

Practical Photosynthetic Carbon Dioxide Mitigation

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Significant literature does exist in the areas of solar collection, fiber optic light delivery, alternative high value uses for biomass, and multipollutant control using biological means. However, current biomass literature lacks sources regarding practical photosynthetic systems for greenhouse gas control.

The concept behind affordable engineered photosynthesis systems is simple. Even though CO_2 is a fairly stable molecule, it is the basis for the formation of complex sugars (food) by green plants through photosynthesis. The relatively high content of CO_2 in flue gas (approximately 14% compared to the 350 ppm in ambient air) has been shown to significantly increase growth rates of certain species of cyanobacteria. Therefore, this application is ideal for a contained system engineered to use specially selected (but currently existing) strains of cyanobacteria to maximize CO_2 conversion to cyanobacterial biomass and thus not emit the greenhouse gas into the atmosphere. In this case, the cyanobacteria biomass represents a natural sink for carbon sequestration.

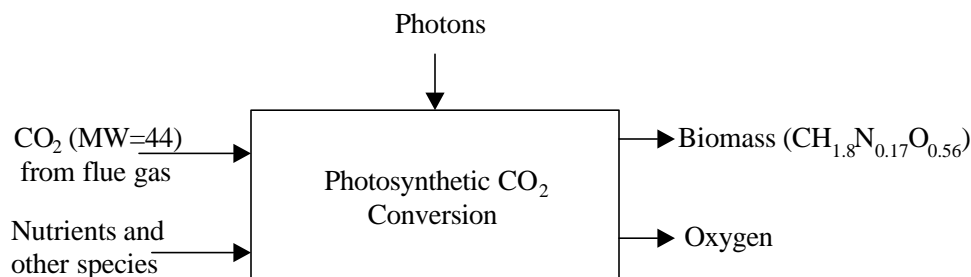


Figure 1. Photosynthetic conversion of CO_2 to biomass and oxygen

Photosynthesis reduces carbon in the gas stream by converting it to biomass. As shown in Figure 1, if the composition of "typical" cyanobacteria (normalized with respect to carbon) is $\text{CH}_{1.8}\text{N}_{0.17}\text{O}_{0.56}$, then one mole of CO_2 is required for the growth of one mole of cyanobacteria. Based on the relative molar weights, the carbon from 1 kg of CO_2 could produce an increased cyanobacteria mass of 25/44 kg, with 32/44 kg of O_2 released in the process, assuming O_2 is released in a one-to-one molar ratio with CO_2 . Therefore, a photosynthetic system provides critical oxygen renewal along with the recycling of carbon into potentially beneficial biomass.

Enhanced natural sinks are the most economically competitive and environmentally safe carbon sequestration options because they do not require pure CO_2 , and they do not incur the costs (and dangers) of separation, capture, and compression of CO_2 gas. Among the options for enhanced natural sinks, the use of existing organisms in an *optimal* way in an engineered photosynthesis system is low risk, low cost, and benign to the environment. Additionally, this engineered photosynthesis system has the advantage of being at the source of the emissions to allow measurement and verification of the system effects, rather than being far removed from the emissions source, as is the case with forest-based and ocean-based natural sinks. Finally, the use

of ocean-based sinks could present significant problems. It will be necessary to add large amounts of iron to the ocean to “use” the vast quantities of CO₂ that might be added. As a result, there will be no control over resulting growth. “Weed” plankton, the most likely organisms to grow, will not provide sufficient nutrients for the food webs and there is a high probability of significant negative environmental impact. In the case of CO₂ stored at the bottom of the ocean in “lakes,” the adverse effects on the ocean-floor ecosystem cannot be predicted, but are likely to be considerable. The system we are proposing has little or no adverse environmental impact.

For low concentration CO₂ streams (such as the 14% mean CO₂ concentration in waste flue gases from coal-fired power plants), the joint consideration of conversion of collected solar energy (using the Oak Ridge process) and natural carbon capture has the potential for significantly lowering carbon management costs. An engineered photosynthesis system can use (or recycle) waste CO₂ to generate a store of reduced carbon in the form of biomass that could be used as a fuel, fertilizer, feedstock or sink for disposal. Also, engineered photosynthesis systems will likely benefit from current research into enhancing the process of photosynthesis, either genetically or via catalysts. This synergistic effect could lead to significant CO₂ reductions not otherwise possible.

The process presented in this proposal (and shown schematically in the Appendix) would be suitable for application at existing and future fossil units. It also has several advantages compared to other natural sequestration techniques. For this project, optimization is based on design of a mechanical system to best utilize existing organisms rather than on optimizing the desirable features of an organism by genetic manipulation. Genetically engineered organisms are notoriously unstable, especially when forced to grow at the high rates expected in this application. The process also requires relatively small amounts of space (1/25th of a raceway cultivator design) and most of the required energy is provided by passively collected sunlight. Because the organisms are grown on membrane substrates arranged much like plates in an electrostatic precipitator, there is little pressure drop. From a solar energy utilization standpoint, this proposal offers a unique and cost-effective alternative using a new hybrid system that leverages two decades of advancements and cost improvements in the solar, optical coating, and large-core optical fiber industries. This method far surpasses previous attempts at distributing sunlight to enhance cyanobacteria growth. Finally, this system could be used in virtually any power plant with the incorporation of translating slug flow technology to create favorable conditions for cyanobacteria growth, such as reduced temperatures and enhanced bicarbonate concentration.

One of the great advantages of carbon sequestration via an engineered biological system is that the sequestration is performed by the well-understood and natural process of photosynthesis. The challenges are therefore more engineering-based than scientific. However, there are a number of challenging concepts that will be faced in this work.

Cyanobacteria were picked for this application because they are one of only two groups of organisms capable of growing at the experimental temperatures of 50-75°C. Although the cyanobacteria are treated as a photosynthetic “black box” in that a mechanistic study of the photosynthesis process is not part of this work, maximizing certain behaviors is a key to long-term success of this application. For example, the optimal blend of nutrients (including nitrates

and bicarbonates) that maximize growth and carbon fixation rates must be determined. Further, because the organisms are grown on vertical substrates to minimize the pressure drop of the flue gas, cyanobacteria that "cling" to these surfaces is critical. However, if the attachment is too strong, cleaning the surface and harvesting becomes problematic. In addition, growth characteristics must be characterized to design the optimal harvesting system. For example, if the organisms reach maturity (or die) they consume less carbon than if they are growing. Therefore, an identifiable characteristic of growth must be quantified to maintain maximum carbon fixation.

Another consideration is the potential effects of the cyanobacteria on local environments should containment be lost. While they are naturally occurring organisms, their effects on colder ecosystems must at least be considered. Thermophilic ("heat" loving) or mesophilic cyanobacteria were selected, in part, because their growth ceases or is drastically decreased when exposed to lower temperatures. However, growth rate data at lower temperatures for target species should be quantified for understanding potential adverse impact.

The distribution of photosynthetic photon flux (light energy in the visible spectrum - wavelength of 400-700 nm) is a key to promoting uniform and maximum growth. Simply put, if growth is maximized, carbon fixation will be maximized. Distributing light is not a simple task. Light intensity varies according to Beer's law. Thus, a particulate-laden flue gas can result in a large loss of photon flux due to scattering. As a result of the non-uniform distribution of light, growth rates could be decreased or more lighting capacity (to shorten the average transmission path) could be required, requiring more energy to achieve maximum photosynthetic response.

The specific challenges of the passive sunlight delivery system relate to: 1) the ability to simultaneously minimize cost and optimize the material dispersion and scattering properties of the large-core optical fibers so that a maximum amount of visible light emerges radially from the fibers (glowing much like a fluorescent lamp), and 2) design the illumination system to spatially illuminate all regions of the growth membranes evenly. In addition to these project-specific challenges, the practical matter of integrating readily available components into a practical working light distribution prototype has yet to be experimentally validated. These issues include optimizing the performance and cost of two-axis sunlight trackers, dish concentrators, UV Cold mirrors, and optical fibers. Similarly, the optical system design and management of wasted thermal energy residing in highly concentrated sunlight must be optimized. Researchers at Oak Ridge National Laboratories are addressing this effort.

Lighting methodology considerations do not stop at delivery mechanisms. Lighting cycle duration (duration of light exposure for the organisms) is also an important consideration. While some "rest" or "dark" period is required, the optimum length of the light and dark cycles to promote carbon fixation is not well known. It is estimated that the natural maximum for the lighting cycle (about 16 hours) might be optimal, but further testing is required to understand the effect of the wide range of lighting cycles that could be experienced.

Another concern regards growth substrate composition and orientation. The growth substrate must be resistant to wear in the harsh environment of the flue gas and corrosive potential of the growth media and offer a high degree of adhesion with the cyanobacteria because of the vertical position. However, the degree of adhesion can be too high, becoming problematic for harvesting.

Harvesting, or the process of separating young from mature cyanobacteria, and reapplication of growing (not yet mature) cyanobacteria to growth surfaces are other key concerns. Preliminary tests indicate that cyanobacteria, removed in "clumps" from the growth strata, are easily agitated into a diffuse state. At this point, mature or dead cyanobacteria can be removed and cyanobacteria that are maturing (and thus maximizing their consumption of carbon) can be repopulated on the growth strata. The harvesting process is also necessary to promote cell division and to reap the benefits of post-processed biomass.

A schematic illustrating the overall biologically-based greenhouse gas control system with a fossil-fired electric generation plant is shown in the Appendix. This illustration shows the bioreactor exposed to the flue gas, even after the flue gas is "scrubbed" of CO₂ by the slug-flow reactor. This arrangement was chosen because it is the anticipated configuration.

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<http://www.eia.doe.gov/>

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FOSSIL GENERATION PLANT WITH BIOREACTOR

The bioreactor contains cyanobacteria (referred to here as algae) that metabolize carbon dioxide to biomass with the help of a slug flow reactor that provides needed ions. Light, which is necessary for the process of photosynthesis, is transmitted through special solar collectors via large core fiber optic cables.

STEAM

Steam produced by the furnace powers high-pressure turbines and generators to produce electricity.

COOLING TOWER

Hot water from the slug flow reactor must be cooled to increase the ability of the water to transport bicarbonate.

SOLAR COLLECTORS

Special parabolic dishes collect light that is transmitted via fiber-like cables to the bioreactor.

White cloud-like discharge

