# Capture of $CO_2$ Emissions Using Algae

**A Research Document by Oilgae**

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**This document was prepared by Oilgae as a free report for those interested in knowing more about algae-based capture of $CO_2$ emissions.**

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**Those interested in knowing more about our publications may kindly see the following:**

**Comprehensive Oilgae Report** - http://www.oilgae.com/ref/report/report.html - the most detailed report on all aspects of algae fuels.

**Oilgae Report Academic Edition** - http://www.oilgae.com/ref/report/academic/academic_report.html - algae fuels report specifically targeted at the academic and research community.

**Oilgae Digest** - http://www.oilgae.com/ref/report/digest/digest.html - a precise guide that provides answers and data for the critical questions in algae fuels

**Algae-based Waste Water Treatment** - http://www.oilgae.com/ref/report/wastewater_treatment/wastewater_treatment.html - a comprehensive guide on all aspects of waste water bioremediation using algae.

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## 1. Composition of Power Plant Flue Gas

Typical coal power plant flue gases have carbon dioxide levels ranging from 10%–15% (4% for natural gas fired ones). The typical carbon dioxide percentages in the atmosphere are 0.036%. Various studies have shown that microalgae respond better to increased carbon dioxide concentrations, outgrowing (on a biomass basis) microalgae exposed only to ambient air.

Example of a typical flue gas composition from coal fired power plant

| **Component** | $N_2$ | $CO_2$ | $O_2$ | $SO_2$ | NOx | Soot dust |
|---|---|---|---|---|---|---|
| **Concentration** | 82% | 12% | 5.5% | 400 ppm | 120 ppm | 50 mg/$m^3$ |

## 2. Ideal Attributes for Photosynthetic Sequestration

An ideal methodology for photosynthetic sequestration of anthropogenic carbon dioxide has the following attributes:

- Use of concentrated, anthropogenic $CO_2$ before it is allowed to enter the atmosphere.
- Highest possible rates of $CO_2$ uptake
- Mineralization of $CO_2$, resulting in permanently sequestered carbon
- Revenues from substances of high economic value

## 3. Characteristics of Algae-based $CO_2$ Capture

- 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.
- Some combustion products such as NOx or SOx can be effectively used as nutrients for microalgae. This could simplify flue gas scrubbing for the combustion system.
- 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 algae species, either one or combination or two can be produced.
- The proposed process is a renewable cycle with minimal negative impacts on environment.

Source: NREL, Source link: http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/5a3.pdf

## 4. Algal Species Suited for $CO_2$ Capture of Power Plant Emissions

Several species of algae have been tested under $CO_2$ concentrations of over 15%. For example, *Chlorococcum littorale* could grow under 60% $CO_2$ using the stepwise adaptation technique (Kodama et al., 1994). Another high $CO_2$ tolerant species is *Euglena gracilis.* Growth of *Euglena gracilis* was enhanced under 5-45 % concentration of $CO_2$. The best growth was observed with

5% $CO_2$ concentration. However, the species did not grow under greater than 45% $CO_2$ (Nakano et al., 1996). Hirata et al. (1996a; 1996b) reported that *Chlorella* sp. UK001 could grow successfully under 10% $CO_2$ conditions. It is also reported that *Chlorella* sp. can be grown under 40% $CO_2$ conditions (Hanagata et al., 1992). Furthermore, Maeda et al (1995) found a strain of *Chlorella* sp. T-1 which could grow under 100% $CO_2$, although the maximum growth rate occurred under a 10% concentration. *Scenedesmus* sp. could grow under 80% $CO_2$ conditions but the maximum cell mass was observed in 10-20% $CO_2$ concentrations (Hanagata et al., 1992). *Cyanidium caldarium* (Seckbach et al., 1971) and some other species of *Cyanidium* can grow in pure $CO_2$ (Graham and Wilcox, 2000). The table below summarizes the $CO_2$ tolerance of various species. Note that some species may tolerate even higher carbon dioxide concentrations than listed in the table. Overall, a number of high $CO_2$ tolerant species have been identified.

*$CO_2$ Tolerance of Various Species*

| **Species** | **Known maximum $CO_2$ concentration** | **References** |
|---|---|---|
| *Cyanidium celdanum* | 100% | Seckbach et al. 1971 |
| *Scenedesmus sp.* | 80% | Hanagta et al. 1992 |
| *Chlorococcum littorale* | 60% | Kodama et al. 1993 |
| *Synechococcus elongates* | 60% | Miyairi 1997 |
| *Euglena gracilis* | 45% | Nakano et al., 1996 |
| *Chlorella sp.* | 40% | Hanagta et al. 1992 |
| *Eudorine spp.* | 20% | Hanagta et al. 1992 |
| *Dunaliella tertiolecta* | 15% | Nagase et al., 1998 |
| *Nannochloris sp.* | 15% | Yoshihara et al., 1996 |
| *Chlamydomonas sp.* | 15% | Miura et al., 1993 |
| *Tetroselmis sp.* | 14% | Matsumoto et al., 1995 |

*Source:* Mark E. Huntley (University of Hawaii) and Donald G. Redalje (University of Southern Mississippi)

## 5. Case Studies

### CEP & PGE, USA

Oct. 2008

One of the most recent algae-inspired projects is being undertaken by Washington-based Columbia Energy Partners LLC (CEP), which hopes to convert carbon dioxide from a coal-fired electricity plant into algal oil.

CEP is a renewable energy company that primarily focuses on wind and solar energy. Two years back, the company approached one of Oregon's electric utilities, Portland General Electric (PGE) to pitch the idea of converting carbon dioxide from the utility's coal-fired plant in Boardman, Ore., into algal oil for the production of biodiesel.

CEP is currently conducting the first phase of what will potentially be a three-phase project. A feasibility study is underway at the 600 megawatt Boardman facility to determine if algae can feed on the carbon dioxide emitted from the plant and what amounts of carbon dioxide, and potentially other greenhouse gases, can be consumed by the algae. Seattle-based BioAlgene LLC is providing the algae strains for this portion of the project. The possibility of a larger build-out is also being researched at this time. He anticipates a full-scale operation to include 7,500 acres of open air algae ponds.

Results from the first phase should be available sometime in December 2008. At that point, if the results are positive, the company plans to move forward with engineering details and the construction of larger, in-ground algae tanks while continuing to research the process. PGE had requested the project be conducted in "baby steps" and one can expect a commercial-scale project to be three to five years away. Some of the challenges that are being faced by the team have to do with keeping open-air algae ponds free from contamination and the actual process of squeezing oil from the algae. CEP is financing the project. The company hopes to eventually sell the carbon credits it would gain from the process back to PGE or another buyer, as well as generate revenue from the algae oil and potential animal feed byproducts.

**Linc Energy & BioCleanCoal, Australia**

Nov 2007

Two Australian firms, Linc Energy and BioCleanCoal, have partnered together in a joint venture to sequester carbon dioxide emissions from Australian coal-fired power stations to use as fuel or fertiliser, even re-burning it to produce additional energy.

The companies will spend $1 million to build a prototype reactor in Chinchilla, which will use the carbon dioxide emissions from the power plant to grow algae, which can then be dried and turned into biofuels. A company director of BioCleanCoal says that the process can easily remove 90 percent of carbon dioxide from the plant's emissions, with 100 per cent removal possible but unlikely due to the increased costs.

**Seambiotic, Israel**

The Israeli company Seambiotic has found a way to produce biofuel by channeling smokestack carbon dioxide emissions through pools of algae that clean it. The growing algae thrive on the added nutrients, and become a useful biofuel.

For the last two years, the company has tested their idea with an electric utility company - a coal-burning power plant in the southern city of Ashkelon operated by the Israel Electric Company (IEC).

The company's prototype algae farm in Ashkelon uses the tiny plants to suck up carbon dioxide emissions from power plants. Seambiotic's eight shallow algae pools, covering about a quarter-acre, are filled with the same seawater used to cool the power plant. A small percentage of gases are siphoned off from the power plant flue and are channeled directly into the algae ponds.Originally when the prototype started operating, a common algae called Nannochloropsis was culled from the sea and used in the ponds. Within months, the research team noticed an unusual strain of algae growing in the pools - skeletonema - a variety believed to be very useful for producing biofuel.

According to Noam Menczel, Seambiotic's director of investor relations, the company's developments have stirred interest around the world, specifically in Brazil, which has become one of the champions of R&D in the area of alternative and renewable fuels.

If all goes according to plan, Seambiotic plans to build its first large-scale biofuel reactor by next year and hopes to do so with a large international partner. Several potentials are already knocking on the door. Menczel reports that Seambiotic is meeting with electric plant operators from Hawaii, Singapore, Italy and India, all keen on hearing about Seambiotic's technology. (Aug 2007)

**Trident Exploration, Canada**

Trident Exploration Corp. is a natural gas exploration company. The company was looking at ways to reduce its $CO_2$ emissions. Trident approached a number of companies looking for solutions, and ended up teaming up with Menova last year.

Menova's Power-Spar system uses solar concentrators to focus the sun on photovoltaic solar cells, which produce electricity, and fluid-filled channels that capture the sun's heat. But the system goes one step further, capturing the sunlight and redirecting it where necessary through fibre-optic cables.

What this means is that an algae farm – Menova's photobioreactor – can be designed in a way where heat and light are concentrated in a relatively more confined area, allowing for the high-density growth of algae without the need for acres and acres of land.

On top of this, any algae system using Menova's collectors can produce electricity that can be sold into the grid or, in the case of Trident, used for their own power needs. Suddenly the economics, compared to other models on the market, begin looking attractive – even in Canada. Companies that purchase such a system can earn revenues generating electricity, producing raw material for making fuels and other bioproducts, and selling carbon credits into cap-and-trade markets.

In fact, Trident and Menova expect the system will reduce by half the amount of carbon emissions resulting from petroleum processing. The pilot project is expected to begin shortly, and a working commercial system is being targeted for 2010. (July 2007)

**EniTecnologie, Italy**

The objective of the EniTecnologie R&D project on microalgae biofixation of $CO_2$ was to evaluate on pilot scale the feasibility of using fossil $CO_2$ emitted from a NGCC power plant to produce algal biomass. The biomass would be harvested and then fermented by anaerobic digestion to methane to replace a fraction of the natural gas, with the residual sludge, containing most of the N, P and other nutrients, recycled back to the cultivation ponds. In a preliminary mass balance calculation, assuming near-theoretical productivities, a 700 ha system was projected to be able to mitigate 15% of the annual $CO_2$ emissions from a 500 MWe NGCC power plant. The R&D focuses on how to increase the productivities of algal mass cultures under outdoor operating conditions. The target is to double biomass productivities from the currently projected 30 g (dry weight)/m2/day to 60 g (dry weight)/m2/day for peak monthly productivities, corresponding to a solar energy conversion efficiency of about 5%. This would reduce land area requirements (footprint of the process) and costs of algal biomass production. As a first step towards this goal the team set out to demonstrate the currently achievable algal biomass productivity under outdoor conditions using a simulated NGCC-flue gas for $CO_2$ supply and two different mass cultivation systems

Source: http://uregina.ca/ghgt7/PDF/papers/nonpeer/075.pdf

*Details of another experiment at EniTechnologie in Feb 2007*

Researchers at EniTecnologie in Italy conducted a field experiment of $CO_2$ uptake by algae in a raceway pond. The *tetraselmis suecica* algae were supplied with $CO_2$ from natural gas turbine flue gas. The experiment was conducted between the months of April to November and it measured the rates of production correlated to ambient temperature and available light. EniTecnologie reported growth rates as mass of dry algae produced each day per square meter of raceway. During the April to November time period, productivity ranged between 10 and 30 $g/m^2/day$. The $CO_2$ uptake represents roughly half the weight of the dry algae, or ~5 to 15 g $CO_2/m^2/day$.

Source: http://mydocs.epri.com/docs/public/000000000001012796.pdf

**MBD Energy, Australia**

Aug 2009

Melbourne company MBD Energy is about to introduce technology that allows algae to capture half or more of the greenhouse gases emitted by a power station, at virtually no cost to the utility. Managing director Andrew Lawson says testing at James Cook University in Townsville suggests for every two tonnes of carbon captured, the MBD technology can produce almost 1 tonne of algae, of which one-third can be made into oil products and two-thirds into meal. With meal sales about $400/tonne (rival soymeal product sells at about $780/tonne) and oil selling at $800/tonne, that equates to about $570 of revenue from each tonne of algae, or more than $250 for each tonne of $CO_2$ captured.

The first 1ha display plant of its "fuel synthesiser" is to be installed at the Loy Yang A coal-fired power station in the next six months. If the concept is proved over six to 12 months, MBD will move ahead to build a commercial pilot plant over 80ha.

That will require a $25 million investment, but Lawson estimates it will produce earnings before interest, taxes, depreciation and amortisation of $15 million. If that project succeeds, the facility can quickly be scaled up to a $300m demonstration facility.

Australia's largest power station, NSW's Eraring Energy, and a large-scale emitter in Queensland have signed agreements with MBD to install display plants over the next 12 months.

The company says a privately funded, $1.2 billion facility could capture half of Loy Yang's carbon emissions and generate $740m of meal income a year and $660m of oil income, as well as carbon credits of about $225m, while using just 10MW of energy. It also recycles water.

The process can currently capture only half a utility's emissions because it relies on sunlight to cause photosynthesis, but Lawson says more can be captured if future testing with LED lighting proves successful.

$1.2 billion for a massive algae farm may sound costly, but Lawson says this is likely to be funded as a separate infrastructure project, with the utilities having the option to co-invest. Each project of that scale would create 2000 regional jobs.

MBD Energy is in the process of raising about $10 million from three cornerstone investors, including an international energy company and a local carbon fund.

**Arizona Public Service Co., USA**

Sep 2009

Arizona Public Service Co. has landed a $70.5 million US Department of Energy grant to try to feed algae with the carbon dioxide coming from its coal-fired electricity plants.

The grant will support the utility's carbon sequestration project at its Cholla Generating Station in northeastern Arizona. The project calls for the plant feed its carbon emissions to an algae pond, and that algae will be converted to biofuel. The grant comes from the DOE's roughly $1.4 billion Clean Coal Power Initiative, which has also seen applications from Duke Energy, NRG, Southern Co. and American Electric Power Co., among other utilities.

At least one other project of its kind is seeking DOE funding. Algae-to-biofuel company Origin Oil said last month that it was seeking grants for a project that would see captured carbon fed into algae ponds.

**RWE, Germany**

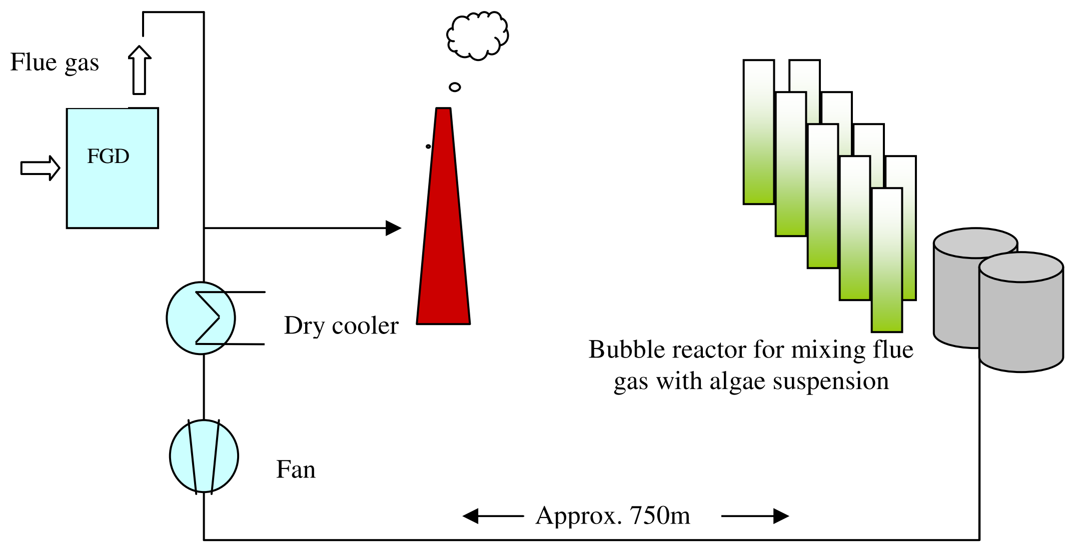
RWE has studied in detail various options for climate-beneficial recycling and trapping $CO_2$ in order to identify potentials and obtain recommendations for action. One result of these investigations is the project launched by RWE for binding $CO_2$ using micro-algae. RWE – together with partners – has launched a project: flue gases from the Niederaussem power station are fed into an algae production plant in the vicinity of the station to convert the $CO_2$ from the flue gas into algae biomass. On the basis of the algae biomass thus produced, a further aim is to investigate different conversion routes for the algae involving energetic and material use, e.g. for construction materials or fuels. Flue gas is withdrawn from a power plant unit and transported through pipes to the micro-algae production plant. The $CO_2$ contained in the flue gas is dissolved in the algae suspension and absorbed by the algae for growth. The algae are removed (harvested) and further explored for conversion into fuel and chemicals.

*Flue-gas withdrawal* - The flue gas to provide the algae with the $CO_2$ is withdrawn from a conventional lignite-based power-plant unit. The amount of flue gas needed is diverted downstream of the flue-gas desulphurization (FGD) system, i.e. in a state in which it is normally released into the environment. The flue gas downstream of the FGD contains high shares of water vapour. To ensure that this water vapour does not condense in and corrode the flue gas pipes, the flue gas is dried before being transported. The flue gas is then propelled with the aid of a fan through a pipe to the algae farm.

*Flue-gas pipe* **-** The pipe consists of PE. This plastic was selected to prevent any corrosion from the condensation of residual amounts of water vapour. The greenhouse in which the algae production system is built stands on a site adjacent to the power plant. The flue-gas pipe is approx. 750 m long in all.

*Bubble reactor* - **T**he flue-gas pipe ends in front of the greenhouse in which the algae production plant is located. The flue gases are fed into a so-called bubble reactor outside the greenhouse using a process from Novagreen Projektmanagement GmbH. The container has an algae suspension consisting of saltwater and the micro-algae in it. The flue gases mix with the algae suspension.

*Schematic diagram of the flue-gas link-up*




*Algae project data*

| | |
|---|---|
| Cooperation partners in the algae project | • RWE Power AG<br>• Jacobs University Bremen<br>• Forschungszentrum Julich GmbH<br>• Phytolutions GmbH |
| Contractors | • Bong, gardening firm<br>• Novagreen Projektmanagement GmbH, Vechta, algae reactors |
| Location of the algae project | • Bergheim-Niederaussem, in immediate vicinity of RWE's Niederaussem power plant<br>• Pilot plants at Jacobs University Bremen and the Julich Research Centre |
| Link-up to power plant | • 750 m flue-gas pipe with compressor |
| Max area of photobioreactors | • Approx. 1000 sq.m. |
| Expected algae production | • Approx. 6 T / year dry algae biomass (on 600 sq.m) |
| Expected $CO_2$ binding | • Approx 12 T/year from power plant flue gas (600 sq.m.) |
| Term for overall project | • 3 years |
| In operation since | • 2008 |

Source link: http://www.rwe.com/web/cms/mediablob/en/247480/data/235578/34391/rwe-power-ag/media-center/lignite/blob.pdf

**E-On Hansa, Germany**

In Nov 2007, German energy group E-On Hansa said it would build a $3.2 million pilot algae farm at its Hamburg power plant with support from the city government.

From October 2005 to October 2006 Thomsen, in collaboration with Eon Ruhrgas, Essen, and Bluebio-Tech, Kollmar, carried out a feasibility study of the capture of greenhouse gases by algae. It used marine microalgae as a natural carbon dioxide sink for the flue gases of a 350-MW coal-fired power station in the Bremen precinct of Farge. The aim was to capture 1% of the total emissions of this power station in a closed reactor system within five years. Two strains of algae used as animal feed and to produce oil were used.

Outcomes of the pilot experiment:

- Per ton of dry matter, the algae captured about two tons of $CO_2$
- Concurrently, the production fluctuated between 0.6 and 10 tons of dry algae mass per hectare and month, the highest yields achieved in summer
- Parallel to this the Bremen state government has installed a glass photo-bioreactor in a greenhouse of the university's ocean laboratory
- It's to be used for experiments in the use of marine microalgae for renewable primary products
- The Eon project is ongoing with the aim to cut production costs from one euro per Kg of dry algae mass to 60 cents.

**NRG Energy, USA**

April, 2007

NRG Energy and GreenFuel Technologies have started testing GreenFuel's algae-to-biofuels technology at a 1,489 megawatt coal power plant in Louisiana. GreenFuel's Emissions-to-Biofuels™ process uses engineered algae to capture and reduce flue gas carbon dioxide ($CO_2$) emissions into the atmosphere. The algae can be harvested daily and converted into a broad range of biofuels or high-value animal feed supplements, according to the company.

In the initial field testing, which is to last approximately four months, algae species will be selected to optimize biofuel production based on the site's flue gas composition, local climate and geography. The ultimate goal is construction of a commercial-scale facility. A full scale commercial deployment could recycle enough $CO_2$ to yield as much as 8,000 gallons of biodiesel per acre annually under optimum conditions, GreenFuel claimed. NRG owns a diverse portfolio of power-generating facilities, primarily in Texas and the Northeast, South Central and West regions of the United States.

## 6. Challenges while Using Algae for $CO_2$ Capture

- There are no comprehensive and authoritative estimates of cost of sequestering $CO_2$ from power plants using algae. Some initial estimates question the economics of having algae sequestration of $CO_2$, with current cultivation technologies and bioreactors. The economics of $CO_2$ sequestration for power plants could be affected owing to the following:

- Many power stations might not have the requisite area nearby. This would increase the capital costs for the pipes and the power used to move the gas through them by around twenty-fold. To cope with this change, the piping costs of instead of are used to approximate a more realistic situation, along with additional piping for distribution to the individual algae farm 'modules' and increase pumping requirements for the gas.
- High land costs near power plants

- A quote from an algae-based power plant sequestration effort in Canada (Jan 2009) – "In view of the interest and potential utility of algae culture for carbon capture, a preliminary calculation of the costs was conducted using a base model scenario, running for 6 months. The current cost of producing algae for carbon sequestration in BC (British Columbia) is $793 per tonne of $CO_2$. Note that this calculation only considers the carbon fixed in the algae biomass; full lifecycle carbon losses due to electricity and fertilizer use, etc. and other costs such as transportation and deep burial would have to be included, which will increase the cost per tonne. This cost is prohibitively high, about twenty times higher than the estimated cost of burying $CO_2$ underground, and at least one order of magnitude higher than the cost of the fuel, indicating that at this point carbon capture using algae is not cost effective in BC."-

http://www.bcic.ca/images/stories/publications/lifesciences/microalgae_report.pdf

- Sub-optimal Location of Power Plants - The ASP Program by NREL report concluded that flue gas sources would be a poor source for $CO_2$ for the microalgae ponds, as power plants were not generally located in a suitable area for microalgae cultivation.

## 7. Research and Data for Algae-based $CO_2$ Capture

**Select List of Research on Microalgae Fixation as a Process for Post-combustion $CO_2$ Capture**

| Reagent / Technology | State of Development | Research/Development Organization | Description |
|---|---|---|---|
| *Tetraselmis suecia* | Sub-scale demonstration | EniTecnologie | NGCC flue gas bubbled through open raceway pond with low rate algae – 8 month field trial |
| Micro-algae | Sub-scale | GreenFuel | Bubble flue gas through photobioreactors of high-rate micro-algae for CO2, NOx removal |
| Cyanobacterial: | Laboratory | Idaho National Lab | In photosynthetic |

| | | | |
|---|---|---|---|
| synechococcus sp. Strain PCC 8806 | | | bacteria, uptake of inorganic carbon raises pH, promoting CaCO3 precipitation |

Derived from: EPRI, 2006 - http://mydocs.epri.com/docs/public/000000000001012796.pdf

**$CO_2$ Transportation Using Pipelines**

Algae-based $CO_2$ capture will require large tracts of land even using the most advanced cultivation environments. It is unlikely that such large tracts of land will be available within or right next to power plant premises. This leads to the possibility of using pipelines to transport the $CO_2$ to a different location where the algae are cultivated.

Transportation of $CO_2$ over long distances using pipelines is a proven technology. The costs of such transportation could depend on a number of factors, and could be in the range of $2-$10 /T of $CO_2$. For example, for a 200 km pipeline, the cost of transport for a 100 MW power plant is $8.96 per tonne, whereas for a 500 MW power plant the cost is approximately $3.17 per tonne, and for a 1000 MW power plant the cost decreases to approximately $2.04 per tonne. (Source: Carnegie Mellon University, 2005 – Source link: http://www.netl.doe.gov/publications/proceedings/05/carbon-seq/Tech%20Session%20Paper%2092.pdf )

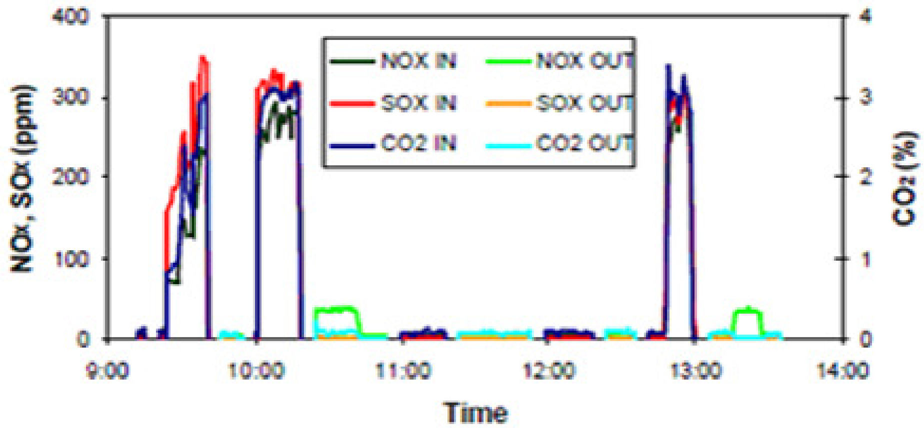
**Microalgal Removal of $CO_2$ from Flue Gases: $CO_2$ Capture from a Coal Combustor**
M Olaizola, T Bridges, S Flores, L Griswold (all four from Mera Pharmaceuticals, Inc. Kailua-Kona, Hawaii, USA), J Morency, T. Nakamura (the two from Physical Sciences Inc., Andover, Massachusetts, USA), 2004
Source link: http://www.netl.doe.gov/publications/proceedings/04/carbon-seq/123.pdf

*Composition of gas mixtures used in the simulated flue gas experiments according to the combusted material. A sixth treatment was 100% $CO_2$*

| **Fuel type** | **A. Bituminous coal** | **B. Sub-bituminous coal** | **C. Natural gas** | **D. Natural gas** | **E. Fuel oil** |
|---|---|---|---|---|---|
| Gas (wt) | Utility boiler | | | Gas Turb Comb | Diesel |
| $CO_2$ (%) | 18.1 | 24.0 | 13.1 | 5.7 | 6.2 |
| $O_2$ (%) | 6.6 | 7.0 | 7.6 | 15.9 | 17.0 |
| $N_2$ (%) | 71.9 | 68.1 | 79.3 | 78.4 | 76.7 |
| $SO_2$ (ppm) | 3504.0 | 929.7 | 0.0 | 0.0 | 113.1 |
| NO (ppm) | 328.5 | 174.3 | 95.1 | 22.1 | 169.7 |
| $NO_2$ (ppm) | 125.9 | 66.8 | 36.5 | 8.5 | 65.0 |

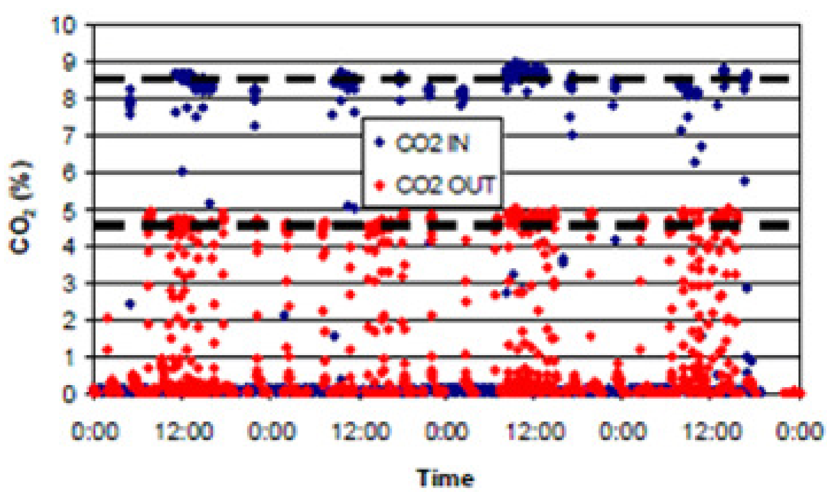
Typical composition of coal combustion flue gases, before and after entering the pilot scale PBR (2,000 liter) microalgal photobioreactor, are shown in Figure 11. On average, the mass calculations indicate that the microalgal culture was able to capture nearly 70% of the available $CO_2$ when the culture was maintained at pH 7.5.

*Gas analysis of coal combustion gases before (IN) and after (OUT) passage through the pilot scale photobioreactor*




Typical $CO_2$ composition of propane combustion flue gases, before and after entering the full scale PBR (25,000 liter) microalgal photobioreactor, are shown in Figure 12. On average, the mass calculations indicate that the microalgal culture was able to capture about 45% of the available $CO_2$ when the culture was maintained at pH 7.5.

*Concentration of $CO_2$ in the gas stream supplied from the propane combustor into the photobioreactor (IN) and in the gas stream leaving the photobioreactor (OUT) for a 4-day period*




In this report it is shown that:

- Microalgae are able to capture anthropogenic $CO_2$ from a wide variety of simulated flue gases and from actual coal and propane combustion gases.
- Microalgae are able to capture anthropogenic $CO_2$ under a wide variety of pH and gas concentrations
- The efficiency of $CO_2$ capture by microalgae is directly dependent on the pH of the culture but is not affected by differences in gas composition.
- The process is scalable to industrially significant scales.

## 8. Algae-based CO2 Capture - Factoids

- Some pertinent data related to algae-based CO2 capture are provided in the table below:

| | |
|---|---|
| Amount of $CO_2$ required the cultivation of 1 T of algae ( in T) | 1.8 |
| Amount of $CO_2$ emitted by a coal plant per MWh (in T) | 0.9 |
| Yield of algal biomass per hectare per day [(1)] (in T) | 0.3-1 |

1: The varying yields correspond to different culture conditions, such as in open ponds, closed ponds and photobioreactors. The estimates are approximate and could vary depending on algal strains used.

- During their ASP program research, the team estimated that $CO_2$ recovery from existing processes was relatively lower in cost from ethanol and ammonia plants, and much more expensive from cement, refineries, or power plants

- *Production of marine unicellular algae from power plant flue gas* - In order to have an optimal yield, these algae need to have $CO_2$ in large quantities in the basins or bioreactors where they grow. Thus, the basins and bioreactors need to be coupled with traditional thermal power centers producing electricity which produce $CO_2$ at an average tenor of 13% of total flue gas emissions. The $CO_2$ is put in the basins and is assimilated by the algae. It is thus a technology which recycles $CO_2$ while also treating used water. In this sense, it represents an advance in the environmental domain, even if it remains true that $CO_2$ produced by the centers would be released in the atmosphere by the combustion of biodiesel in buses and cars. Diatoms, which millions of years ago helped create the conditions necessary for the formation of hydrocarbons consumed today, will be useful to us a second time.

- Some researchers considered the effect of trace acid gases on $CO_2$ sequestration by microalgae, such as NOx and $SO_2$. As a source of trace elements, both model flue gas (Maeda et al., 1995; Nagase et al., 1998; Yoshihara et al., 1996) and actual flue gas (Matsumoto et al., 1995) have been used. It is reported that Nannochloris sp. could grow under 100 ppm of nitric oxide (NO) (Yoshihara et al., 1996). Less than 1000 ppm of NO and15% $CO_2$ concentration, *Dunaliella tertiolecta* could remove 51 to 96% of nitric oxide depending on the growth condition (Nagase et al., 1998). *Tetraselmis* sp. could grow with actual flue gas with 185 ppm of SOx and 125 ppm of NOx in addition to 14.1% $CO_2$ (Matsumoto et al., 1995). Maeda et al (1995) examined the tolerance of a strain of *Chlorella* and found that the strain could grow under various combinations of trace elements and concentrations. According to Geva Technologies (South Africa), direct use of flue gas reduces the cost of pre-treatment, but the high concentration of $CO_2$ and the presence of $SO_x$ and $NO_x$ inhibit the growth of cyanobacteria and other microalgae

- *$CO_2$ mitigation from photosynthetic microbes* - Reported here are results of a privately funded US$20 million program that has engineered, built, and successfully operated a commercial-scale (2 ha), modular, production system for photosynthetic microbes. The production system couples photobioreactors with open ponds in a two-stage process - a combination that was suggested, but never attempted - and has operated continuously for several years to produce *Haematococcus pluvialis*. The annually averaged rate of achieved microbial oil production from *H. pluvialis* is equivalent to <420 GJ $ha^{-1}$ $yr^{-1}$, which exceeds the most optimistic estimates of biofuel production from plantations of terrestrial ``energy crops." The maximum production rate achieved to date is equivalent to 1014 GJ $ha^{-1}$ $yr^{-1}$. Evidence is presented to demonstrate that a rate of 3200 GJ $ha^{-1}$ $yr^{-1}$ is feasible using species with known performance characteristics under conditions that prevail in the existing production system. At this rate, it is possible to replace reliance on current fossil fuel usage equivalent to 300 EJ $yr^{-1}$ - and eliminate fossil fuel emissions of $CO_2$ of 6.5 GtC $yr^{-1}$ - using only 7.3% of the surplus arable land projected to be available by 2050. By comparison, most projections of biofuels production from terrestrial energy crops would require in excess of 80% of surplus arable land. Oil production cost is estimated at $84/bbl, assuming no improvements in current technology. Enhancements that could reduce cost to $50/bbl or less are suggested ($CO_2$ Mitigation and Renewable Oil from Photosynthetic Microbes[1]

- *One calculation showed that 1600 giga-watt power plants converted to algae production* could manufacture enough ethanol and biodiesel to replace the US annual consumption of 146 billion gallons of gasoline. Replacing convention diesel too would increase this requirement to over 2000 giga-watt sized power plants—or twice the number of suitably located major plants. Smaller facilities or other industries might conceivably close the gap.

- *A different perspective for algae-based $CO_2$ sequestration* - Although recycling carbon from power generation for transportation would be a huge advance, it could slow the transition to a truly sustainable economy by prolonging dependence on fossil fuels. A 50% emission reduction would no doubt be a great victory, and one we would likely accept from anything less uncharismatic than coal. Any net carbon emissions to the atmosphere, however, are unsustainable in the long run.

- In October 2004, a report from the testing firm CK Environmental indicated that during a measuring period of 7 days for emissions, the bioreactors reduced nitrogen oxides by 85.9% (+/-2.1%); reduced $CO_2$ by 82.3% (+/-12.5%) on sunny days, and by 50.1% (+/-6.5%)on overcast or rainy days. Previous systems using algae managed to reduce $CO_2$ emissions by 5% and NOx emissions by 70%. The system can be used in latitudes where solar exposure is weak, albeit with relatively reduced efficiency. It is theoretically possible to achieve 90% $CO_2$ capture, but financial and technological constraints must be taken into account to reach such levels. Nevertheless, this bioreactor already constitutes a considerable technological advance.

- In Lake Elsinore, Calif., BioCentric Energy will collaborate with Southern Pacific Energy Inc. to deliver its carbon dioxide reduction and algae growth solution for biodiesel production, as well as residue gasification process to produce electricity (Oct 2008)

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[1] http://www.hrbp.com/PDF/Huntley%20&%20Redalje%202006.pdf

- In Wuhan, China, through a joint venture BioCentric Energy will work with a coal-fired steel facility to implement its carbon dioxide reduction/algae growth solution for biodiesel production, and residue gasification process to produce electricity (Oct 2008)

- In Orange County, Texas, BioCentric Energy will collaborate with joint venture partner Petroleum Equipment Institute, which purchased 54 acres owned by a prior Exxon refinery, to implement a project involving the development of two acres of both covered and non-covered algae canals to absorb carbon dioxide emissions and produce biodiesel and electricity (Oct 2008).

- Estimates of Ohio university researchers are that a 2000 MW power plant would require around 2500 acres of land around it to grow algae and reabsorb the emitted carbon dioxide.

- Much work has been done on the effect of different flue gas constituents on microalgal growth rates and carbon dioxide fixation. Typical power plant flue gases have carbon dioxide levels ranging from 10%–15%. At the typical carbon dioxide percentages, microalgae show no signs of significant growth inhibition. Furthermore, studies have shown that microalgae respond better to increased carbon dioxide concentrations, outgrowing (on a biomass basis) microalgae exposed to only ambient air (Maeda et al., 1995; Brown, 1996).

- In some experiments, it was estimated that the average yearly productivity of unicellular marine algae on flue gas in open ponds ~20 g/m2/day

- The pH of the culture medium is an important factor in algal cultivation. It can determine the solubility and availability of $CO_2$ and minerals in the culture (Bunt 1971 Raven 1980)

- It is known that growth of algae is positively influenced at all levels of $CO_2$ increase. (Lee and Lee 2003). Strains that grow well at $CO_2$ concentrations of 5-10% show drastic decreases in their growth rate above 20% (Watanabe et al. 1992).

- Mark Capron of PODenergy has a plan to establish giant "forests" of kelp seaweed at the surface of the ocean. These would be harvested and placed in large plastic bags suspended in the sea. Natural bacteria in the bags would digest the kelp, breaking it down into CO2 and methane. The two gases would be separated, with the CO2 sent to the deep ocean for permanent storage and the methane piped to the surface for use as a renewable heating and cooking fuel

- In July 2009, Algenol partnered with Dow Chemical. The companies announced plans to build and operate a demonstration plant on 24 acres of property at Dow's sprawling Freeport, TX, manufacturing site. The plant will consist of 3,100 horizontal bioreactors, each about 5 feet wide and 50 feet long and capable of holding 4,000 liters. The bioreactors are essentially troughs covered by a dome of semitransparent film and filled with salt water that has been pumped in from the ocean. The photosynthetic algae growing inside are exposed to sunlight and fed a stream of carbon dioxide from Dow's chemical production units

- In June 2009, a US Department of Energy program announced that chemical companies and other industrial sources of greenhouse gas emissions are eligible for $1.3 billion in grants for large-scale carbon capture and sequestration (CCS) demonstration projects. The same announcement also offered $100 million in funding for demonstrations of beneficial uses of CO2, such as using it to grow algae or converting it to fuel or chemicals. The announcement also says that DOE's targets for the grants are projects that are integrated into the plant's operations and are designed to capture and sequester 1 million tons of CO2 per plant per year by 2015.

- Renewed World Energies (RWE) wanted to clean up power plant and industrial plant emissions using algae and then have the algae turn the CO2 captured to generate both oil and a cake product. In June 2009, RWE will be building its first facility in Georgetown County, South Carolina. The company grows several different strains of algae and has a proprietary automated harvesting technology. RWE recently announced a process that captures the CO2 and nitrous oxide from smokestacks to grow algae

- In May 2009, Cynthia J. Warner, president of Sapphire Energy, testified before the full U.S. Senate Committee on Environment and Public Works Hearing on ‘Business Opportunities and Climate Policy’ to ensure that upcoming Cap and Trade legislation included a proper ‘carbon accounting’ for emerging and proven algae-based fuel.

- In May 2009, the company BioProcessAlgae has been awarded a $2.1 million grant from the state of Iowa to build the first photobioreactor systems attached to an industrial plant in the United States. The pilot project, which is supposed to be installed by the fall of this year, would capture CO2 from a Green Plains corn ethanol plant in Shenadoah, Iowa, and use it to grow algae.

- MRI’s Center for Integrated Algal Research (www.mriresearch.org) - MRI’s Center for Integrated Algal Research focuses on research and technology development associated with identifying and optimizing algal species for carbon dioxide sequestration and biofuel production. MRI scientists and engineers have expertise in:
    - Isolating and purifying algal seed cultures
    - Optimizing growth kinetics
    - Integrating processing technologies (harvesting, de-watering, oil extraction, refining) for scale-up
    - Operating and maintaining open, closed and hybrid algal production systems
    - Identifying and eliminating bioreactor contamination
    - Recovering and processing algal products for other sustainable applications
    - Integrating instrumentation to monitor system performance in algal culture systems
    - Characterizing algal species (expression profiling , lipid, protein, phylogenetic analysis, gene sequencing)
    - Providing carbon sequestration test and evaluation
    - Conducting studies for bioprocess mass and energy balance and economic feasibility
    - Designing and constructing algae bioreactor systems
    - Bioprospecting native algae species to determine suitability for specific applications. (e.g. evaluation of algae in a wastewater treatment facility)

## 9. Algae Cultivation Coupled with $CO_2$ from Power Plants – Q&A

**Is there a possibility of heavy metal contamination in algae due to their presence in the flue gases?**

Yes. The possibility exists because most of the absorption of toxic metals by algae is of the passive type.

**How do the constituents other than $CO_2$ in flue gas from power plants affect algal growth?**

Sulfur oxides, particularly $SO_2$, can have a significant effect on the growth rates and health of the microalgae. Of greatest concern is the effect $SO_2$ has on the pH of the microalgal growth medium. When the $SO_2$ concentration reaches 400 ppm, the pH of the medium can become lower than 4 in less than a day, which significantly affects the productivity of the microalgae. However, if the pH is maintained at 8 using NaOH, the productivity does not decrease (Matsumoto et al., 1997). Other researchers have demonstrated tolerances to sulfur oxides at approximately half of what Matsumoto and coworkers (1997) demonstrated (Brown, 1996; Zeiler et al., 1995). Nannochloris sp. (NANNO02) was found to be resistant to 50 ppm $SO_2$, but without pH control, 300 ppm $SO_2$ inhibited growth within 20 hours (Negoro et al., 1991).

Nitrogen oxides also comprise a significant portion of power plant flue gas. As with the sulfur oxides, nitrogen oxides can affect the pH of the algal medium, but to a lesser degree. Microalgae have been shown to tolerate and grow in a medium containing 240 ppm NOx, with pH adjustment. Brown (1996) and Zeiler and coworkers (1995) also demonstrated that microalgae are not growth inhibited by the presence of 150 ppm NO. Negoro and coworkers (1991) found that NANNO02 grew in the presence of 300 ppm NO after a considerable lag time. A point of interest is that the nitrogen oxides can serve as a nitrogen source for the microalgae. NO is absorbed into the medium and oxidized into $NO_2$ in the presence of oxygen (Negoro et al., 1991). The greater the oxygen contents of the medium, the greater the $NO_2$ production and microalgal productivity rates (Matsumoto et al., 1997; Brown, 1996). However, the presence of elevated concentrations of oxygen results in algal photorespiration, which inhibits microalgal growth.

The effect of soot dust and ash containing heavy metals has received limited attention. Matsumoto and coworkers (1997) confirmed that when soot dust concentration is greater than 200,000 $mg/m^3$ (0.2 g/L), algal productivity is influenced. It is rare for the soot dust concentration to reach such an elevated value since it is most commonly on the order of 50 mg/m3 (5 × 10!5 g/L). The same argument can be applied to the presence of trace heavy metals. Higher concentrations can affect algal productivity, but only in rare situations will the concentrations exceed those that will result in a significant impact.

**Will NOx present in the flue gas serve as a nutrient, in addition to the $CO_2$?**

Flue gas supplies the carbon dioxide and has the ability to supply some of the nitrogen (from nitrogen oxide; it absorbs $SO_2$ as well). However, it has been demonstrated that the nitrogen contribution from the flue gas is insufficient to maintain stable growth rates (Weissman and Tillett, 1992). Therefore, nitrogen (along with phosphorus and trace nutrients) needs to be added and maintained as necessary with proper engineering.

**Can algae withstand the high temperatures in the flue gases?**

In a commercial application, flue gas from the desulphurization scrubbers would be sent to the $CO_2$ sequestration ponds for treatment. Temperatures exiting the scrubbers at many coal power stations are 140°F (60°C) and above – this could reach even upwards of 100$^{o}$C. Although most organisms cannot survive at these higher temperatures, some cyanophycean algae have been shown to grow at 176°F (80°C).

Since the temperature of waste gas from thermal power stations is high, the use of thermophilic, or high temperature tolerant species are also being considered (Bayless et al., 2001). Themophiles can grow in temperature ranging from 42-100$^{o}$C. An obvious advantage of the use of thermophilies for $CO_2$ sequestration is reduced cooling costs. In addition, some thermophiles produce unique secondary metabolites (Edwards, 1990), which may reduce overall costs for $CO_2$ sequestration. A disadvantage is the increased loss of water due to evaporation. *Cyanidium caldarium*, which can grow under pure $CO_2$ is a thermophilic species (Seckbach et al., 1971). Miyairi (1995) examined the growth characteristics of *Synechococcus elongatus* under high $CO_2$ concentrations. The upper limit of $CO_2$, concentration and growth temperature for the species was 60% $CO_2$ and 60ºC (Miyairi, 1995). Currently, an unidentified thermophilic species isolated from Yellowstone National Park has been examined by the group of researchers supported by the U.S. Department of Energy. Although less tolerant than thermophiles, some mesophiles can still be productive under relatively high temperature (Edwards, 1990). Such species also can be candidate species for the direct use of flue injection.

**What is amount of $CO_2$ required for algae growth?**

It is estimated that approximately 2 T of $CO_2$ will be required to produce one T of algal biomass.

**Can we grow macroalgae for power plant $CO_2$ sequestration?**

Macroalgae cultivation in marine environments have been studied as a possible means of large scale $CO_2$ sequestration, and many experts think that this avenue has good potential. A study has even estimated that a combination of micro- and macroalgae grown in open oceans could sequester between 0.7 to 3 gigatons (billion tons) of carbon per year from the atmosphere, at an estimated cost of $5 to 300 per T of carbon.

However, limited research has been done on growing macroalgae next to power plants for $CO_2$ sequestration. These researches have suggested that there are some disadvantages in using macroalgae for $CO_2$ sequestration, specifically in the context of the ability of macroalgae to survive in power plant flue gas. For instance, a patent by Friedlander et al, Israel Oceanographic & Limnological Research, National Institute of Oceanography (Feb 1996), suggests that Gracilaria cultures (a genus of macroalgae) did not survive more than 2-8 weeks in the power plant effluents during the one-year-long repeated experiments. The major reason was the high accumulation of copper, iron, lead and chromium from the power plant effluents as compared to concentrations in Gracilaria cultured in ambient seawater.

**What are the major problems faced by companies implementing algae based $CO_2$ sequestration techniques near power plants?**

Some of the major problems with algae based $CO_2$ sequestration technology are:

- The high cost of implementing the sequestration infrastructure
- The limited availability of land space near power plants for building algae systems
- There are some specific operational problems as well, which could result in significant inefficiencies. For instance, high $CO_2$ concentrations could cause the algae suspension to become acidic, thereby stunting algae growth.

**Can power plants use waste water from their facilities for growing algae?**

Power plants may not be able to use waste water from their facilities. In the power plant industry, large volumes of water are used by cooling systems. Water is also used in the FGD (flue gas desulfurization) plant, boiler cleaning, ash transport, demineraliser plant regeneration, and water also accumulates from coal stockpile run-offs. As a consequence, the effluent from power plant industry has higher temperature and also has heavy metals such as chlorine, copper, aluminum, mercury and phosphorus. It is difficult to grow algae in these effluents. However, some strains that have tolerance to heavy metal contamination and high temperature could possibly be grown.

**What are the methods by which flue gas can be cooled before passing it into algae systems?**

Studies have found that direct cooling with no heat exchangers using cooling towers and mechanical chillers, is the most efficient and low cost cooling method of cooling the flue gas.

**Is it necessary that algae ponds need to be constructed right next to power plants?**

Construction of algae systems near power plants is mostly preferred for the reduced capital costs, which will otherwise be required for putting up the pipelines for $CO_2$ transportation from the power plant to algae cultivation systems.

**What is the average area required for the construction of algae ponds for each power plant?**

Efforts at putting up algae-based CO2 sequestration systems near power plants are in a nascent stage. Hence only preliminary data are available regarding areas required and their attendant costs. Some initial research done at universities and during pilot projects suggest that it could take an open pond of about 8 square miles (5120 acre pond) to produce enough algae to remove carbon dioxide from a midsized — 500 MW — power plant.

## Guides and Reports from Oilgae

**Comprehensive Oilgae Report** - http://www.oilgae.com/ref/report/report.html - the most detailed report on all aspects of algae fuels.

**Oilgae Report Academic Edition** - http://www.oilgae.com/ref/report/academic/academic_report.html - algae fuels report specifically targeted at the academic and research community.

**Oilgae Digest** - http://www.oilgae.com/ref/report/digest/digest.html - a precise guide that provides answers and data for the critical questions in algae fuels

**Algae-based Waste Water Treatment** - http://www.oilgae.com/ref/report/wastewater_treatment/wastewater_treatment.html - a comprehensive guide on all aspects of waste water bioremediation using algae.

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