Capture and Sequestration of CO_2 From Stationary Combustion Systems by Photosynthesis of Microalgae

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Introduction

Emissions of carbon dioxide are predicted to increase this century[1] leading to increases in the concentrations of carbon dioxide in the atmosphere. While there is still much debate on the effects of increased CO_2 levels on global climate, many scientists agree that the projected increases could have a profound effect on the environment. Most of the anthropogenic emissions of carbon dioxide result from the combustion of fossil fuels for energy production. It is the increased demand for energy, particularly in the developing world, which underlies the projected increase in CO_2 emissions. Meeting this demand without huge increases in CO_2 emissions requires more than merely increasing the efficiency of energy production. Carbon sequestration, capturing and storing carbon emitted from the global energy system, could be a major tool for reducing atmospheric CO_2 emissions from fossil fuel usage.

The costs of removing CO_2 from a conventional coal-fired power plant with flue gas desulfurization were estimated to be in the range of \$35 to \$264 per ton of CO_2.[2] The cost of power was projected to increase by anywhere from 25 to 130 mills/kWh. DOE's goal is to reduce the cost of carbon sequestration to below \$10 /ton of avoided net cost.

Photosynthesis has long been recognized as a means, at least in theory, to sequester anthropogenic carbon dioxide. There has been relatively little research aimed at developing the technology to produce a gaseous combustion effluent that can be used for photosynthetic carbon sequestration. However, the photosynthetic reaction process by plants is too slow to significantly offset the point source emissions of CO_2 within a localized area. Aquatic microalgae have been identified as fast growing species whose carbon fixing rates are higher than those of land-based plants by one order of magnitude.

The Department of Energy has been sponsoring development of large-scale photovoltaic power systems for electricity generation. By this analogy, a large-scale microalgae plantation may be viewed as one form of renewable energy utilization. While the PV array converts solar energy to electricity, the microalgae plant converts CO_2 from fossil combustion systems to stable carbon compounds for sequestration and high commercial value products to offset the carbon sequestration cost. The solar utilization efficiency of some microalgae is ~ 5%, as compared to ~ 0.2% for typical land based plants. Furthermore, a dedicated photobioreactor for growth of microalgae may be optimized for high efficiency utilization of solar energy, comparable to those of some photovoltaic cells. It is logical, therefore, that photosynthetic reaction of microalgae is considered as a mean for recovery and sequestration of CO_2 emitted from fossil fuel combustion systems.

Objective

Physical Sciences Inc. (PSI), Aquasearch Inc., and the Hawaii Natural Energy Institute at the University of Hawaii are working together to develop technologies for recovery and sequestration of CO_2 from stationary combustion systems by photosynthesis of microalgae. The research is aimed primarily at quantifying the efficacy of microalgae-based carbon sequestration at industrial scale. Our principal research activities will be focused on demonstrating the ability of selected species of microalgae to effectively fix carbon from typical power plant exhaust gases. Our final results will be used as the basis to evaluate the technical efficacy and associated economic performance of large-scale carbon sequestration facilities. Our vision of a viable strategy for carbon sequestration based on photosynthetic microalgae entails combining CO_2 from the fossil fuel combustion system and nutrients in a photobioreactor where microalgae photosynthetically convert the CO_2 into compounds for high commercial values or mineralized carbon for sequestration.

Approach

Our vision of a viable strategy for carbon sequestration based on photosynthetic microalgae is shown conceptually in Figure 1. In this figure, CO_2 from the fossil fuel combustion system and nutrients are added to a photobioreactor where microalgae photosynthetically convert the CO_2 into compounds for high commercial values or mineralized carbon for sequestration. The advantages of the proposed process include the following.

(1) High purity CO_2 gas is not required for algae culture. It is possible that flue gas containing 2~5% CO_2 can be fed directly to the photobioreactor. This will simplify CO_2 separation from flue gas significantly.

(2) Some combustion products such as NO_x or SO_x can be effectively used as nutrients for microalgae. This could simplify flue gas scrubbing for the combustion system.

(3) Microalgae culturing yields high value commercial products that could offset the capital and the operation costs of the process. Products of the proposed process are: (a) mineralized carbon for stable sequestration; and (b) compounds of high commercial value. By selecting appropriate algae species, either one or both can be produced.

(4) The proposed process is a renewable cycle with minimal negative impacts on environment.

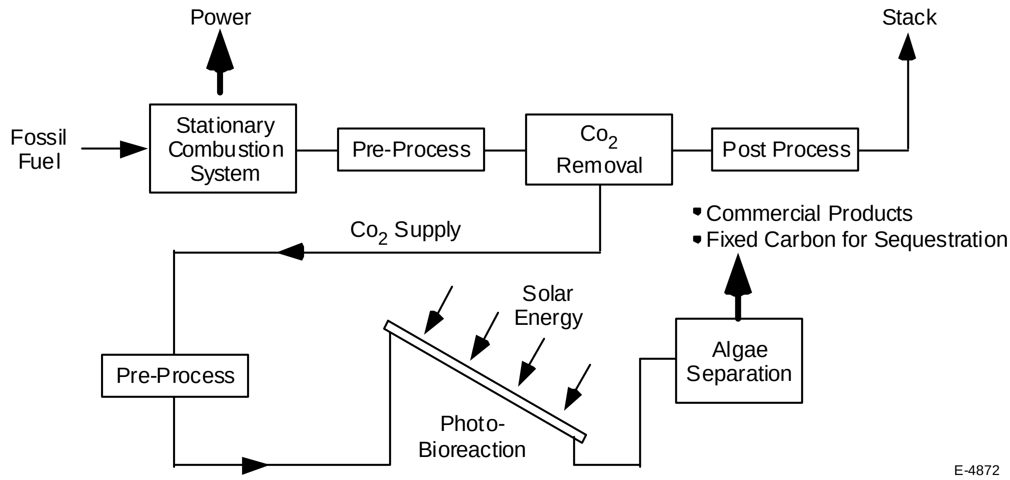

Figure 1. Recovery and sequestration of CO_2 from stationary combustion systems by photosynthesis of microalgae.

The research and experimentation will examine and quantify the critical underlying processes. To our knowledge, the research represents a radical departure from the large body of science and engineering in the area of gas separation. The research has significant potential to create scientific and engineering breakthroughs in controlled, high-throughput, photosynthetic carbon sequestration systems.

Project Description

The research program calls for development of key technologies pertaining to: (1) treatment of effluent gases from the fossil fuel combustion systems; (2) transferring the recovered CO_2 into aquatic media; and (3) converting CO_2 efficiently by photosynthetic reactions to materials to be re-used or sequestered.

The challenging nature of the proposed program requires a qualified and multidisciplinary team. Aquasearch Inc., a U.S. company, has developed full-scale, operating photobioreactor technology with its own investment of more than $13 million. Aquasearch photobioreactor technology now produces commercial quantities of high-value microalgae products. The University of Hawaii provides unique expertise in the understanding and analysis of carbon sequestration processes. PSI has extensive government program management experience and unique technical expertise in the areas of pollution control from stationary power systems and solar engineering.

The three-year program consists of the following tasks; (1) recovery of CO_2 from power plant flue gas to photobioreactor; (2) selection of microalgae best suited for the proposed process; (3) optimization and demonstration of industrial scale photobioreactor; (4) carbon sequestration system design; and (5) economic analysis.

Results

The issue of supplying CO_2 from power plant flue gas to the photobioreactor system entails that the team reproduce representative types of industrial flue gas and test their ability to support microalgal carbon fixation. In the United States coal and natural gas are the primary fuels used for power generation, although fuel oil is important in some regions. Conventional boilers (as opposed to gas turbine combustors) employ modest amounts of excess air for combustion. The CO_2 content of flue gas from boilers used for power generation ranges from 7 vol% to 15 vol%. Stationary diesel combustors and gas turbines fired with natural gas, also used for power generation, use much higher amounts of excess air and have, therefore, much lower CO_2 content, on the order of 3 vol%.

Concentrations of the trace acid gas species such as NO_x and SO_2 depend on the composition of the fuel and on the pollution control system employed. Natural gas-fired combustors have virtually no SO_2 in the flue gas, while coal-fired systems can have an SO_2 content in the range of 50 ppmv up to 600 ppmv; the lower end of the range represents systems with FGD systems, about 25% of the boilers in the United States.

We are preparing to conduct a preliminary set of laboratory experiments using approximately 20 species of microalgae and 5 different, representative flue gases. These experiments will be used to select microalgae for the large-scale photobioreactor demonstrations. We will use species that grow optimally at high temperatures, since this can yield order-of-magnitude increases in photosynthesis. We also seek species whose size, physiology and behavioral characteristics may favor reduced final processing costs. Finally, carbon-mineralizing species tend to be more effective at high pH, and can withstand significantly higher concentrations of dissolved inorganic carbon.

Application and Benefits

Stationary combustion sources, particularly electric utility plants, represent 35% of the carbon dioxide emissions from end-use of energy in the United States.[1] The costs of removing CO_2 from a conventional coal-fired power plant with flue gas desulfurization were estimated to be in the range of \$35 to \$264 per ton of CO_2.[2] The cost of power was projected to increase by anywhere from 25 to 130 mills/kWh. DOE's goal is to reduce the cost of carbon sequestration to below \$10 /ton of avoided net cost. The proposed process addresses this goal through the production of high value products from carbon dioxide emissions.

Microalgae can produce high-value pharmaceuticals, fine chemicals, and commodities. In these markets, microalgal carbon can produce revenues of order \$100,000 per kg C. These markets are currently estimated at >\$5 billion per year, and projected to grow to >\$50 billion per year within the next 10-15 years. Revenues can offset carbon sequestration costs.

The expected cost of producing microalgae for high-value products is quite high, based on current technology and practices. Here we provide an approximate analysis of costs based on current technology, at a scale of approximately 10 acres. A 25 MW power plant will require a facility of almost 1,500 acres, a size at which we would expect significant economies of scale.

Capital expenditures, depreciated over 20 years, contribute in the range of $25 to $50/tC to the cost. More than 40% of these costs relate directly to processing equipment. Cost of goods sold (COGS) is much greater, in the range of $10,000/tC. The greatest contributors to COGS are manpower and CO_2. We assume the use of pure carbon dioxide, which represents more than 35% of the cost of raw materials.

These costs pale by comparison to the revenues generated from high value products, which are of order $100,000/kg C, and can be substantially greater. For carbon-mineralizing species, we have assumed the resulting mineral (calcite, for example) could fetch the same price as industrial-grade limestone ($3 to $4.50/tC), which also provides an offset, though not as substantial as for high value products. Obviously, if a power plant supplies CO_2 at its own cost of $10/tC, then a microalgae high-value product facility would realize a substantial reduction in operating costs.

As a commercial proposition, there is no question that the $50B market projected for microalgae products by 2015 will utilize substantial quantities of carbon dioxide. How much carbon is used, and how much larger this market grows by 2025 and 2050 are a focus of our proposed economic analysis. Our present expectation is that the gross cost of microalgal carbon sequestration could be brought into the range of $100/tC. However, the net cost, which takes into account significant revenues from high-value products and to some extent from carbonate minerals, can be offset to zero at a certain scale (i.e. where the cost of sequestration is equal to the value of the total global markets for all microalgal products). We note that microalgae could also be used as a source of renewable fuels, the revenues from which could provide additional offsets.

By comparison to certain other biological processes, microalgal carbon sequestration is clearly superior in some respects. It is the potential for production of high-value products that makes microalgal sequestration cost-competitive. Granted, agricultural products can produce revenues, but these are generally for low-value products. Furthermore, many other sequestration technologies, such as ocean fertilization and deep ocean burial, produce no marketable products and have questionable or unknown environmental impacts that could add to long-term costs.

Future Activities

The majority of our proposed research activities will be performed at the Aquasearch Research and Development Facility, located in the Hawaii Ocean Science and Technology (HOST) business park on the island of Hawaii. This unique 3.5-acre compound provides all the basic facilities for the work we propose, including:

- Laboratories equipped for microscopy, chemistry and computing
- Environmentally-controlled culture laboratories for small-scale algal culture, including capability for computerized process-control and data acquisition

- 1 acre of commercial-scale (and smaller scale-up) photobioreactor systems
- Complete processing facilities for dewatering, homogenization and drying
- A propane-fired boiler system, providing a source of carbon dioxide-rich exhaust.

Aquasearch will make available approximately 25% of its R&D Facility for the research proposed here, including all the infrastructure listed above. This will provide our proposed research project the ability to maintain numerous laboratory-scale cultures, to conduct simultaneous experiments in as many as eight scale-up photobioreactors (2,000 L), four mid-size photobioreactors (8,000 L), and four commercial-scale photobioreactors (25,000 L). The Aquasearch facility has the ability to produce as much as 100 kg C per day in the form of dry algal biomass. Furthermore, an existing propane-fired boiler system provides a ready source of exhaust that we may use to demonstrate an important facet of the complete carbon sequestration system. In Year 1 selection of microalgae best suited for the proposed carbon recovery and sequestration system will be made. We will quantify the performance of 15 to 20 microalgae species at a small laboratory scale according to the following criteria.

- Ability to withstand the most untreated forms of industrial exhaust gases;
- High rate of photosynthetic carbon fixation; and
- Ability to produce high-value products; *<u>or</u>*
- Ability to produce carbonate minerals

These experiments will involve the use of exhaust gases that are manipulated to represent exhaust streams from a variety of typical power plants. We will then determine, based on the preceding experiments, the degree to which separation or purification of the gas exhaust is necessary, and which species of microalgae are best suited to a scaled up demonstration.

In Years 2 and 3, we will demonstrate the carbon sequestration process at large scale. This approach will employ two to three species from each category (high-value *or* carbon-mineralizing), cultivated with industrial-scale photobioreactors and using selected power plant exhaust gases as the primary carbon source. The nature of the exhaust gases may be modified by separation, purification or other alterations in physical characteristics as dictated by preceding experiments.

Component development and a study of subsystem integration of a large-scale carbon sequestration facility will begin in Year 1 and carry over into subsequent years. Optimization of each component and of the integrated system will be made. The purpose of this study is to provide the design parameters for such a facility in sufficient detail to enable a detailed economic analysis of capital and operating cost requirements, expected return on capital, and a variety of related performance characteristics, both technical and economic nature. Finally, we will conduct a detailed economic study in Task to assess viability of the proposed system for recovery and sequestration of CO_2 from stationary combustion systems.

References

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