cement to the ready-mixed plant is an incredible win for everyone in the portland cement industry.

Senator BENNETT. Okay. Will you furnish for the record some national figures so that if everybody who is in the cement and aggregate business shifted over, what the national amount of sequestration would be?

Dr. CONSTANTZ. Sure. So, in the United States, we use about 124 million tons of portland cement a year, and that goes into about roughly 600 million tons of concrete, okay? So from that 124 million tons of portland cement, we are producing 124 million tons of CO_2.

The larger aspect of it is in the United States, we use 3 billion tons of aggregate a year. And approximately 500 million of those tons go into concrete. The other 2.5 billion tons go into asphalt and road base.

Senator BENNETT. And all of that would include sequestered CO_2.

Dr. CONSTANTZ. All 300 million tons. And limestone is the preferred aggregate because it is stable at high pH, and concrete, as you know, has a pH of 14.

Senator BENNETT. Okay. That is the kind of scale that I was looking for.

Mr. Muhs, you have listened to Ms. Tatro. Can you two make music together? Can you make fuel?

Mr. MUHS. Well, I think so. In both cases, we are using solar energy, ultimately. And there are different uses for solar. And biological systems obviously require sunlight.

One of the things that we have done at Utah State to try to help the scalability of algae, for example, is improve the volumetric growth of algae. That is how much algae you can grow in a volume of aqueous or water solution. We are also looking at using saline water from the Great Salt Lake, and we found some strains of algae that have a lot of oil and grow very fast there.

So I think, to follow on that question, yes, we can. And one of the things that we are doing to try to embed better solar energy use is look at ways to increase the amount of sunlight we can get into these algae systems.

You have seen some of these vertical reactors and things of that nature that Senator Dorgan had mentioned. By using sunlight more constructively, we can reduce surface shading and increase the volumetric growth by maybe a factor of 10. If we do that, then we use 10 times less water. And in doing that, we have a whole lot less energy moving energy around—or moving water around, and it makes algae more scalable.

We think that—our industry colleagues who helped write our report say 5 years, some of the academic folks say 10 years to sort of commercial viability, economically. Maybe there somewhere between those two points is where the real number lies.

Senator BENNETT. Well, Mr. Chairman, thank you for your indulgence for this. I have been told, growing up there, that the Great Salt Lake is only good for two things—salt and sunsets.

And if, indeed, we can use the brackish water that is there to create energy, that is enormous because one of the primary challenges with respect to corn ethanol is the enormous amount of water that it uses. And water is the new oil, looking ahead.

The water resources are going to be as scarce as the oil resources around the world. And to be able to use this kind of thing with brackish water, this is a very exciting prospect. And I, again, thank you and congratulate you for convening the hearing.

Senator DORGAN. Senator Bennett, thank you very much.

Senator Tester?

Senator TESTER. Yes, thank you, Mr. Chairman.

I am going to stay with Dr. Constantz for a second. During your answers with Senator Bennett, you had said that the price without subsidies was competitive. And then I drifted for a second, and then we were talking about not being competitive. Is it competitive on the concrete and not competitive on the aggregate? Is that what it was?

Dr. CONSTANTZ. Right. So concrete has both cement and aggregate in it——

Senator TESTER. Yes.

Dr. CONSTANTZ [continuing]. To make the concrete and the price to the gate, the national average in the United States is about $30. Most of the cost in a delivered yard of concrete, though, isn't in that. It is in the transportation.

Senator TESTER. Transportation.

Dr. CONSTANTZ. For aggregate, on a national average, it would be sort of $10 to $20 a ton would be the retail price. So, for cement, the average price varies around $100 to $110. So the portland cement replacement component is extremely profitable.

Now, in the aggregate, the specialty aggregates like the lightweight aggregate can be $70 a ton.

Senator TESTER. It can work. Okay.

And did you say in your testimony that you did not have to separate the CO_2 flow?

Dr. CONSTANTZ. Yes. I think that is the principal distinction. If you have a coal plant and you want to get into chilled ammonia or MEA, you also have to scrub all your SO_2. And even if you are currently compliant with SO_2, it is not to the level you would need it to be to then put an MEA unit on the end.

So if you own a coal plant and you want to do MEA or chilled ammonia, you have to upgrade your sulfur control and take more parasitic load and then put on the other. We take raw flue gas, and we have greater than 70 percent absorption.

Senator TESTER. Okay. You have 70 percent absorption from the CO_2, and the NO_X and the SO_X are not an issue because they are automatically absorbed, too?

Dr. CONSTANTZ. Right now, we know we are taking all the SO_2. And we are investigating the NO conversion to NO_2 and the mercury, arsenic, lead, selenium as well.

Senator TESTER. Okay. So the jury is still out on those, but you are——

Dr. CONSTANTZ. For sure, the SO_2, yes.

Senator TESTER. Okay, all right.

Dr. CONSTANTZ. As well as the CO_2. My VP of emission control has 15 patents going on already. It is something we are pretty knowledgeable about.

Senator TESTER. You said you are making 5 tons of cement a day?

Dr. CONSTANTZ. In a batch process.

Senator TESTER. In a batch process.

Dr. CONSTANTZ. But we have a continuous pilot plant up and running now, which is running 24–7, just putting out a ton a day. And that plant is allowing us to look at the key process indicators, which are needed to define a plant of any scale according to the EPC contractors.

Senator TESTER. So what is the inhibitor of Colstrip, Montana, with their four coal-fired generators, starting up a cement plant in Colstrip, Montana? What is stopping that?

Dr. CONSTANTZ. Actually, we have been having a lot of support. We put a grant together for a coal plant, and we went out to the local ready-mixed suppliers, and they all wrote very laudatory letters of support saying if you make it, we will sell it.

Senator TESTER. Oh, for sure.

Dr. CONSTANTZ. And so, just you have to have a local cement market. But even if you don't have a local cement market, they are putting in asphalt roads. You need the road base. There are plenty of uses almost anywhere.

And the fact is the electrical powerplants and the cement plants are always in the same place because they are where the people are. And they are both things that are hard to transport.

Senator TESTER. Yes. So what is stopping it?

Dr. CONSTANTZ. Well, we are going as fast as we can.

Senator TESTER. Is it because there is not a price on CO_2 that is stopping it, or what is stopping it? Because if you can make money making cement out of CO_2, eliminate and not have to separate all the CO_2 by scrubbing and all that stuff, and if you use your flue gas, what is inhibiting this from happening?

Because it looks to me like if I was on a board of directors, I would say, "Do this. Do it tomorrow." And we just eliminated one big old headache.

Dr. CONSTANTZ. Well, that is what my board is telling me.

Senator TESTER. So there is nothing inhibiting it other than a lack of knowledge?

Dr. CONSTANTZ. We are moving as fast as we can. I am giving one of the addresses at the National Coal Council next Friday.

Senator TESTER. Very good.

Dr. CONSTANTZ. And I will have a much more extensive discussion of what——

Senator DORGAN. Can I just——

Senator TESTER. Yes, go head.

Senator DORGAN. If I might just interrupt? My staff has indicated there still is remaining lifecycle testing for CO_2 lifecycle balance in this process, is that correct?

Dr. CONSTANTZ. Actually, one of my specialties is isotope geochemistry, and we have a whole team. We have 18 Ph.D.s in the company. One of them is just using Carbon-13 analyses. So this will be the most—these are the most sophisticated lifecycle analyses ever done on any carbon technology.

And we are following—we can tell an atom of carbon from coal versus water versus the atmosphere and where it goes in these analyses.

Senator DORGAN. And then the technical testing to meet the industry standards? Are you there?

Dr. CONSTANTZ. Well, that is what we presented back in February at the World of Concrete, the ASTM testing.

Senator DORGAN. And have they been accepted?

Dr. CONSTANTZ. The way it works is every State has their own department of transportation. So, in California, we have Caltrans. Caltrans has a lab in Sacramento. You send them your product. They do their own testing. Every State is different. And that takes them about 18 months to do that testing on concrete.

Senator TESTER. Okay. Thank you.

And I want to move on. And by the way, I think that how we deal with our carbon is just how we deal with our energy policy. It has to be multifaceted, very diverse. And so, I think there is room for everybody in this equation.

But it does intrigue me that you are this far along with this technology, and I have heard of it, but I certainly didn't think it was this far along, which is good news.

I want to talk a little bit about algae for a second. Has all your work been enclosed, Mr. Muhs? All your work—or Mr. Klara, all the work been done in enclosed systems, or is there some work that is being done out in the open?

Mr. MUHS. A lot of work being done in open systems. They are easier to build. They are easier to operate.

Senator TESTER. Are they limited to the southern part of the United States, or can they be done all over?

Mr. MUHS. They are not limited to the southern part of the United States. Matter of fact, the issue of water supply is such that it may be just as viable up north in some—one limiting factor may be temperature in northern regions.

Senator TESTER. And in the end, have you done any analysis on once it gets right down to it, of making diesel fuel out of the algae, and how many gallons of water it takes to make a gallon of diesel fuel? This is a big discussion about coal to liquids.

Mr. MUHS. In the enclosed systems, it is very minimal because you are essentially recycling most all the water.

Senator TESTER. Okay.

Mr. MUHS. In the open systems, it is much higher. And I looked at an analysis yesterday from Sandia and Los Alamos on water use and algae, and I still don't have a number from them yet in terms of actual in open systems.

Senator TESTER. We would love to get that, although I would imagine a lot of it depends upon sunshine.

Mr. MUHS. Exactly. Where you are at, for example, arid climates are going to have a whole lot more evaporative losses than up north.

Senator TESTER. Exactly. I am just going to make the assumption that when you use wastewater, it improves the quality of the wastewater?

Mr. MUHS. That is correct.

Senator TESTER. Because it removes the nutrient load?

Mr. MUHS. It removes the nutrients. For example, in Logan, Utah, we have a huge wastewater facility, and we are already working towards that.

Senator TESTER. Is lack of nutrient load an issue when you are not using wastewater?

Mr. MUHS. It can be. It can be because, obviously, you need the same nutrients that regular farm crops need, and so issues in algae, one of the main ones is proximity to nutrients as well as proximity to CO_2, enhanced CO_2.

Senator TESTER. Has anybody done any analysis about the amount of wastewater? If we were to maximize this to all its ability, do we have plenty of wastewater to fill the need in the country?

Mr. MUHS. That is a good question. I don't have an answer to that. My estimate would be that we do have an excess supply of wastewater right now, and it would take quite a long time for us to get through that before we need it.

Senator TESTER. All right. Yes, I would tend to agree with that.

Ms. Tatro, you talked about disincentives in policies that we may put forward or potentially appropriations. Could you give me any examples of that that exist now that is a disincentive to any one of these industries or potential industries that we have done?

Ms. TATRO. I myself and my organization are not policy experts, so let me just caveat this response.

Senator TESTER. No problem. Neither am I.

Ms. TATRO. I can't cite a particular policy that has disincentivized recycling, and I don't know what all the conversations are in Washington about various ways to either put a price on carbon or to limit the cap and trade. All of those policies have implications for recycling, and I don't know. I just think that needs to be part of the conversation in the formulation.

Senator TESTER. I agree. I just need to make sure that we don't have unintended disincentives in some policy we make. So if you see that coming down the pipe, I would love to hear about it. Because, truthfully, I think that it needs to be a multifaceted arrangement that we deal with CO_2, and I don't want to disincentive anybody if they have got a good idea.

Which brings me to my next question, you had talked about the fact that we haven't really called for these new ideas. Is that the same case since Dr. Chu is in the DOE, or are there things we can do that really could help excite people to step up to the plate?

Ms. TATRO. Absolutely. I am really excited by Dr. Chu's direction and the support I think he also has from Congress in creating these collaborative energy grant challenge centers that may be focused on some of these problems. That is a fabulous way to get cross-organizational teams working on some of these problems.

I am very excited. I think he sees the benefit of getting coordinated teams across different parts of the Department of Energy and with different Federal agencies to motivate people to work on these problems. I am very excited by what I see. I think it will help tremendously, and I know we appreciate the support from Congress that he is receiving for that.

Senator TESTER. Okay. Just a couple more, and then I am done.

Mr. Muhs, you talked about one-tenth the area of a State like Utah or North Dakota could be used to fill all our diesel needs. Is that in a closed loop, open loop, or does it matter?

Mr. MUHS. That was based on something in between, essentially in terms of——

Senator TESTER. A little bit of each?

Mr. MUHS. Yes. Essentially took values for production that were lower than enclosed but higher than open systems to make that calculation.

Senator TESTER. All right. The other thing, Ms. Tatro, you talked about a heat engine that could make methane out of CO_2 and water and sunlight and heat. I will ask you the same question I asked Mr. Muhs. What is the water use in making the methane? Is it 1-to-1 or less than that or more than that?

Ms. TATRO. The product that is produced is methanol, which is a liquid material.

Senator TESTER. Yes, methanol. I am sorry.

Ms. TATRO. That is all right. But then the question is still valid, and I don't know the number off the top of my head. The amount of water that is used compared to the amount of CO_2 to produce a gallon of fuel?

Senator TESTER. Yes.

Ms. TATRO. Let me get back with you on that number. I don't know it off the top of my head.

Senator TESTER. That would be great. I would just love to know it.

And that is probably about it. I want to thank you all for your testimony. I think that you have all thought outside the box.

Mr. Constantz, do you see CO_2 as an asset at this point in time? You can make money off CO_2?

Dr. CONSTANTZ. Yes, in many ways. From aggregate, from cement, from fresh water, and if there is further carbon monetization from the CO_2 emitter, we believe it could be a very profitable and job-creating enterprise.

Senator TESTER. Mr. Klara, my apologies. I didn't ask you any questions, next time.

Mr. KLARA. No problem, sir.

Senator TESTER. Thank you. Thank you very much.

Senator DORGAN. I think my colleague, Senator Tester, just talked about thinking outside the box, and Senator Bennett talked about stovepipes. In many ways, it is kind of the same discussion.

We do in our Government, I think, push a lot of money toward research and so on, but a lot of it is done in a stovepipe. And I think when we try to address this larger issue of climate change and carbon capture and so on we really do need to think outside the box.

I was just thinking, as Senator Tester was asking questions, about Dr. Venter, Dr. Craig Venter, who came to see me a while back. This is probably such a simpleton, layman's description. But he has got scientists, I think a couple hundred scientists working on the prospect of perhaps of creating synthetic microbes that would consume coal and in that consumption produce methane.

And so, that is thinking outside the box, right, perhaps doing it in situ. I have no idea about the carbon issue there, but I am assuming consuming coal underground with synthetic microbes and turning coal into methane probably also is an outside-the-box approach to deal with the carbon issue.

But the reason that I wanted to have this hearing is that I want us to begin thinking differently about this issue and this challenge. We do have issues in front of us that the Congress is going to be required to address. And the question is not "whether," it is "how" do we address it?

And I appreciate very much your willingness to come. Some of you have traveled a long distance to just share with us some thoughts about what you are working on and what we might consider in a different way when we consider the word "carbon" and "CO_2" and what we might do with it.

I, too, think that if we are smart and we go about this the right way, we might well find that you can create an asset in terms of trying to deal with what we consider a liability. If that is the case, we ought to run in that direction and say to those that are looking at sequestration, good for you. Keep up your work as well because we need to do a lot of everything to find out what works really well.

And the other piece I would say, finally, is this. It is one thing to do something in a laboratory. It is quite another thing to scale it up and demonstrate it at commercial scale. And even as we encourage the development in laboratories, we need to encourage the scaling up at commercial scale of those opportunities so that we know what we have here. Does this work?

Then I think the private sector will beat a path to the door of that person who has demonstrated an idea that will provide the ability to make some money and sequester carbon at the same time.

CONCLUSION OF HEARING

Senator Bennett and I have a 10 o'clock markup at the Energy Committee that we have to attend, and let me thank all of the witnesses for coming this morning. Your entire statements will be part of the record, and you may feel free to submit any additional material you wish for 2 weeks from the date of this hearing.

This hearing is recessed.

[Whereupon, at 10:10 a.m., Wednesday, May 6, the hearing was concluded, and the subcommittee was recessed, to reconvene subject to the call of the Chair.]

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