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Techno-economic analysis and engineering design consideration of algal biofuel in southern Nevada

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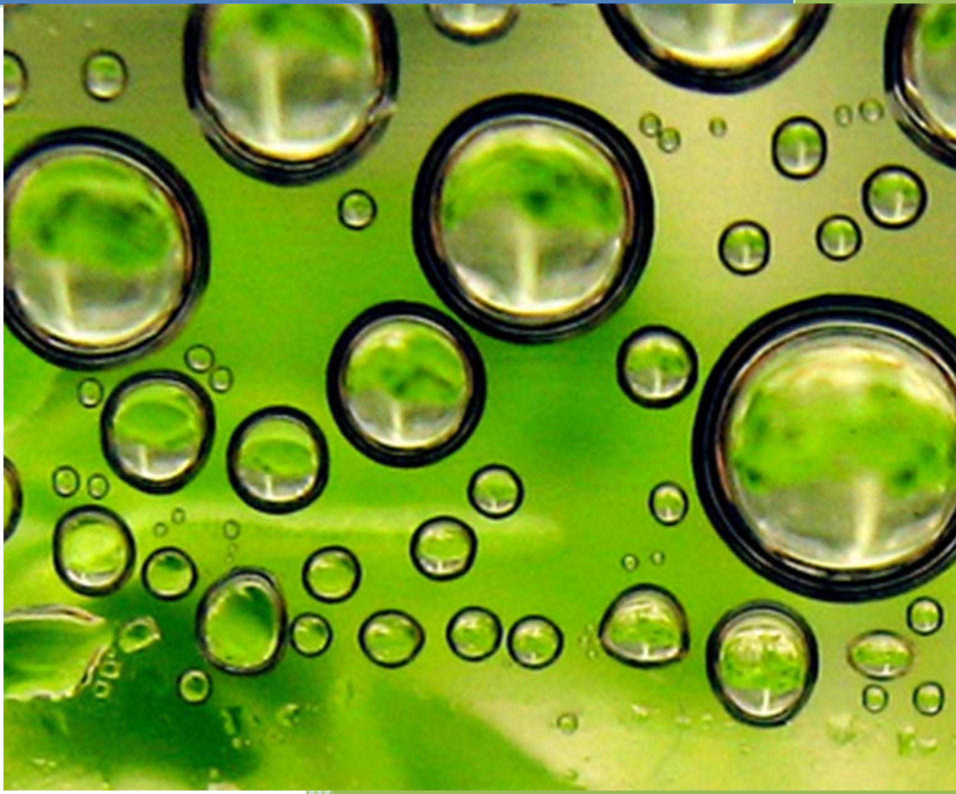
Techno-Economic Analysis and Engineering Design Consideration of Algal Biofuel in Southern Nevada



Dr. Jian Ma

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Final Report

Techno-Economic Analysis and Engineering Design Consideration of Algal Biofuel in Southern Nevada

For Subtask 1.3 of Project of Nevada Renewable Energy Consortium

Report Prepared by

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Date: January, 2011

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1. Project Objectives

As the biological and chemical technologies in algae biofuels production, engineering design, siting and resources are playing same dominant role in successfully developing and scaling locally. The southwest region in U.S. has been identified by DoE and the USDA as the most suitable area for developing algal biofuel production due to several merits like the high level of solar radiation, large arid land not good for food production. Among this region, Southern Nevada has unique advantage to grow microalgae biomass, which is the large amount of CO2 emission from about 16 power plants in Clark County to support the world famous entertainment city, Las Vegas. The intensive CO2 emission provides plenty of carbon sources for microalgae cultivation. In addition, millions of tourists from all over the world visiting Las Vegas generate lots of wastewater to be treated in Las Vegas valley. Including the local residents, there are about 100 million gallons wastewater generated per day in the Clark County. Together with CO2, wastewater provides sufficient inorganic components (or nutrient) for large scale microalgae cultivation.

Abundant sunlight in the desert area like Las Vegas definitely enhances the annual productivity of algal biomass. On the other hand, it will cause huge amount of water evaporation, if the traditional open pond cultivation technology is employed. Although one of the benefits of growing microalgae is that algal culture can utilize municipal wastewater, huge evaporation is still need to be avoided to gain more return flow credits to satisfy the growing demands of fresh water supply from Colorado River System. The annual evaporation rate in the Clark County area is about $2.28m^3/m^2$-day, according to the 1997-1999 Lake Mead survey data. About 10% of the water used for open pond cultivation will be lost only due to evaporation. Growing microalgae in closed photobioreactor or covering open pond with plastic film will be the solution to reduce significantly water evaporation. However the capital cost of material and labor will be high. The techno-economic analysis, therefore, is important to provide information for decision-making.

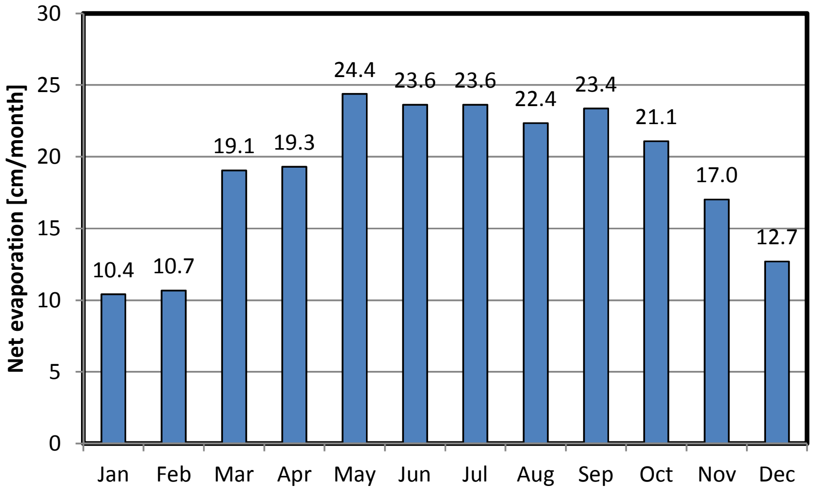


Figure 1. Average monthly evaporation from Lake Mead, Arizona and Nevada, July 1997-December 1999.

Unlike the mature high rate open pond technology, closed photobioreactor has high potential to push the algal productivity per area to its limits. With many processing parameters can be optimized on an overall system level, closed photo-bioreactor has so many benefits, like

- The closed configuration makes the control of contaminants easier and make the cultivation system stable;
- Harvesting cost per unit mass can be significantly reduced because of the higher cell mass productivities attained (up to 3-fold those obtained in open systems);
- And less water evaporation, high rate CO2 usage etc.

Additionally, the growth rate of microalgae is heavily dependent on cultivation media. In summer, higher temperature of cultivation water makes high productivity of microalgae in open pone to about 38 g/m^2-day. In the winter climates, out-door water body temperature drops to lower level and the productivity of algal biomass reduced to 4 g/m^2-day accordingly.

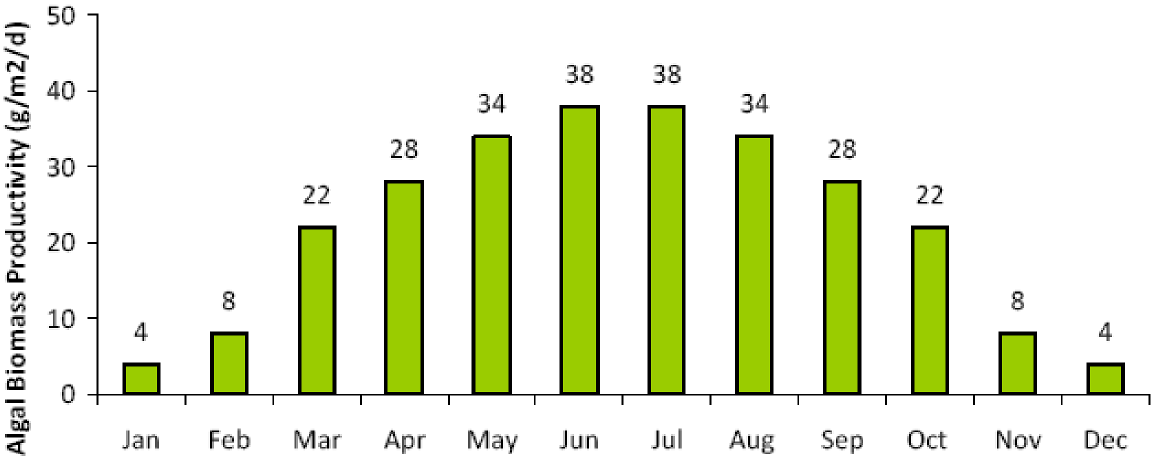


Figure 2. Assumed daily areal biomass productivity on a monthly average basis.

The almost ten-fold variation between highest and lowest productivity is one the major challenges in the design of proposed process. The less water usage in closed photobioreactor makes it easier and energy saving to design practical engineering system to maintain cultivation system at higher temperature using waste heat from power plant. As a result, the annual average productivity of algal biomass will be enhanced significantly.

If the closed photobioreactor (PBR) technology is chosen for large scale cultivation of algal biomass, another challenge is the life time of material for PBR. Among several closed PBR designs, tubular and flat plate reactors are the most popular choices with high possible area-to-volume ratio while ensuring reasonable working volume, mixing pattern and carbon dioxide level. Similar to the tubular and flat plate reactor, hanging bag using polyethylene film is believed to be the cheapest and easy handling technology of closed PBR. The life-time analysis as well as the light transmittance properties and price were investigated in this report.

Finally, closed-photobioreactor with hanging bag design was the focus of investigation for large scale microalgae cultivation. Other relevant research topics associated with the closed PBR were carried out and are listed as below,

1. Efficiencies of Photosynthesis and Solar Conversion of microalgae;
2. Reflection loss of solar energy using hanging bag PBR;

3. Maximum ideal productivity of algal biomass in Southern Nevada;
4. Feasibility of artificial light illumination for microalgae cultivation;
5. Several PBR prototype design and testing;
6. Evaporation estimation in Southern Nevada;
7. Effects of CO2 level to the grow rate of green ***Chlorella***;
8. Low density polyethylene thin-film material for closed photo-bioreactor
9. Thermo-economic analysis of microalgae co-firing process for fossil fuel-fired power plants;
10. Economic analysis of microalgae with oil extraction or oil extraction and biogas from anaerobic digester in Southern Nevada
11. Software development for Techno-Economic Analysis of Algal Biomass

2. Project Activities and Results

2.1 Efficiencies of Photosynthesis and Solar Conversion of Microalgae

The productivity of microalgae is depended on lots of parameters, such as temperature, pH value, nutrient level, CO2 level and solar irradiation, respectively. Some companies claim their productivity is quite high, which is possibly in-correct. In order to find out the reasonable number of productivity of algal biomass used for correct economic estimation, investigation of efficiency of photosynthesis and solar conversion locally were carried out.

Efficiency of Photosynthesis

Photosynthesis is the formation of carbohydrates in the chlorophyll-containing tissues of plants exposed to light. During photosynthesis in green plants, light energy is captured and used to convert water, carbon dioxide, and minerals into oxygen and energy-rich organic compounds. (Wikipedia 2009)

In many green plants, carbohydrates are the most important direct organic products of photosynthesis. The formation of a simple carbohydrate, glucose, is indicated by the following chemical equation:

$$6CO_2 + 12H_2O + light + greenplant = C_6H_{12}O_6 + 6O_2 + 6H_2O \qquad [1]$$

Carbon dioxide glucose oxygen water

Glucose is then converted in the plant to starch and cellulose (which are polymers of glucose), sucrose, amino acids, proteins, fats, pigments, and other organic compounds. Chemical bonds are broken between the carbon and oxygen (in the CO_2) and between the hydrogen and oxygen (in the water), and new chemical bonds are formed in the organic compounds. More energy is required to break the bonds of CO_2 and H_2O than is released when the organic compounds are formed. This excess bond energy accounts for the light energy stored as chemical energy in the organic compounds form during photosynthesis. The amount of light, the carbon dioxide concentration and the temperature are the three most important environmental factors that directly affect the rate of photosynthesis. Plant species and plant physiological state also affect the rate of photosynthesis.

The energy efficiency of photosynthesis is the ratio of the energy stored to the energy of light absorbed. The chemical energy stored is the difference between that contained in gaseous oxygen and organic compound products and the energy of water, carbon dioxide, and other reactants. The amount of energy stored can only be estimated because many products are formed, and these vary with the plant species and environmental conditions. If the equation for glucose formation given earlier is used to approximate the actual storage process, the production of one mole (*i.e.*, 6.02×10^{23} molecules; abbreviated N) of oxygen and one-sixth mole of glucose results in the storage of about 117 kilocalories (kcal) of chemical energy. This amount must then be compared to the energy of light absorbed to produce one mole of oxygen in order to calculate the efficiency of photosynthesis. (Britannica 2009)

Light can be described as a wave of particles known as photons; these are units of energy, or light quanta. The quantity N photons is called an einstein. The energy of light varies inversely with the length of the photon waves; that is, the shorter the wavelength, the greater the energy content. The energy (e) of a photon is given by the equation $e = hc/\lambda$, where c is the velocity of light, h is Planck's constant, and λ is the light wavelength. The energy (E) of an einstein is $E = Ne = Nhc/\lambda = 28{,}600/\lambda$, when E is in kilocalories and λ is given in nanometers (nm; 1 nm = 10^{-9} meters). An einstein of red light with a wavelength of 680 nm has an energy of about 42 kcal. Blue light has a shorter wavelength and therefore more energy than red light. Regardless of whether the light is blue or red, however, the same number of einsteins are required for photosynthesis per mole of oxygen formed. The part of the solar spectrum used by plants has an estimated mean wavelength of 570 nanometers; therefore, the energy of light used during photosynthesis is approximately 28,600/570, or 50 kilocalories per einstein.

In order to compute the amount of light energy involved in photosynthesis, one other value is needed: the number of einsteins absorbed per mole of oxygen evolved. This is called the quantum requirement.

The quantum requirements of the individual light reactions of photosynthesis are defined as the number of light photons absorbed for the transfer of one electron. The quantum requirement for each light reaction has been found to be approximately one photon. The total number of quanta required, therefore, to transfer the four electrons that result in the formation of one molecule of oxygen via the two light reactions should be four times two, or eight. It appears, however, that additional light is absorbed and used to form ATP by a cyclic photophosphorylation pathway (see next section). The actual quantum requirement, therefore, probably is nine to ten.

The minimum quantum requirement for photosynthesis under optimal conditions is about nine. Thus the energy used is 9 × 50, or 450 kilocalories per mole of oxygen evolved. Therefore, the estimated maximum energy efficiency of photosynthesis is the energy stored per mole of oxygen evolved—117 kilocalories—divided by 450; that is, 117/450, or 26%.

The actual percentage of solar energy stored by plants is much less than the maximum energy efficiency of photosynthesis. An agricultural crop in which the biomass (total dry weight) stores as much as 1 percent of total solar energy received on an annual area-wide basis is exceptional, although a few cases of higher yields (perhaps as much as 3.5 percent in sugarcane) are reported. There are several reasons for this difference between the predicted maximum efficiency of photosynthesis and the actual energy stored in biomass. First, more than half of the incident sunlight is composed of wavelengths too long to be absorbed, while some of the remainder is reflected or lost to the leaves. Consequently, plants can at best absorb only about 34 percent of the incident sunlight. Second, plants must carry out a variety of physiological processes in such nonphotosynthetic tissues as roots and stems; these processes, as well as cellular respiration in all parts of the plant, use up stored energy. Third, rates of photosynthesis in bright sunlight sometimes exceed the needs of the plants, resulting in the formation of excess sugars and starch. When this happens, the regulatory mechanisms of the plant slow down the process of photosynthesis, allowing more absorbed sunlight to go unused. Fourth, in many plants, energy is wasted by the process of photorespiration. Finally, the growing season may last only a few months of the year; sunlight received during other seasons is not used. Furthermore, it should be noted that if only agricultural products (*e.g.,* seeds, fruits, and tubers, rather than total biomass) are considered as the end product of the energy conversion process of photosynthesis, the efficiency falls even further.

Solar Conversion Efficiency of Microalgae in Southern Nevada

Some claims of high photosynthesis efficiency are based on the data from laboratory scale using artificial illumination, which has narrow spectra in comparing with solar radiation.

Light is an electromagnetic radiation, with wave and particle properties. The electromagnetic radiation has a spectrum or wavelength distribution from short wavelength (10^{-6} nm, gamma and x-rays) to long wavelength (10^{15} nm, long radio waves). About 99% of the Sun's radiation is in the wavelength region from 300 to 4000 nm and it is called the broadband or total solar radiation. Within this broadband, different forms of energy exist, which can be associated with specific phenomena such as harmful and potentially mutagen ultraviolet radiation (UV 100-400 nm), sigh (visible light 400-700 nm), and heat (infrared radiation 700-4000 nm). Therefore, what we see as visible light is only a tiny fraction of the electromagnetic spectrum; detecting the rest of the spectrum requires an arsenal of scientific instruments ranging from radio receivers to scintillation counters.

The spectrum of the Sun's solar radiation is close to that of a black body with a temperature of about 5,800K (Wikipedia 2009 b). About half of the solar radiation spectrum lies in the visible short-wave part of electromagnetic spectrum and the other half mostly in the neat-infrared part. Some also lies in the ultraviolet part of the spectrum.

The average intensity of the total solar radiation reaching the upper atmosphere is about 1.4 kWm^{-2} (UV 8%, visible light 41%, and infrared radiation 51%). (Barsanti 2006) The amount of this energy that reaches any one "spot" on the Earth's surface will vary according to atmospheric and meteorological (weather) conditions, the latitude and altitude of the spot, and local landscape features that may block the Sun at different times of the day. In fact, as sunlight passes through the atmosphere, some of it is absorbed, scattered, and reflected by air molecules, water vapor, clouds, dust, and pollutants from power plants, forest fires, and volcanoes. Atmospheric conditions can reduce solar radiation by 10% on clear, dry days, and by 100% during periods of thick clouds. At sea level, in an ordinary clear day, the average intensity of solar radiation is less than 1.0 kWm^{-2} (UV 3%, visible light 42%, and infrared radiation 55%).

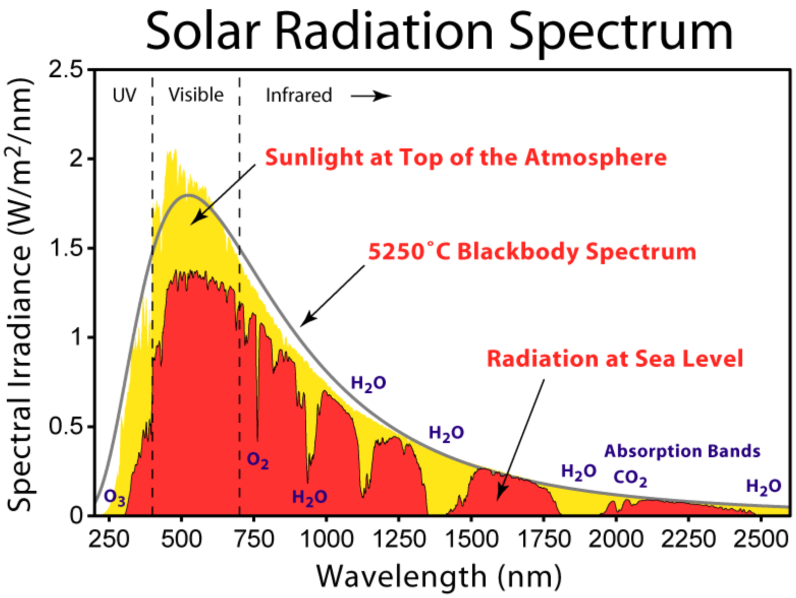


Figure 3. Solar radiation spectrum

The total maximum solar conversion efficiency of microalgae (from solar energy into stored chemical energy) can be obtained by production of photosynthesis efficiency and 42% visible light intensity of solar radiation at sea level, which is 42%×26%, 10.9%.

In practice, however, the magnitude of photosynthetic efficiency observed in the field, is further decreased by factors such as poor absorption of sunlight due to its reflection, respiration requirements of photosynthesis and the need for optimal solar radiation levels. (Miyamoto 2009)

2.2 Reflection Loss of Solar Energy in Micro-algal Cultivation

If cultivate algae in open pond, much of the incident light is reflected from the water surface, more light being reflected from a ruffled surface than a calm one and reflection increases as the Sun descends in the sky, due to its increasing incident angle. As light travels through the water column, it undergoes a decrease in its intensity (attenuation) and a narrowing of the radiation band is caused by the combined absorption and scattering of everything in the water column including water.

If closed photobioreactor is used for growing microalgae, the reflection loss becomes more complicated depending on the shape of photobioreactor (e.g. circular tube, planner channel, or elliptical shape of hanging bag), layout angle of photobioreactor and the position of sun.

The minimum reflection loss of solar energy can be estimated based on Fresnel equations and Snell's law. When light moves from a medium of a given refractive index n_1 into a second medium with refractive index n_2, both reflection and refraction of the light may occur. The fraction of the incident power that is reflected from the interface is given by the reflectance R and the fraction that is refracted is given by the transmittance T. The media are assumed to be non-magnetic.

The calculations of R and T depend on polarization of the incident ray. The transmission coefficient in each case is given by $T\mathrm{s} = 1 - R\mathrm{s}$ and $T\mathrm{p} = 1 - R\mathrm{p}$. If the incident light is un-polarized (containing an equal mix of *s*- and *p*-polarizations), the reflection coefficient is $R = (R\mathrm{s} + R\mathrm{p})/2$. For the case of light pass through from air into water, the reflection coefficient variations with incidence angle are illustrated in Figure 1. The refractive index of air is $n_1 = 1$, and for water is 1.33.

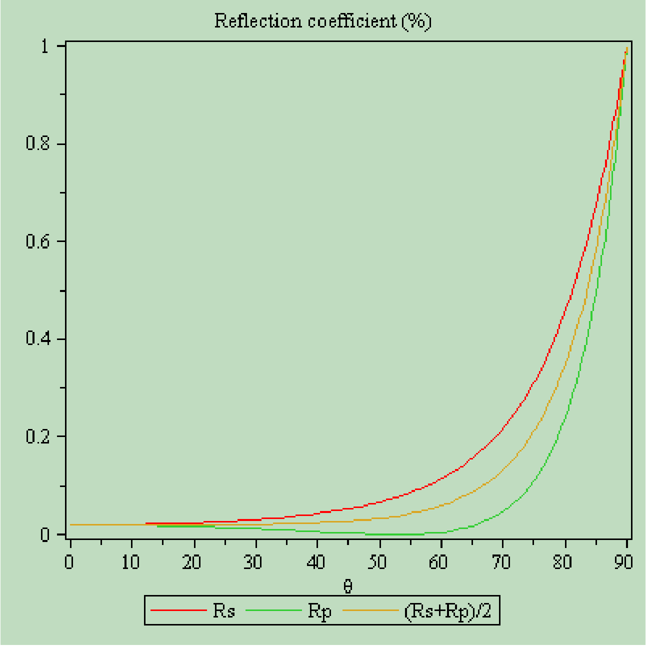


Figure 4. Reflection coefficient from air to water n_1=1(air), n_2=1.33 (water)

For the case of light pass from air into water, the reflection coefficient is 0.02 (or 2%), when light is at near-normal incidence to the water surface. This 2% will be valid until the incident angle is larger than 45°, which is the critical angle to keep the minimum reflection loss. Therefore, we have to consider about 2% loss of light by reflection.

If the close photobioreactor is taken into consideration, the refractive indices for different material have to be used to obtain the reflection coefficients. For example, material of PE (Polyethylene) used for the plastic bag design has refractive index of 1.51. (TexLoc) About 4.1% incident light lost by reflection from air into polyethylene. If we check further light pass from PE into water, there are about 0.4% the reflection loss, as shown in Figures 4 and 5.

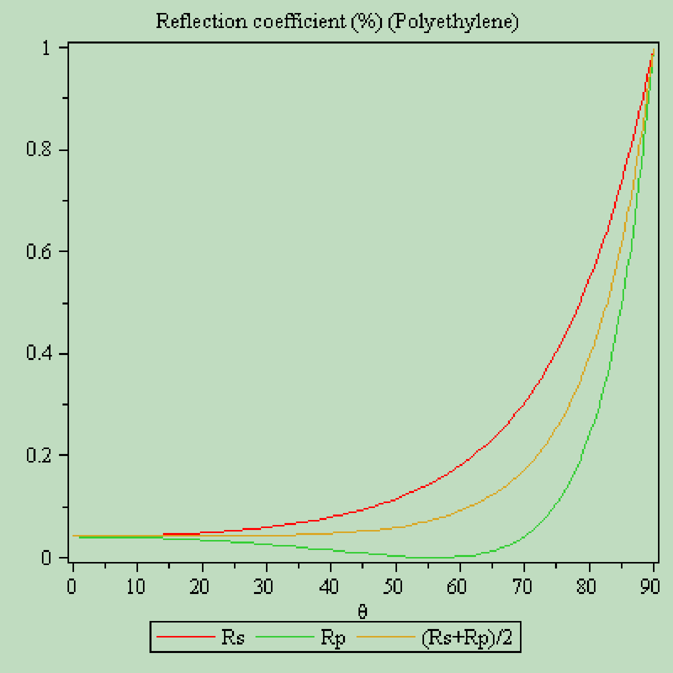


Figure 5. Reflection coefficient from air to polyethylene, n_1=1(air), n_2=1.51 (polyethylene)

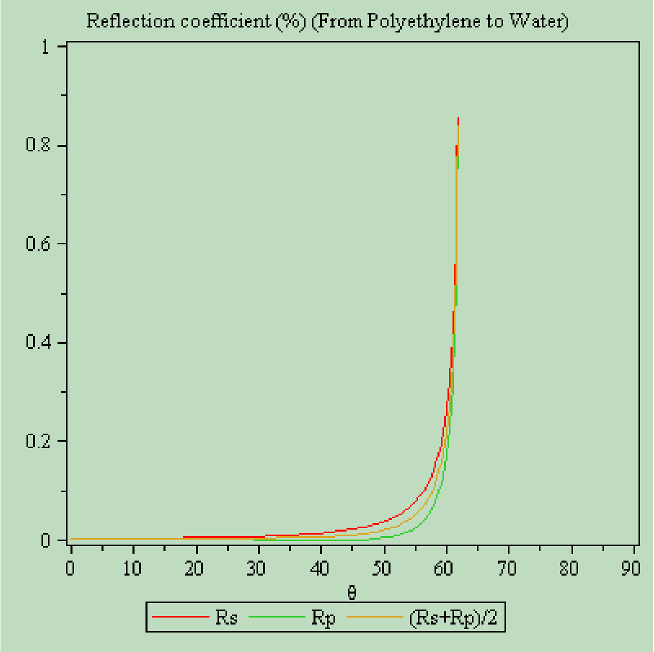


Figure 6 Reflection coefficient from polyethylene to water, n1=1.51 (polyethylene), n2=1.33 (water)

Glass and acrylic glass are two other common materials for photobioreactor. For common glass, refractive index is about 1.517. For acrylic glass (Poly (methyl methacrylate-PMMA), the refractive index at wavelength of 587.6 nm is 1.4914.

Therefore, the critical incident angle and total reflection loss of light passing through from air into different materials are listed in Table 1.

	Water	PE	Glass	Acrylic glass
Refractive index	1.33	1.51	1.52	1.49
Air->material	2%	4.1%	4.2%	3.9%
Material to water	N/A	0.4%	0.4%	0.3%
Critical angle for reflection	45°	46°	43°	45°
Combined reflection by two side	N/A	7.9%	8.1%	7.5%

Table 1. Minimum reflection loss and their critical incident angles.

2.3 Maximum Ideal Productivity of Algal Biomass in Southern Nevada

Solar Insolation in Southern Nevada (Las Vegas)

Insolation (Incoming Solar Radiation) is the amount of solar radiation incident on any surface. The amount of insolation received at the surface of the Earth is controlled by the angle of the sun, the state of the atmosphere, altitude, and geographic location. The values of solar insolation are commonly expressed in kWh/m^2/day. This is the amount of solar energy that strikes a square meter of the earch's surface in a single day. Geographic locations with low insolation levels require larger solar energy collection area than locations with higher insolation levels. Based on the data provided by NASA, the top five yearly average solar insolation levels locates at Phoenix, Los Angeles, Miami, Honolulu, and Las Vegas. In the southern Nevada, Las Vegas has yearly average solar insolation of 5.3 kWh/m^2/day. (see Figure 7 blow)

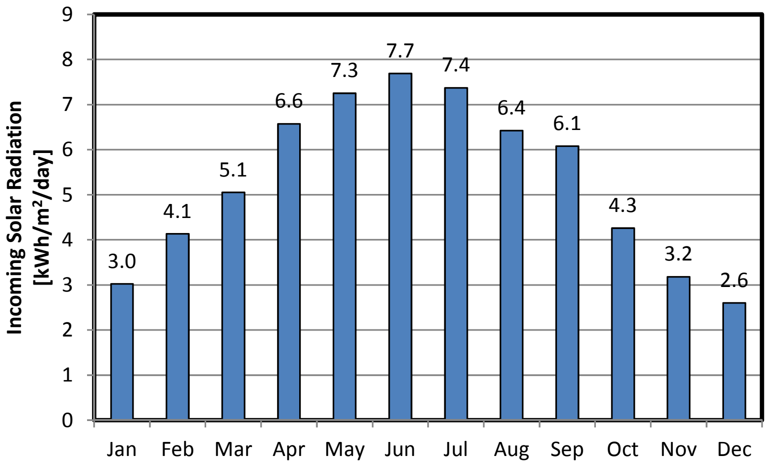


Figure 7. Insolation (Incoming Solar Radiation) of Las Vegas in 2007 (Latitude 36'18" N, Longitude 115'16" W).

Single day luminance (Lux) was measured at location 36°02'13.85" N and 115°07'40.67" W, as shown in Figure. The sets of experiments were carried out. One is find out the optimal angle of Lumen Sensor facing to sun, another is simple set on ground facing perpendicularly to the ground.

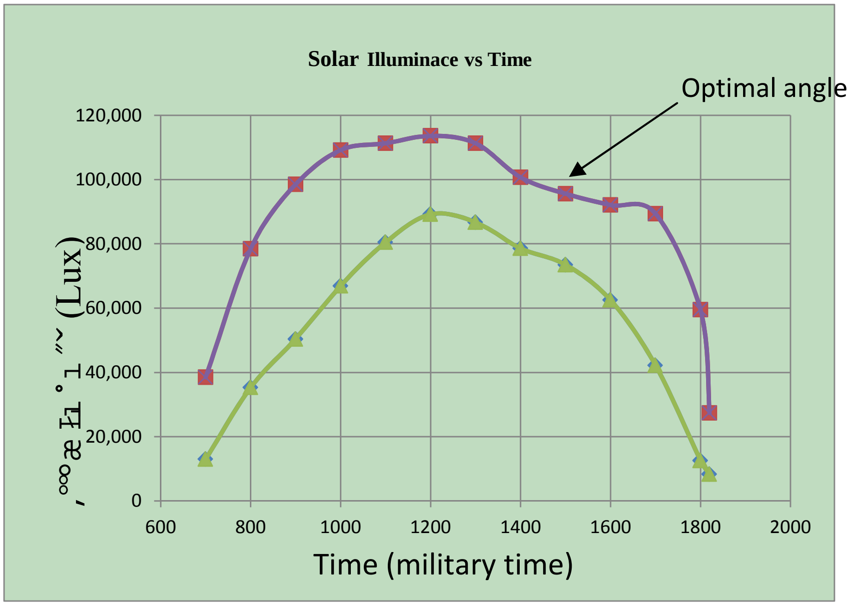


Figure 8. Solar luminance in single day vs time in Las Vegs (location 36°02’13.85” N and 115°07’40.67” W)

Productivity of Microalgae

A wealth of information is contained in the closeout report of the United States of Department of Energy, Aquatic Species Program (ASP). (Sheehan et al. 1998) This summarises US$25.05 million of work done by the US National Renewable Energy Laboratory (NREL) over a 20 year period until 1996, mostly on algal growth in open ponds. In contrast the Japanese RITE program from the around the same period concerned highly engineered PBRs. (Murakami 1997) Packer provide recently published data of algal biomass productivities. (Packer 2009) It is difficult to directly compare figures of productivity for the bioreactors used in these studies with the ponds, as usually productivity per unit area is given for ponds where it is given as productivity per unit volume for enclosed bioreactors. The most useful way to express productivities for comparison between different production methods would be in biomass per unit light energy used or falling over a particular area.(Bosma et al. 2007) The potential of enclosed bioreacotrs can be demonstrated in that many incorporating artifical lighting show huge productivity. The highest reported is 9.2 gL-1d-1 dry weight biomass for a culture of the marine green algae Chlorococum littorale at 20 gL-1 densigy for a flat-plate bioreactor with very high intensity artificial lighting. (Hu et al. 1998)

For enclosed bioreactors utilizing sunlight, productivity per unit area is also useful. The commercial bioreactor supplier AlgaeLink claim year round productivity of several different species of algae in the order of 365 ton/ha/yr for one of their systems. Greenfuel Technologies Corporation, based in Massachusetts USA, who has several large-scale pilot plants operating and focus on CO_2 capture from industrial emitters, demonstrate dry weight productivities between 250 and 292 t/ha/yr in their sunlight-powered algal bioreactors. In a recent report describing algal biomass for potential production in New Zealand, Heubeck and Craggs say high rate algal pond production with CO_2stimulation is between 40 and 75 t /ha/yr. (Heubeck and Craggs 2007)

In the open pond system, 30g/m2/day or 109.5 ton/ha/yr productivity of microalgal biomass was measured by seventh year Hawaii ARPs project during 1986 and 1987 (Sheehan et al. 1998). This data indicates that the space required for growing same amount of microalgal biomass in open pond system will be about three times of growing in closed photobioreactor.

Maximum Ideal Productivity of Algal Biomass

The maximum ideal productivity of algal biomass can be estimated by the local solar isolation, efficiency of photosynthesis and solar energy transferring rate. In the area of Southern Nevada, annual average insolation is 5.3 $kWh/m^2/day$, and only 42% of them is visible light and can be utilized by microalgae. In the simplest chemical reaction in photosynthesis, one mole of CO_2 captured requires energy about 450 kilocalories/mol, which is 0.52 kWh/mol. The maximum ideal CO_2 captured by algal biomass, therefore, is 4.26 $mol/m^2/day$ (or 0.188 $kg/m^2/day$). The ideal maximum productivity of algal biomass is 0.104 $kg/m^2/day$ (or 379.6 ton/ha/yr).

2.4 Feasibility of artificial light illumination for microalgae cultivation

Hybrid cultivation system of combining solar energy and artificial illumination may be one option to reduce the required space. But the electric energy to lit light is the concern of using this concept, including the capital cost and maintenance cost. The preliminary study of artificial illumination is discussed here to cultivate biomass and capture only the 50% CO2 emission from the 500MW coal-fired power plant.

Cree INC issued a press release on November 19, 2008 about a laboratory prototype LED achieving 161 lumens/watt at room temperature. The total output was 173 lumens, and the correlated color temperature was reported to be 4689 K. (CREE 2008) Note that these efficiencies are for the LED chip only, held at low temperature in a lab. In a lighting application, operating at higher temperature and with drive circuit losses, efficiencies are much lower. United States Department of Energy (DOE) testing of commercial LED lamps designed to replace incandescent or CFL lamps showed that average efficacy was still about 31 lm/W in 2008 (tested performance ranged from 4 lm/W to 62 lm/W). For comparison, a conventional 60–100 W incandescent light bulb produces around 15 lm/W, and standard fluorescent lights produce up to 100 lm/W. (Wikipedia 2009 c)

One most popular fluorescent 34 watt, T-12 Rapld Start Econo-Watt of 4100K cool white buld has light output 2300 lumens, which as light efficiency of 68 lm/W. 2,300 lumens equivalent to about 3.44 watts, which shows 10% energy efficiency.

As described above, 0.52 kWh/mol energy is needed for one mole of CO2 captured in photosynthesis chemical reaction. If consider 50% of the CO2 emission (3.5 million ton/yr CO2 emission) is captured for growing microalgae using artificial illumination, total energy required is

$$50\% \times 3.7 \times 10^{12}(\text{g})/44(\text{g/mol}) \times 0.52(\text{kWh/mol}) = 21.9 \times 10^{9}\text{kWh} \quad [3]$$

In addition, the actually total energy will be 219 billion kWh if 10% fluorescent light bulbs are used. This electric energy requirement is much higher than the output from this 500MW power plant (3.5 billion kWh/yr). Indeed, this concept is impractical, even use a couple of hours daily by artificial light for growing microalgae in large scale.

2.5 Several PBR prototype design and testing

Despite several research efforts developed to date, there is no such thing as “the best reactor system” –defined, in an absolute fashion, as the one able to achieve maximum productivity with minimum operation costs irrespective of the biological and chemical system at stake. In fact, choice of the most suitable system is situation-dependent, as both the species of alga available and the final purpose intended will play a role. The need of accurate control and reduce water evaporation impairs use of open system configurations in desert area (like Southern Nevada). Therefore current investigation has focused mostly on closed systems. As mentioned at the very beginning, the cost of closed system will be a primary concern. Hanging bag technology is considered as the practical engineering design with low capital and maintenance cost.

The main parameter that affects reactor design is provision for light penetration, which implies a high surface-to-volume ration. The light penetration is important for reducing the reflection loss and improving the solar conversion efficiency, which is in turn a key condition to achieve high productivity of biomass. Other parameters include gaseous transfer, medium mixing and temperature, pH and nutrient level control.

Experiences are required to be built up for future improvement of PBR design. Several prototypes of PBR were built for this purpose and would be able to provide some data for system and processing modeling in future. First prototype is the small PBR for macro-algae cultivation (as shown in Figure). One kind of filament shape macro-algae was found grow well in Flamingo Wash during summer. The size and shape of macro-algae growing waste water flow has benefit for reducing energy cost in harvesting. Second prototype is the hanging bag PBR with CO2 bubbling at the bottom of bag. The thickness of 6 mil polyethylene film is strong enough to hold about 20 gallons water.

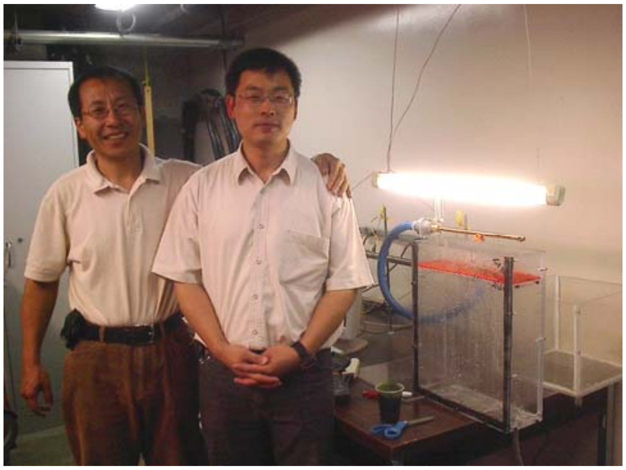


Figure 9. Photobioreactor for macroalgae collected from Flamingo Wash at Las Vegas.

Figure 10. Photobioreactor of hanging bag

A new design of photobioreactor is accomplished with enhancement of CO2 and water mixture. Cultivation of ***Nannochloris*** in this photobioreactor was tested, but failed. Fungal cells were found after two weeks continuous cultivation.

Figure 11. small scale flat Photobioreactor.

2.6 Evaporation estimation in Southern Nevada

Open water evaporation data in open pond cultivation system for algal biomass are incomplete. The accurately estimate evaporation in arid or desert area would allow accurate calculation of water use and management for large scale cultivation. The evaporation from outdoor algae ponds is a function of, mainly, air temperature, wind and relative humidity. The maximum evaporation rate in the US is typically found in Yuma, Ariona- with annual losses of up to 12 feet (about 3.6 m) recorded. The more typically net annual evaporation rates are 6 to 8 feet (about 1.8 to 2.4 m) in most of the areas considered suitable for algae biofuel production. (Lundquist etc. 2010) The evaporation form open pond with intensive mechanically mixing and CO2 bubbling with much shallower (about 0.3 m deep) is considered to have higher evaporation rates in comparing with reservoir data.

In order to figure out the evaporation rate data in Las Vegas area, the evaporation rate at the fountain dancing of Bellagio Casino was obtained for comparison.

He fountain dancing above Las Vegas version of Lake Como consume about 12 million gallons of water a year, according to resort officials. The Bellagio's 8.5 acre lake holds 22 million gallons and is replenished annually with another 12 million, representing the amount lost to evaporation, leaky pipes, or really thirsty ducks. Assuming evaporation is responsible for the entire amount, that would break down to 1,200 gallons lost in each of the roughly 10,000 – plus fountain shows performed throughout the year (about 27 shows per day and about 55 minutes interval between each show). The evaporation loss rate will be 1.32 m/ year.

From geological survey date (reported by Westenburg etc. 2006), the average evaporation rate from Lake Mead (Arizona and Nevada) during 1997 to 1999 is about 2.28 m/yr (sea Figure 1), which is larger than the date observed from Bellagio music fountain. It can be conclude that the evaporation rate data of 2.28 m/yr from Lake Mead reservoir is able to provide accurate estimation for open pond system. Actually, the intensive mechanical mixing in open pond only happens around the area of peddle wheels. And, the depth of open pond will only affect the variation of temperature of water body, which can be considered small. Becker (1994) observed the maximum evaporation rate from open pond surface is about 10 liter/m2-day, which is about 1 cm/day. This date is matching to the value of Lake Mead evaporation data in summer (about 0.9 cm/day).

2.7 Effects of CO2 level to the grow rate of green Chlorella

The method of supplying CO2 to algal culture is a key engineering consideration, which include the mixing regime, the CO2 concentration in the pond and the effect caused by the reaction of dissolved CO2 with OH^- to produce bicarbonate. The concentration of CO2 in the flue gas from fossil fuel powered power plan is around 8% to 15% depended on the type of fuel (coal or natural gas) and efficiency of boiler. In this report, we only consider the CO2 concentration to the growth rate of green *Chlorella* to answer the question of which is the practical solution of using CO2 from ambient air or flue gas.

Some preliminary data of growth rate under different CO2 concentration were obtained. Green algae Chlorella was under investigation at different CO2 concentrations in the input mixed gas. The gas flow rate was set to 70 sccm (Standard Cubic Centimeters per Minute) for all experiments. Three gas mixtures were tested, one is ambient air, 2% CO2 mixed with 98% Argon, and 5% CO2 mixed with 95% Argon. The microalgae growth rate is presented using the oil content increasing rate in mg/ml/day. The experiment results are illustrated in the figure below. The growth rate increase significantly when CO2 concentration in the mixed gas increased. It was noticed that about 5% of CO2 concentration has the highest growth rate for *Chlorella*.

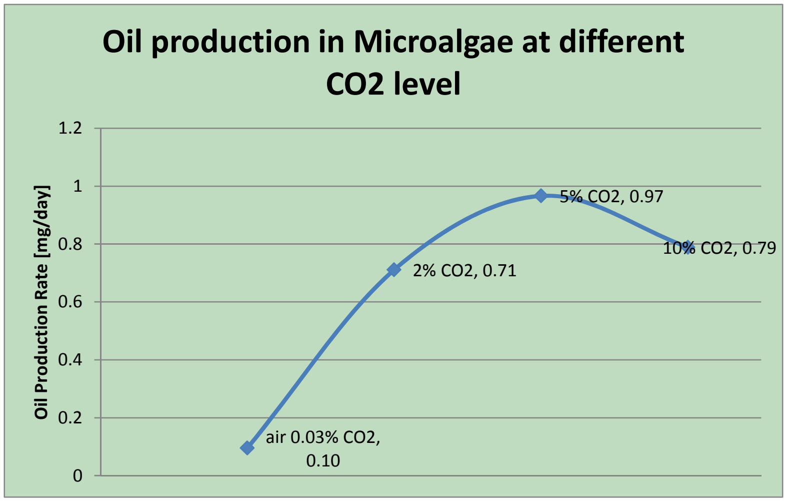


Figure 12. Oil production in Microalgae (*Chlorella*) at different CO2 level.

2.8 Low density polyethylene thin-film material for closed photo-bioreactor

Plastic films can be found widely in agricultural applications, like greenhouse, walk-in tunnel and low tunnel covers and mulching. (Espí, et al. 2006) The raw materials are usually low density polyethylene (LDPE) and ethylene-vinylacetate (EVA) or ethylene-butyl acrylate (EBA) copolymers for the covers and linerar low density polyethylene (LLDPE) for mulching. Nowadays, their lifetime varies between 6-45 months, depending on the photostabilizers used, the geographic location, use of pesticides, etc. The assessment of plastic film include their life time, dimensions, mechanical and optical properties and IR opacity. However, only optical properties of several films were measured due to the limited funding and time.

One moisture barrier 6-mil polyethylene film from Homedepot was used for making the hanging bag photobioreactor.

The coefficients of reflection, transmission and absorption are illustrated in Figure. The light wavelength range is from 200 nm to 1800 nm, which is covered the visible range. It shows that the transmission rate of this plastic film is lower about 40% in visible range.

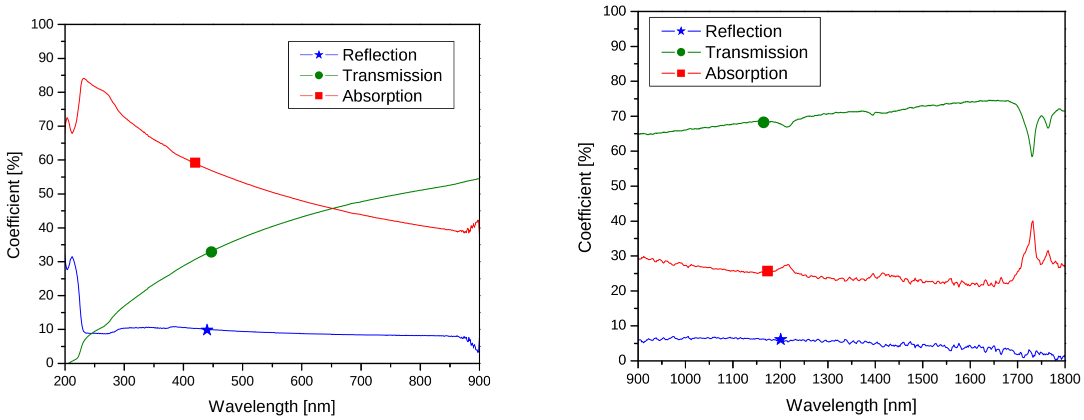


Figure 13. Coefficients of light reflection, transmission and absorption of Homedepot plastic film.

One new generation of super GT Plastics' films in 1997 was the results of years of research and product developent trials conducted with growers worldwide. Using advanced technology, this plastic film created a clear, gouther, long lasting greenhouse film that allows 91% light transmission per layer. The guaranteed life time is long about 4 years with advanced UV up to 33% longer life. With the 3-mil film the retail price is about \$0.04/ft^2.

2.9 *Thermo-economic analysis of microalgae co-firing process for fossil fuel-fired power plants;*

2.9.1 Case studies of Coal fired Power Plants

A 500 megawatt coal plant power a city of about 140,000 people. It burns 1,430,000 tons of coal, uses 2.2 billion gallons of water and 146,000 tons of limestone. (How Coal Works 2009) Other output from coal fired power plant can be found in Table 2.

Items	**Numbers**
Coal fired power Plant Capacity	500 MW
Electric Generation	3.5 billion kWh
Coal burned	1.43×10^6 ton/yr
Water consumed	2.2 billion gallon/yr
Limestone consumed	146,000 ton/yr
Carbon dioxide emission	3.7 million ton/yr
Sulfur dioxide	10,000 ton/yr
Nitrogen oxide	10,200 ton/yr
small particles	500 ton/yr
hydrocarbons	220 ton/yr
carbon monoxide	720 ton/yr
ash	125,000 ton/yr
sludge from the smokestack	193,000 ton/yr
arsenic	225 pound/yr
lead	114 pound/yr
cadmium	4 pound/yr
Many other toxic heavy metals	?

Table 2. 500MW coal fired power plant.

The 500 MW coal-fired power plant produce 3.5 billion kilowatt-hr electricity annually, which indicates about 82% of continuous operation twenty four hours a day and seven day a week. This percentage will be assumed as same for the next case of natural gas fired power plant.

2.9.2 CASE 2 - Natural Gas fired power plant

In Las Vegas, The Sunrise Power Plant has the capacity of 149 MW, and it is powered by natural gas. The estimation of natural gas consumption and carbon dioxide emission can be obtained based on the combustion value of natural gas (54MJ/kg) and 1999 national average output rate 1.321 pounds CO2 emission per killowatthour electricity generated. (NaturalGas 2004)

Many of the new natural gas fired power plants are known as 'combined-cycle' units. In these types of generating facilities, there is both a gas turbine and a steam unit, all in one, which are much more efficient than steam units or gas turbines alone. In fact, combined-plants can achieve thermal efficiencies of up to 50 to 60 percent. 50% is used for our estimation of natural gas consumption, combined with 82% of full operation. It will burn natural gas about 142.7×10^3 metric tons per year.

Calculating with the 149 MW output, and assuming 82% of rated power output with continuous operation for a year, the amount of CO_2 emission is about 0.641 million tons per year. The key numbers are listed in Table 3.

Items	**Numbers**
Natural Gas fired Power Plant Capacity	149MW
Electric Generation	1.07 billion kWh
Natural Gas Burned	0.143×10^6 ton/year
Carbon dioxide emission	0.641 million ton/yr

Table 3. 149 MW gas fired power plant

2.9.3 Price of Coal, Natural Gas and CO2 Sequestration Credit

The prices of coal and natural gas posted on the webpage of Energy Information Administration fluctuates with markets. During August 2009, the price at the Henry Hub spot market is $3.61 per MMBtu for natural gas and $53.92 per metric ton for coal. (EIA 2009 a, b)

In 2008, Department of the Treasury Internal Revenue Service allow taxpayer to claim the carbon dioxide sequestration credit. Qualified carbon dioxide captured after October 3, 2008, at a qualifiled facility and disposed of in secure geological storage and if captured after Feb. 17, 2009, not used as a tertiary injectant in a qualified enhanced oil or natural gas recovery project can claim $20 per metric ton CO2 captured and disposed of.

2.9.4 Space Required for Growing Microalgae

Definitely, the open pond will need more space than the closed photobioreactor and has more water evaporation. Growing 1.03 million tons algal biomass annually by capturing 50% emitted CO2 from coal-fired power plant, need about 10.9 mile^2 space. This number is not acceptable by most of the power plant. All the corresponding numbers (such as capture CO2 percentage, carbon credit etc.) can be shrunk proportionally with available space, other than 10.9 mile^2. Similarly, the required space rate per mega watt is 11.24 ha/MW if all CO2 emission was captured.

2.9.5 Economics Analysis of Microalgal Biomass Co-firing Process for Fossil Fuel-fired Power Plants

Flue gas emitted from the fossil fuel (coal or natural gas) fired power plants can be first extracted, compressed, dehydrated and transported to microalgae farms. A transportation distance of 100 km was assumed in one study by Kadam in 1997. The study was used to evaluate the efficacy of directly using the flue gas instead of the ~100% CO2 extraction. The option of directly using the flue gas was found to be more expensive due to more handling cost will be expended for delivering directly flue gas at a CO2 concentration of only 10%-15%.

If the flue gas is directly injected into microalgae farms, microalgae must be screened to be resistant to the mixture of gases (such as SOx and NOx) produced by power plants. Morais et al. (2007) present their research results of using microalgae of *Scenedesmus obliquus* and *Chlorella kessleri* from the waste treatment ponds of the Presidente Medici coal fired thermoelectric power plan.

Algae lipid content and growth rate both weigh heavily on the economics. However, they can be traded off, i.e. a high lipid content and low growth rate combination can be equivalent to a low lipid content and high growth rate combination. The isolation and screening of microalgae will not be discussed in the paper. The maximum productivity claimed from AlgaeLink of 365 ton/ha/yr is used for economic analysis. The high HHV of 29MJ/kg of *Chlorella emersonii*, which has 63% lipid will be used for economic analysis as well.

For the case of coal-fired power plant, if 50% CO2 is captured by microalgae, there will be about 1.85 million tons per year of CO2 for microalgae cultivation. All of the carbon in microalgal biomass is typically derived from carbon dioxide. The approximately 49.20% carbon by dry weight (Mirón et al.2003), in microalagal biomass leads to the estimation of CO2 captured for 100 tons of algal biomass produced. 100 tons biomass has 49.2 ton carbon. The molecular weight of carbon and carbon dioxide is 12 and 44 g/mol, respectively. Therefore, producing 100 tons of algal biomass neutralizes roughly 180.4 tons of carbon dioxide.

According to eq. (1), every one mole of CO2 captured will generate one mole of O2. The molecular weight of oxygen is 32 g/mol. 100 tons CO2 captured will generate about 72.7 tons of oxygen.

1.85 million ton/yr carbon dioxide captured by microalgae will produce about 1.03 million tons biomass and 2.54 million tons oxygen. Oxygen and other 50% un-captured CO2 can be fed into power plant to increase the oxygen content, which reduce the air consumption for combustion.

Combustion in an oxygen rich atmosphere and recycled combustion gases is a promising new technology (oxy-fuel combustion), which improving combustion efficiency and for CO2 recovery from flue gas without the process of concentration. In addition, it has benefit of reduction in NOx emission and simplification and down sizing of flue gas treatment system (Nakayama et al. 1992, and Hong 2009). The C2/CO2 combustion process is better than the existing air-blow combustion system by some 3.0% in boiler efficiency and about 1.5% in thermal efficiency (gross) because it reduces the volume of flue gas very significantly, leading to a substantial cut in heat loss of boiler (Nakayama et al 1992).

Co-firing with coal and generated algal biomass will reduce the consumption of coal. The HHV value (29MJ/Kg) of microalgal biomass is equivalent to HHV (27MJ/kg) of anthracite coal. For 500MW coal-fired power plant, there is about 1.11 million tons coal can be replaced by algal biomass (50% CO2 capture), if consider the HHV of 1.03 million tons biomass generated. Totally, there are about 77.6% coal can be replaced by biomass. Based on the price of $53.92/ton, and $20 carbon credit for captured CO2, the 500MW power plant will save $59.9

million for coal and have \$37 million carbon credit, which will bring totally \$96.9million/yr credit back to coal-fired power plant. In order to extended this analysis to other rated power plants, credit rate per mega watt is obtained as \$0.386 million/MW/yr for coal fired power plant if capture all CO2 emission.

The similar results can also be obtained using same equations for the natural gas fired power plant. For convenience, all the calculation results for cases of coal and gas fired power plants are listed in Table 4.

	Coal	Gas
capacity (MW)	500.00	149.00
CO2 Emission (million ton/yr)	3.70	0.64
Electric Generation (billion kWh/yr)	3.50	1.07
Fuel Burned (million ton/yr)	1.43	0.14
CO2 capture percentage %	50%	50%
50% of CO2 capture	1.85	0.32
Generate biomass (million ton/yr)	1.03	0.18
Generate oxygen (million ton/yr)	2.54	0.44
save fuel (million ton/yr)	1.10	0.10
save fuel percentage	77.0%	66.7%
fuel price	\$53.92/ton	\$3.61/MMBTU
save fuel (\$million/yr)	\$59.39	\$17.63
carbon credit (\$million/yr)	\$37.00	\$6.41
Total credit(\$million/yr)	\$96.39	\$24.04
Credit rate (\$million/MW/yr)	\$0.386	\$0.323
Required Space for Cultivation (ha)	2809.59	486.74
Required Space for Cultivation (mi^2)	10.85	1.88
Space rate (ha per MW)	11.24	6.53
Space rate (mile^2 per MW)	0.043	0.025

Table 4. Economic analysis result of co-firing with microalgal biomass for fossil fuel power plants.

2.10 Economic analysis of microalgae with oil extraction or oil extraction and biogas from aerobatic digester in Southern Nevada

Based on the date provided by Lundquist etc. (2010), the economics of two production scenarios of microalgae biofuels was assessed in this report according to local climate conditions in Southern Nevada. Because of the wastewater treatment credit is significant high than GHG carbon credit; those two cases are fully incorporates wastewater treatment in the process design and economics with by-products of bio-oil or electricity from burning of biogas. Both cases involve remediation of some portion of wastewater from the Clark County about 16.4 million gallon/day using 100 ha algae farm. Since the detailed technological data of closed-photobioreactor is missing. Open pond with and without covered low density polyethylene thin film (3 mil) for reducing evaporation is used for analysis.

The difference between the two basic processes that grow algae biomass primarily for liquid fuels (Figure) or for biogas production, is how much of the algae biomass goes to the anaerobic digesters for onsite electricity (and waste heat) production, vs. how much is converted into liquid fuel for offsite use.

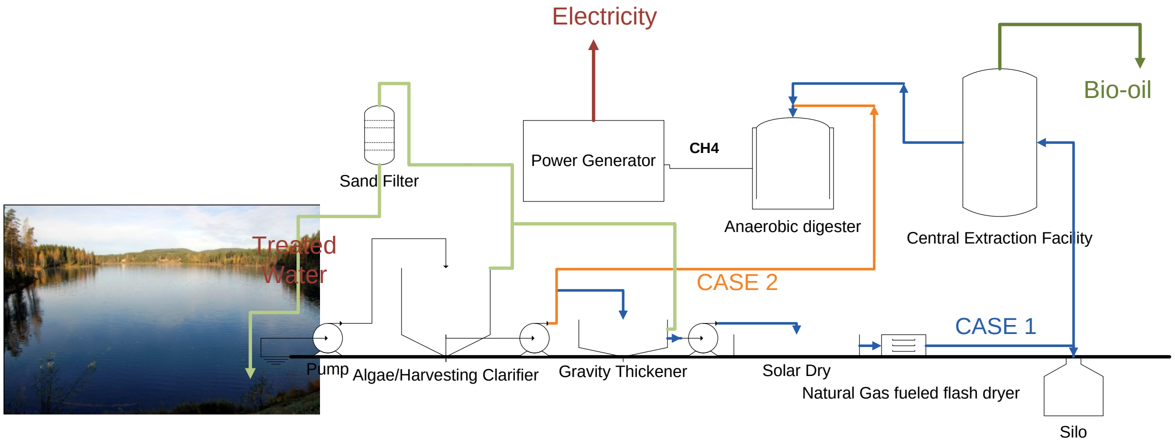
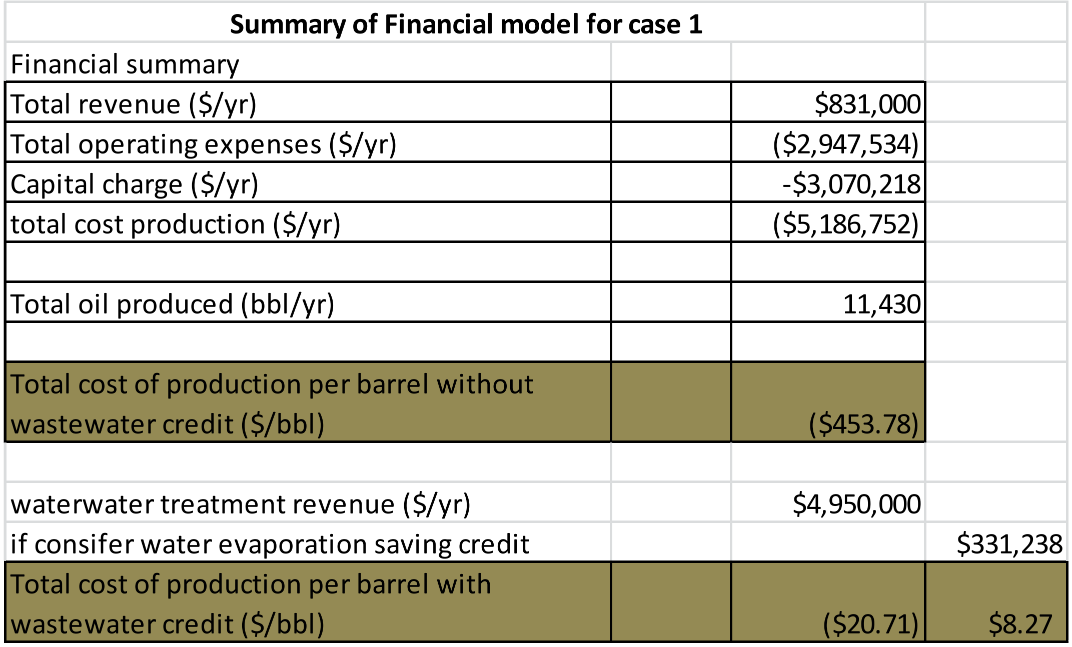


Figure 14. Process Schematic of cases 1 and 2 (wastewater treatment-emphasis and oil production).

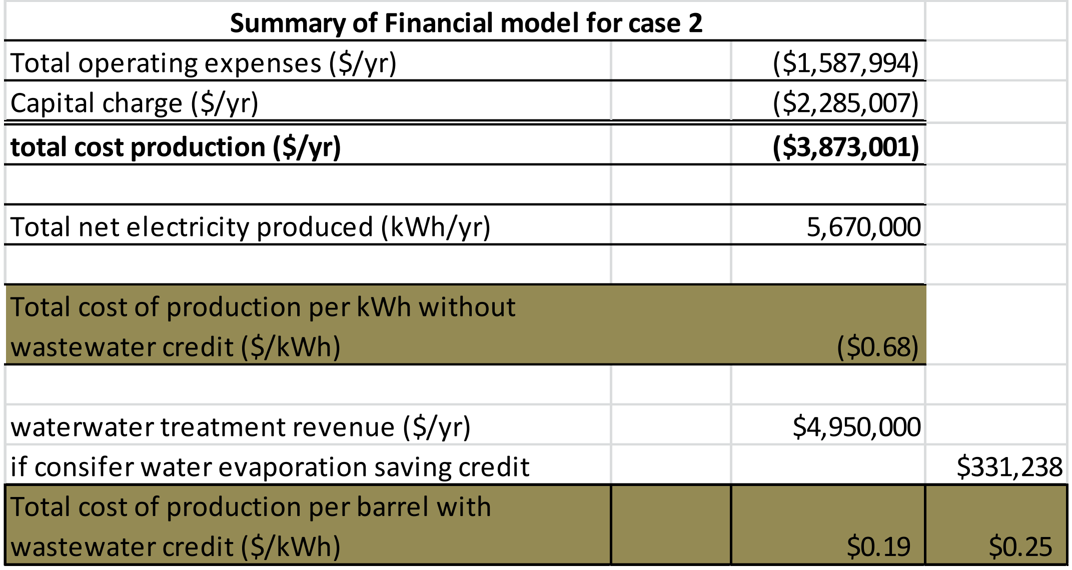
The price of land is only use the half price in California for estimation. The credit from reducing water evaporation is based on the cost of half lowest price for water in the Clark County, which is %0.55/1000 gallons.

The summary of financial model for cases 1 and 2 are listed in Table. The wastewater treatment revenue is based on $1.23/kg BOD removed (SMSA, 2002).



Summary of Financial model for case 1			
Financial summary			
Total revenue ($/yr)		$831,000	
Total operating expenses ($/yr)		($2,947,534)	
Capital charge ($/yr)		-$3,070,218	
total cost production ($/yr)		($5,186,752)	
Total oil produced (bbl/yr)		11,430	
Total cost of production per barrel without wastewater credit ($/bbl)		($453.78)	
waterwater treatment revenue ($/yr)		$4,950,000	
if consifer water evaporation saving credit			$331,238
Total cost of production per barrel with wastewater credit ($/bbl)		($20.71)	$8.27

Table 5. Summary of financial model for case 1.

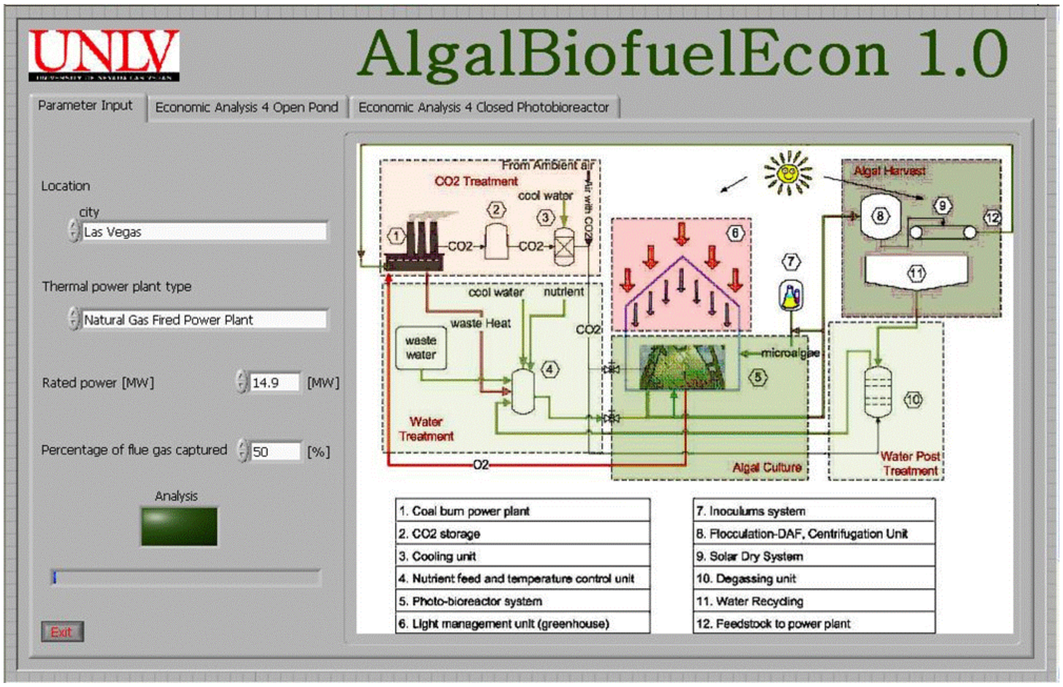


Summary of Financial model for case 2			
Total operating expenses ($/yr)		($1,587,994)	
Capital charge ($/yr)		($2,285,007)	
total cost production ($/yr)		**($3,873,001)**	
Total net electricity produced (kWh/yr)		5,670,000	
Total cost of production per kWh without wastewater credit ($/kWh)		($0.68)	
waterwater treatment revenue ($/yr)		$4,950,000	
if consifer water evaporation saving credit			$331,238
Total cost of production per barrel with wastewater credit ($/kWh)		$0.19	$0.25

Table 6. Summary of financial model for case 2.

2.11 *Software development for Techno-Economic Analysis of Algal Biomass*

One software for productivity estimation of algal biomass was developed. The maximum annual productivities of algal biomass using open pond and closed photobioreactor can be predicted if several parameters are determined, such as location of cultivation from a city list of 55 cities covered 50 states, type of fossil fuel fired power plant and its power output, percentage of usage of flue gas from power plant, etc.



Location
city: Las Vegas

Thermal power plant type: Natural Gas Fired Power Plant

Rated power [MW]: 14.9 [MW]

Percentage of flue gas captured: 50 [%]

1. Coal burn power plant
2. CO2 storage
3. Cooling unit
4. Nutrient feed and temperature control unit
5. Photo-bioreactor system
6. Light management unit (greenhouse)
7. Inoculums system
8. Flocculation-DAF, Centrifugation Unit
9. Solar Dry System
10. Degassing unit
11. Water Recycling
12. Feedstock to power plant

Figure 15. interface of one software for techno-economic analysis for algal biomass.

3. Publications and Presentations

1. Ma, J., O. Hemmers, *Thermo-economic Analysis of Microalgae Co-firing Process for Fossil Fuel-fired Power Plants*, ASME 4th International Conference on Energy Sustainability, May 19-22, Phoenix, Arizona 2010.
2. Ma, J., O. Hemmers, *Thermo-economic Analysis of Microalgae Co-firing Process for Fossil Fuel-fired Power Plants*, Energy Resources Technology, processing, submitted in July 2010, acceptance letter received on 1/18/2011.
3. Ma, J. et al. *Cultivation of Algal Biofuel Feedstock in Desert Area of Southern Nevada using Municipal Wastewater (NVREC Project 1.3)* – Poster for NVREC Project Meeting August 20, 2010
4. Ma, J. *Biological, Chemical and Engineering Research to Study the Viability for an Algal Biofuel Economy in Southern Nevada*, Nevada Renewable Energy Consortium Lecture Series, University of Nevada, Las Vegas, NV April 13, 2010.

4. References:

[1] AMSA, The 2002 financial survey: A national survey of municipal wastewater management financing and trends, Association Metropolitan Sewerage Agencies, 2002.

[2] Barsanti, L. and P. Gualtieri, *Algae - anatomy, biochemistry, and biothechnology*. 2006: CRC Press Taylor & Francis Group.

[3] Becker, E. W., Microalgae Biotechnology and Microbiology, page 95, 1994, Cambridge University Press.

[4] Bosma, R., et al., *Prediction of Volumetric Productivity of an Outdoor Photobioreactor*. Biotechnology and Bioengineering, 2007. **97**(5): p. 1108-1120.

[5] Britannica, E. *Photosynthesis*. 2009 (cited; Available from: www.britannica.com.

[6] CREE. *Achieves 161 Lumens per Watt from a High-Power LED*. November 19, 2008 (cited 02-15-2009); Available from:http://www.cree.com/press/press_detail.asp?i=1227101620851.

[7] de Morais, M.G. and J.A.V. Costa, *Isolation and selection of microalgae from coal fired thermoelectric power plant for biofixation of carbon dioxide*. Energy Conversion and Management, 2007. **48**(7): p. 2169-2173.

[8] EIA. *Coal News and Markets*. 2009 b (cited; Available from: http://www.eia.doe.gov/cneaf/coal/page/coalnews/coalmar.html.

[9] EIA. *Natural Gas Weekly Update*. 2009 a (cited; Available from: http://tonto.eia.doe.gov/oog/info/ngw/ngupdate.asp.

[10] Espí, E., A. Salmerón, A. Fontecha, Y García and A. I. Real, Plastic films for agricultural applications, Journal of Plastic Film & Sheetingm 22, 2006, p. 85-102.

[11] Heubeck, S. and R. Craggs, *Resource assessment of algae biomass for potential bioenergy production in New Zealand*, in *Bioenergy Options Program*. 2007.

[12] Hong, J., et al., *Analysis of oxy-fuel combustion power cycle utilizing a pressurized coal combustor*. Energy, 2009. **34**(9): p. 1332-1340.

[13] *How Coal Works*. 2009 (cited 2009; Available from: http://me.queensu.ca/courses/MECH430/Assets/Files/Recommended%20Reading/How%20Coal%20Works.pdf.

[14] Hu, Q., et al., *Ultrahigh-cell-density culture of a marine green alga Chlorococcum littorale in a flat-plate photobioreactor.* Applied Microbiology and Biotechnology, 1998. **49**: p. 655-662.

[15] Kadam, K.L., *Power plant flue gas as a source of CO2 for microalgae cultivation: Economic impact of different process options.* Energy Conversion and Management, 1997. **38**(Supplement 1): p. S505-S510.

[16] Mirón, A.S., et al., *Shear stress tolerance and biochemical characterization of Phaeodactylum tricornutum in quasi steady-state continuous culture in outdoor photobioreactors.* Biochemical Engineering Journal, 2003. **16**(3): p. 287-297.

[17] Miyamoto, K., *Biological Energy Production*, in *Renewable biological systems for alternative sustainable energy production*. 2009, FAO Agricultural Services Bulletin.

[18] Murakami, M. and M. Ikenouchi, *The biological CO2 fixation and utilization project by rite (2) -- Screening and breeding of microalgae with high capability in fixing CO2.* Energy Conversion and Management, 1997. **38**(Supplement 1): p. S493-S497.

[19] Nakayama, S., et al., *Pulverized Coal Combustion in O2/CO2 Mixtures on a Power Plant for CO2 Recovery.* Energy Conversion and Management, 1992. **33**(5-8): p. 379-386.

[20] NaturalGas. *Electric Generation Using Natural Gas*. 2004 (cited 2009; Available from: http://www.naturalgas.org/overview/uses_eletrical.asp.

[21] Packer, M., *Algal capture of carbon dioxide; biomass generation as a tool for greenhouse gas mitigation with reference to New Zealand energy strategy and policy*. Energy Policy, 2009. **37**(9): p. 3428-3437.

[22] Sheehan, J., et al., *A Look Back at the U.S. Department of Energy's Aquatic Species Program -- Biodiesel from Algae*, U.S.D.o.E.s.O.o.F. Development, Editor. 1998.

[23] *TexLoc Refractive Index of Polymers*. (cited; Available from: http://www.texloc.com/c.oset/co_refractiveindex.html.

[24] Westenburg, Craig L. Guy A. DeMeo, and Daron J. Tanko, Evaporation from Lake Mead, Arizona and Nevada, 1997-99, Scientific Investigations Report 2006-5252, U.S. Department of the Interior, U.S. Geological Survey.

[25] Wikipedia. *Light-emitting diode*. 2009 c (cited; Available from: http://en.wikipedia.org/wiki/Light-emitting_diode.

[26] Wikipedia. *Photosynthesis*. 2009 (cited; Available from: http://en.wikipedia.org/wiki/Photosynthesis.

[27] Wikipedia. *Sunlight*. 2009 b (cited; Available from: http://en.wikipedia.org/wiki/Sunlight.