**Title**
Technical and Economic Model of Marine Micro-algal Bioenergy Production

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# Technical and Economic Model of
# Marine Micro-algal Bioenergy Production

DU NIU

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## MAS Marine Biodiversity and Conservation
## Capstone Project

Capstone Advisory Committee

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# Abstract

The global economy is heavily dependent on the consumption of energy. The use of fossil fuel, from which 80-90% energy is currently produced, is considered unsustainable because of the depleting reserves and hazardous environmental impacts. Energy derived from renewable biomass feedstock provides a sustainable alternative that has the potential to replace fossil fuel, and avoid negative environmental impacts by reducing carbon dioxide emissions. However, the production of bioenergy is not yet economically feasible due to the high generation cost.

In this paper, a model was developed to investigate the feasibility of a hypothetical bioenergy project that uses the combination of marine microalgae-derived biogas and petroleum diesel for electricity generation and recycles carbon dioxide for algae cultivation; Hawaii was used as an example in this model to explore potential policy solutions to bring forward the commercialization of bioenergy. Results calculated from the model indicate that when the algae cultivation system operates at a productivity of 20 VS (volatile solid) g $m^2$ $d^{-1}$ captures 70% of the carbon dioxide generated from the system, and the price of diesel exceeds $2.10/Gallon the project is more economically feasible compared to the equivalent electricity generation project using only diesel. Assuming the project is located in Hawaii, and that the productivity of biomass is as low as 10 VS g $m^2$ $d^{-1}$, a $39/ton carbon dioxide reduction subsidy can make the project economically feasible.

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# Technical and Economic Model of
# Marine Micro-algal Bioenergy Production

## Introduction

The continued use of fossil fuel for transportation and power generation has grown to be a primary concern of human society, due to its devastating economic and environmental consequences. The economy of our modern society relies heavily on the consumption of fossil fuels. In 2008, 80 to 90% of worldwide energy consumption (approx. $5\times10^{20}$ J) was derived from the combustion of fossil fuels (BP 2009). Although exact consumption per GDP varies in different countries, the reliance on fossil fuels is a common feature. However, continued global economic development based on this limited energy resources cannot be sustainable in the long term. According to (Shafiee and Topal 2009), these reserves including oil and gas will be depleted by 2042 if consumption continues at the 2006 rate, except for coal which will be depleted by 2112. Additionally, the global atmospheric concentration of carbon dioxide has grown markedly since 1750 due primarily to this burning of fossil fuels (IPCC 2007). Scientific societies and academies of science from major industrialized countries have endorsed the conclusion that most observed temperature increases since the mid 20th century were caused by anthropogenic carbon dioxide emissions (Society 2005; IPCC 2007). The warming may result in sea level rise, climate pattern change, and ecosystem degradation. In addition to this, the rising carbon dioxide concentration has the potential to catastrophically alter our planet's oceans through ocean acidification.

Bio-fuel, as a renewable resource, has been used to supplement declining fossil fuel resources. The term biofuel is defined as solid (firewood), liquid (ethanol, vegetable oil and biodiesel) or gaseous (biogas, biosyngas and biohydrogen) fuels that are predominantly produced from biomass (Demirbas 2009). Biofuels are attractive for two major reasons: First, producing fuels from biomass can be sustainable. Photosynthetic organisms utilize solar energy to fix carbon dioxide and synthesize organic components, a process that can proceed in perpetuity without the release of additional carbon dioxide into the atmosphere. Second, increasing fossil fuel prices provides significant economic feasibility for biofuel production and marketing (Cadenas and Cabezudo 1998). With the depletion of petroleum reserves, and the growing awareness of environmental hazards from their use, it will be unlikely for the price of fossil fuel to remain at current levels, Thus the economic superiority of this traditional fossil fuels will decline and the large scale commercialization of biofuel may become economically possible.

## History of biofuel

The concept of biofuel is not new. In fact, humans have utilized biofuel for industrial purposes since the nineteenth century, when alcohols were commonly reported as a biofuel (Antoni et al. 2007). Later, Dr. Rudolph Diesel designed the original diesel engine to run on vegetable oil; he used peanut oil to fuel one of his engines at the Paris' world Exhibition in 1900 (Demirbas 2002). Similarly, Henry Ford's Model T (Tin Lizzy) ran on 100% ethanol from corn (Kovarik 1998). During that period, biofuels were widely used or blended with petroleum fuels in the U.S and Europe. However, after the drastic drop in petroleum prices around 1940, the production of biofuel almost completely disappeared (Kovarik 1998; Finlay 2003).

The subject of biofuels was brought up again in the 1970s due to a series of events. First, the passage of the Clean Air Act in 1970 set up the clean fuel standard, causing the cost in fossil fuel production to increase significantly. Then, the 1973-1974 Arab Oil embargo, followed by the Iranian Revolution from 1978-1979, plus the decrease in domestic oil production in the U.S, acted together to increase the price of fossil fuels.

In August 1982, the first International Conference on Plant and Vegetable Oils was held in Fargo, N.D, where a main focus was using vegetable oil as a fuel additive (Hess 2003). Although the stabilization of petroleum prices in 1983 slowed down the momentum on biofuel development, some researchers continued to insist that the economic and environmental concerns of using fossil fuels enhanced the necessity for biofuel commercialization.

## Major types of biofuels

Many kinds of synthesized fuels fall into the category of biofuel. Among them, bio-ethanol, bio-diesel and biogas are the most common and have been commercially used in some regions. These will be reviewed in detail.

### *Bio-ethanol*

Bio-ethanol is derived from alcoholic fermentation of sucrose or simple sugars that are produced from a large variety of carbohydrates from biomass. Current large scale bio-ethanol production is mostly from sugar cane and starch-containing materials such as corn, in Brazil, the US and some European countries (Hahn-Hagerdal et al. 2006). Ethanol can be blended with petroleum or used as pure alcohol in dedicated engines, and is considered a suitable fuel for future advanced flexi-fuel hybrid vehicles.

The production of bio-ethanol is an enzymatic based fermentation process with a two-staged pathway:

1) Enzyme conversion is substrate–specific without any by-product formation that would otherwise reduce the inhibition of the subsequent steps. However, the reaction is very slow unless the biomass is pretreated to expose the cellulose fibers to the enzymes or make it more accessible by hydrolyzing the hemicelluloses (Mosier et al. 2005). After pretreatment, some carbohydrates are converted to simple sugars, and the remaining fibers are converted to simple sugars via saccharification (hydrolysis reaction, etc).

2) The simple sugars obtained during step 1 are then transferred to the fermentation batch and yeast, nutrients and other ingredients are added simultaneously. The fermentation reaction occurs at 25-30℃ and lasts between 6-72 hours, depending on the composition of the hydrolysates and the type, density and activity of the yeast. The resulting raw product, containing 8-14% (v/v) of ethanol, is then distilled and often dehydrated into 99.6% alcohol (Gnansounou and Dauriat 2005).

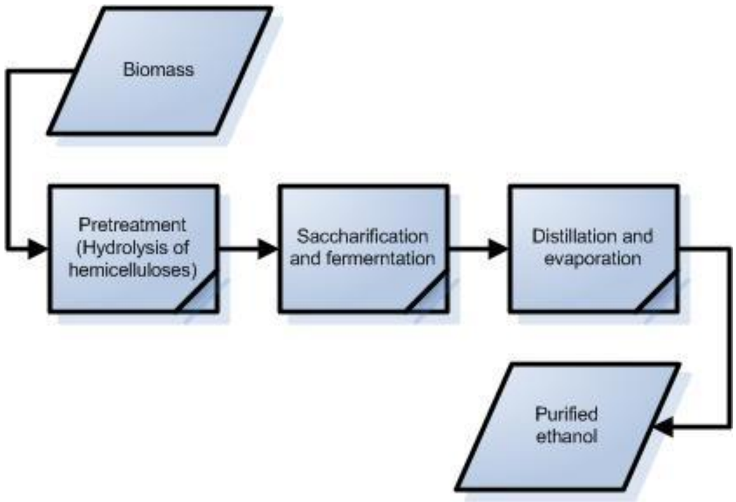

**Figure 1.** Schematic flowchart for the biomass to bio-ethanol conversion

***Bio-Diesel***

Biodiesel is composed of monoalkyl esters of long chain fatty acids derived from renewable feedstock, such as vegetable oil. Vegetable oils usually contain free fatty acids (FFA), phospholipids, sterols, water, odorants and other impurities. The existence of those components may cause problems when vegetable oil is used as fuel in a diesel engine, including carbon deposits, oil ring sticking and lubrication oil thickening. The chemical modification of transesterification can convert vegetable oil to bio-diesel. Typically, bio-diesel is a fatty acid methyl ester (FAME), which has similar chemical and physical features to conventional diesel fuel, and is thus considered a reasonable substitute for existing machinery (Meher et al. 2006).

The chemical mechanism of transesterification is the displacement of alcohol from an ester by another alcohol. The process has been widely used to reduce the high viscosity of triglycerides (TAGs), which are the main constituent in vegetable oil. This high viscosity is one of the main reasons this substance is not usable directly in engines.

Transesterification can be catalyzed by either fulfonic or sulfuric acids (high yield in alkyl esters but slow reaction) or alkali (lower yield but fast reaction) (Freedman et al. 1986; Schuchardt et al. 1998). However, most biodiesel currently produced is from edible oil by using a methanol and alkaline catalyst. For an alkali catalyzed transesterification, the reactants must be substantially anhydrous and free fatty acid (FFA) content should be low (less than 3%) since it cannot be processed by alkaline catalyst. Water causes the reaction to partially change to saponification and produces soap, lowering the yield of esters and rendering the separation of ester and glycerol, and the water washing is then difficult (Ma and Hanna 1999). If FFAs are abundant in the raw material, a two-step process can be used: First the FFAs are converted to fatty acid methyl esters (FAME) by acid catalyst, and the second step is completed by using a base catalyst. (Canakci and Van Gerpen 2001)

### ***Purified biogas***

Biogas can be produced under anaerobic conditions from animal manure, sewage sludge, municipal solid waste, biodegradable waste, or any other biodegradable feed stock,. The composition of biogas varies depending upon the composition of the fermenting materials and the anaerobic digestion process. Under most circumstances, the constituents (by volume) of biogas are: methane (50-75%), carbon dioxide (25-50%), nitrogen (0-10%), hydrogen (0-1%), hydrogen sulfide (0-3%), and oxygen (0-2%) (Hendrickson 1975). Purified biogas contains 95-99% methane and can be directly used as natural gas for energy generation.

The process of anaerobic bio-digestion can be summarized into three stages, and the bio-reactions in each stage are carried out by a different group of bacteria (Leschine 1995; Lastella et al. 2002):

1) Hydrolytic and fermentative bacteria break down insoluble organic polymers such as carbohydrates, cellulose, proteins and fats into sugars and other small molecules that then decompose further to form carbon dioxide, hydrogen sulfide, hydrogen, ammonia, alcohols, and organic acid.

2) Acetogenic bacteria convert alcohols and organic acids to acetate. At the end of this stage, carbon dioxide and hydrogen concentrations begin to decrease, due to the homo acetogenic reaction.

3) Methanogenic bacteria convert the end products from the second stage into methane and carbon dioxide.

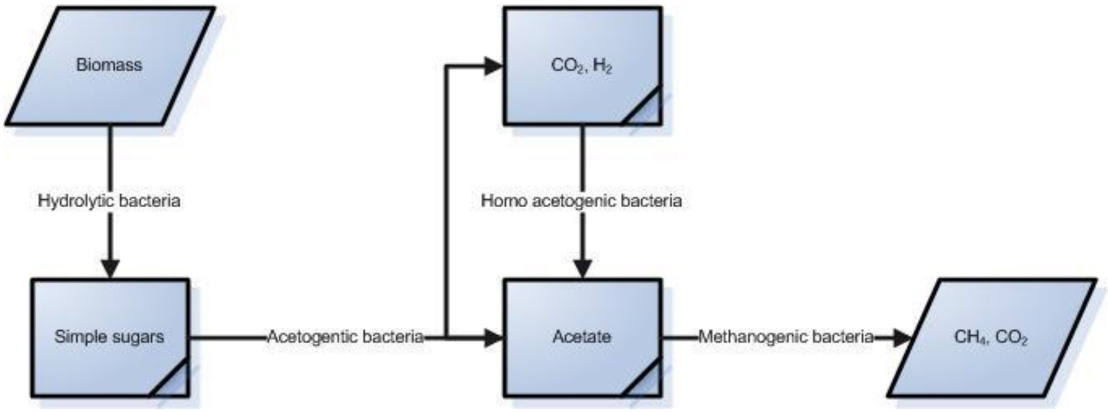

**Figure 2.** Schematic flowchart for the anaerobic bio-digestion process

Physical mixing of the feedstocks in the anaerobic bio-digester (ABD) can improve the contact between the material and the resident bacteria, and thus is important in maintaining a high rate of digestion reactions and a high productivity of methane. Pretreated biogas is further purified to get rid of dust, carbon dioxide and other harmful components that may damage an engine or turbine being used.

## Algal bio-fuel as a potential solution

Fuel extracted from terrestrial farmed crops, such as corn, sugarcane or sunflower seeds, may be unsustainable because the energy invested in the farming process is larger than the energy exported as a fuel product. Additionally, the production requirements for such a massive amount of fuel feedstock may affect food commodity prices (Gross 2008). Lastly, the development of bio-fuel from traditional terrestrial crops can not realistically meet the demand for fuel, due to the inherent limits on biomass productivity and land availability (Pienkos and Darzins 2009).

In contrast to traditional land crops, using microalgae as a fuel source is possibly advantageous for many reasons. Along with their high growth rates and tolerance for currently unused brackish environments (Searchinger et al. 2008), the simple structure of an algal cell, lacks lignin and other polysaccharides which consume energy during synthetic process, allows for high energy conversion efficiency (Falkowski and Raven 1997), making them an ideal feedstock for fuel production. Microalgae include all unicellular and simple multi-cellular photosynthetic microorganisms, including both prokaryotic and eukaryotic microalgae. The most important classes are green algae (*Chlorophyta*), red algae (*Rhodophyta*) and diatoms (*Bacillariophyta*). Algae can either be autotrophic or heterotrophic. Autotrophic algae require inorganic components such as carbon dioxide, nutrients and light as an energy source, while heterotrophic algae require an external source of organic compounds (such as glucose) as well as nutrients (Brennan and Owende 2010). Currently, autotrophic production is technically and economically feasible for large-scale non-energy algal biomass production (Borowitzka 1997), e.g. high value pigments and therapeutic chemicals, using either an open pond production system or a closed photobioreactor (PBR) system. The ideal culture system for any given organism will depend on the intrinsic properties of the selected algae strains.

However, growing a large amount of algae for bioenergy is still in the experimental stages and no example of commercialized production has been reported. In addition to the technical problems associated with mass-producing algae, one of the most important barriers is the high cost for algal biofuel production. Solving this issue on the global scale will take many years, however, more immediate production might be economically feasible in areas where energy cost are higher than average.

In this paper, I have developed an economic model to analyze the feasibility of using purified biogas derived using marine algal biomass as a substitute for diesel to produce electricity on an island, and have been evaluated under different diesel prices and renewable energy subsidy scenarios.

## Model design

This model evaluates the inputs and outputs of a power plant that utilizes purified biogas and diesel in different proportions as its energy sources for electricity production. The $CO_2$ generated during anaerobic digestion and in the combustion related electricity production processes shall be recycled by being pumped into adjacent algae cultivation system, and utilized by algae for biomass production.

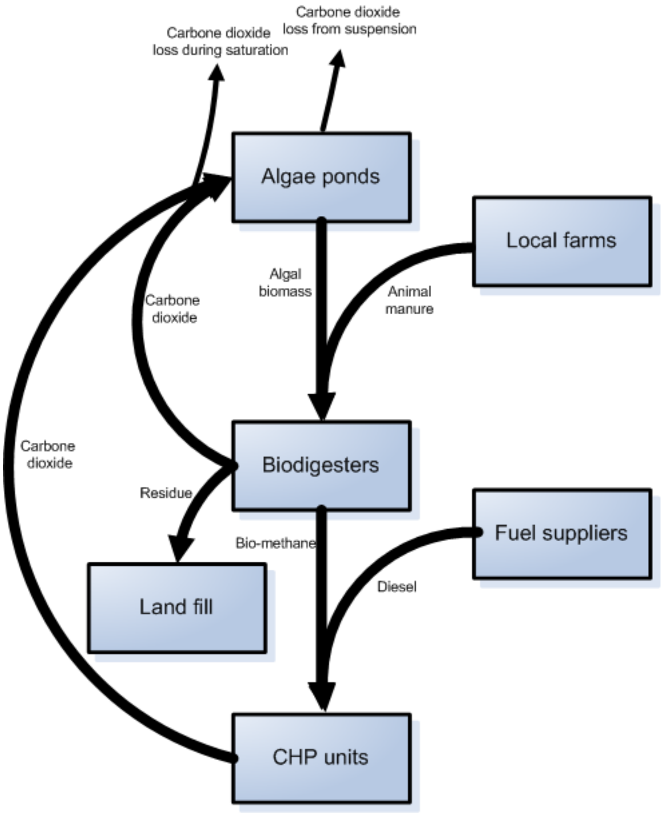

**Figure 3.** Flowchart of carbon cycle

After the algal biomass is harvested, it is combined with waste papers, municipal wastewater, and animal manures, and this are used as raw materials for anaerobic digestion. The biogas produced shall be used in combined heat and power (CHP) units for electricity generation such completing the cycle as shown in Figure 3. For the analysis, the size of algae cultivation system in this model is fixed to 100 ha, while the amount of diesel utilized is determined by the additional quantity of $CO_2$ (in addition to the $CO_2$ produced from anaerobic digestion and biogas consumption) required for sufficient carbon supplement of the algae growth. The capacity of the power plant is based on the running hours and the quantity of electricity generated from the consumption of biogas and diesel.

In the economic analysis, the capital/operation costs of the project are estimated based on the engineering calculation results. A fixed charge rate criterion is adopted to determine the revenue needed to cover investment costs, while the minimal requirement of annual revenue is determined from the combination of carrying charge on the investment and the operation cost. For an easy and direct comparison, the minimal annual revenue is normalized to per kilowatt hour (kWh) cost, and it is equivalent to minimal generation price for the electricity sale.

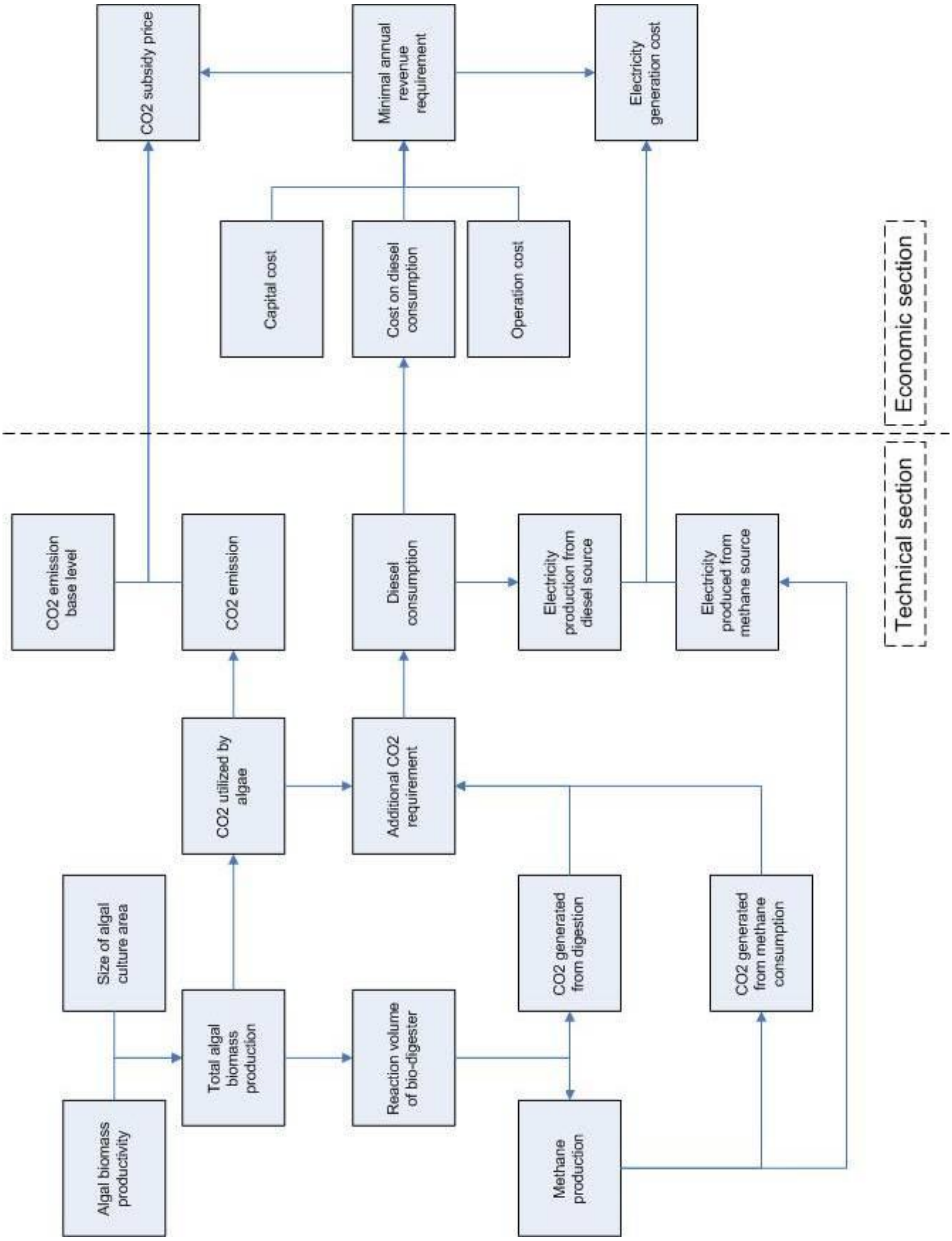

**Figure 4.** Summarized calculation flowchart

## Technical details

The daily production of algae biomass is:

**Equation 1:** $$P_{\mathrm{Alg}ae/d} = \overline{P}_{\mathrm{Alg}ae/d} \times \frac{1000m^2}{ha} \times A_{pond}$$

- $P_{\mathrm{Alg}ae/d}$ Daily total dry biomass production, VS g
- $\overline{P}_{\mathrm{Alg}ae/d}$ Daily dry biomass productivity, VS g/m$^2$
- $A_{pond}$ Size of algal production system, ha

The growth rates of algae are influenced by many factors: light is the most important one in terms of photosynthetic reaction, which determines the energy available for carbon fixation and biomass accumulation. At low intensity, algal growth rate responded to the light level approximately linearly to a threshold beyond which they are inhibited at high light intensity (Moisan and Mitchell 1999). Temperature is also important and its effects on many marine algae in the laboratory and in the environment have been well documented, but how the magnitude of temperature influences annual biomass production is not yet sufficiently acknowledged (Mata et al. 2010). However, 20-30°C is generally considered the feasible temperature for algae growth (Geider 1988). Other factors include macro and micro nutrient concentrations, oxygen and carbon dioxide contents, pH, toxic chemical contaminations, the pressure of invasive species and engineering design of the culture system (Mata et al. 2010).

Closed photo-bioreactors are not economically feasible at this time for the requirement of a low cost production of biogas; high-rate ponds, which are shallow race-way type system with low-RPM paddle wheels mixing the culture at modest velocities of approximately 30 cm s$^{-1}$ (Weissman et al. 1988), have been commonly used for large-scaled algal biomass production. Algae cultivated in high-rate photosynthetic systems with enriched carbon dioxide input, have been demonstrated to be capable of achieving carbon fixation rate of 5-15 g C $m^2$ $d^{-1}$, equivalent to 12-30 g-VS (Volatile Solids) $m^2$ $d^{-1}$ of biomass, when the ratio of carbon/ash-free dry wt is 50% (Sheehan et al. 1998).

After harvesting, the biomass is transferred to an anaerobic bio-digester (ABD) for fermentation and released as biogas, from which methane can be separated via purification. This concept was first proposed by Oswald and Golueke (1960) in their paper, where they described the integrate process of open pond algae cultivation combined with wastewater treatment, followed by fermentation of algal biomass to biogas. Recalcitrance of algal sludge to bio-digestion and ammonia accumulation are the two major issues of anaerobic digestion. Chen and Oswald (1998) improved the efficiency of methane fermentation via heat pretreatment of algal sludge, but such improvement is not economically feasible because the increased methane energy does not compensate the energy lost on the heat pretreatment. The low C/N ratio in algal sludge can result in high total ammonia nitrogen (TAN) and volatile fatty acid (VFA) accumulation in the digester, and inhibit the anaerobic digestion process (Parkin and Owen 1986). Co-digestion of high carbon content materials, e.g. animal manure, municipal solid waste (MSW) and waste paper, can significantly reduce TAN and VFA productivity, and allow for increased loading rate and biogas yield (Mshandete et al. 2004; Yen and Brune 2007). According to Yen, the optimal loading rate of total fermentable biomass is 4~5 VS g/l day, including 2 VS g/l day algal sludge and 2~3 VS g/l day co-ferments. The volume of bio-digester is calculated as:

**Equation 2:** $V_{ABD} = \frac{P_{\mathrm{Alg}\,ae/d}}{L}$

-$V_{ABD}$ Volume of Anaerobic bio-digester, $m^3$

- $L$ loading rate of algae sludge, VS g/l day

The methane productivities are 1175±75ml/l BR day when loading rate is 4 VS g/l day and 1607±17ml/l BR day at 5 VS g/l day. Usually, the methane content in biogas produced from marine algae may vary from 50% to 65%, but higher percentages have been reported for two-phase anaerobic digestion system (Vergara-Fernandez et al. 2008), so 65% is considered a reasonable value. Methane and $CO_2$ together comprise the majority of the biogas content, so $CO_2$ percentage is assumed to be 35% and $CO_2$ generation rate proportional to methane productivity. The methane and $CO_2$ produced from an ABD are calculated as:

**Equation 3:** $P_{CH_4/d} = \overline{P}_{CH_4-ABD} \times V_{ABD}$

**Equation 4:** $P_{CO_2-ABD/d} = \overline{P}_{CO_2-ABD} \times V_{ABD}$

- $P_{CH_4/d}$ Methane produced at day t, m3
- $\overline{P}_{CH_4-ABD}$ Methane productivity, $m^3$ $m^{-3}$-ABD $day^{-1}$
- $P_{CO_2-ABD/d}$ $CO_2$ produced per day, $m^3$
- $\overline{P}_{CO_2-ABD}$ $CO_2$ productivity, $m^3$ $m^{-3}$-ABD $day^{-1}$

The $CO_2$ produced in bioreactor can be partly removed by the algae culture, this concept was proposed by (Conde et al. 1993), and the result shows the purification process can reduce $CO_2$ content from 44-48% to 2.5-11.5%. Pretreated biogas is further treated to remove dust, remaining $CO_2$ and other harmful components that may damage the gas-diesel turbine. To simplify the calculation, $CO_2$ from digestion is regarded as additional $CO_2$ emitted from power generation, and the final emission level is calculated from bulk $CO_2$ quantity.

After purification, biogas is introduced to the gas-diesel turbine and combusted with diesel and compressed air for electricity generation. Combined Heat and Power generator (CHP) is commonly use in biogas plant, in parallel to electricity generation, the CHP also convert certain percentage of energy into heat that can be further utilized, i.e. heating up ABD or heating stables as for the breeding of young animals under infrared emitters. However, long distance transportation of heat energy involves many variables that may influence the transportation efficiency and the results are difficult to predict, so in this study, the heat is assumed 100% consumed within the plant. With modern technology, the total energy conversion efficiency of gas-diesel turbine in CHP can reach 85-90%, but the electrical efficiency only ranges from 35%-40% (Steinhauser 2008). The energy yield from biogas and diesel are calculated as:

**Equation 5:** $E_{el-CH_4/d} = P_{CH_4/d} \times \eta_{el} \times E_{spec-CH_4}$

- $E_{el-CH_4/d}$ Daily electricity production from burning $CH_4$, kWh
- $\eta_{el}$ Efficiency of turbine to produce electrical energy
- $E_{spec-CH_4}$ Energy content of $CH_4$, kWh/m$^3$

$E_{spec-CH_4} = \frac{33{,}368 BTU/m^3 - CH_4}{3415 BTU/kWh} = 9.77 kWh/m^3$ (Brune et al. 2009)

**Equation 6:** $E_{el-diesel/d} = P_{Diesel/d} \times \eta_{el} \times E_{spec-diesel}$

- $E_{el-diesel/d}$ Daily electricity production from burning diesel, kWh
- $E_{spec-diesel}$ Energy content of $CH_4$, kWh/Kg

$E_{spec-diesel} = 10 kWh/Kg$ (Steinhauser 2008)

The total amount of electricity produced daily is calculated as:

**Equation 7:** $E_{el/d} = E_{el-CH_4/d} + E_{el-diesel/d}$

- $E_{el/d}$ Daily electricity produced, kWh

When the electricity production is consistent and works T hours/day, the capacity of the power plant can be calculated as:

**Equation 8:** $E = E_{el/d}/T$

- $E$ Nominal capacity of the power plant, $kW_{el}$
- $T$ Running hours of the electricity generator, h/d

The calculated value of daily electricity productivity represent the gross output, however, after taken into account the energy consumption for running the whole system, this value should be adjusted as

**Equation 9:**

$$E'_{el/d} = E_{el/d} - 24h/d \times (0.0355kW/m^3 \times V_{BR} + 1kW/ha \times A_{pond}) + 0.2kWh/Kg \times P_{Algae/d}\ ^{1}$$

According to the setup of this model, if the $CO_2$ produced from anaerobic bio-digestion and consumption of biogas for electricity can not provide sufficient amount of $CO_2$ to supply algae cultivation, the deficit $CO_2$ should be from the consumption of diesel. In order to calculate the amount of diesel consumed for electricity production, on should determine: 1.the quantity of $CO_2$ been utilized by algae culture; 2.the quantity of $CO_2$ generated from the consumption of biogas; 3. the quantity of $CO_2$ produced from anaerobic bio-digestion should be known in advance. The quantity of $CO_2$ from the digestion process which has

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[1] 0.0355kW/$m^3$ represent the electricity used by bio-digester for mixing the ferments; 1kW/ha is the electricity used by paddle wheels for mixing; 0.2kW/Kg consists of two parts, 0.1kW/Kg of electricity usage for algal biomass harvesting and 0.1kW/Kg for centrifugation.

been calculated, while the other two parameters are calculated as follows:

**Equation 10:** $$U_{CO_2/d} = \frac{\frac{P_{Algae/d}}{R_{C-biomass}} \times \frac{44g-CO_2/mol}{12g-C/mol}}{\rho_{CO_2}}$$

- $U_{CO_2/d}$ Daily carbon dioxide utilization rate, m3

- $R_{C-biomass}$ Ratio of VS weight to carbon in algal cell, g VS/g-C

- $\rho_{CO_2}$ Density of $CO_2$, g/$m^3$

$$R_{C-biomass} = 1/50\% = 2$$

**Equation 11:** $$P_{CH_4-CO_2/d} = P_{CH_4/d} \times R_{CH_4-CO_2}$$

- $P_{CH_4-CO_2/d}$ Daily carbon dioxide produced from methane consumption, $m^3$

- $R_{CH_4-CO_2}$ Carbon dioxide emission per methane consumption, $m^3$ $CO_2$/ $m^3$ $CH_4$

$$R_{CH_4-CO_2} = \frac{3142Kg-CO_2}{1tonne-CH_4} \times \frac{0.717Kg/m^3-CH_4}{1.98Kg/m^3-CO_2} \times \frac{1tonne}{1000Kg} = 1.143m^3-CO_2/m^3-CH_4$$

The transfer efficiency of flue-gas $CO_2$ to algal biomass rages from 60% to 80%, based on culture operation and biomass productivity (Brune et al. 2009). Assuming the transfer efficiency is constant and equals an average 70%. Thus, 100% carbon dioxide recycling is actually 70% carbon dioxide recycling. The amount of $CO_2$ from diesel consumption is:

**Equation 12:** $$P_{Diesel-CO_2/d} = \frac{U_{CO_2/d}}{\eta_{CO_2}} - P_{CH_4-CO_2/d} - P_{CO_2-ABD/d}$$

- $P_{Diesel-CO_2/d}$ Carbon dioxide produced from diesel consumption at day t, $m^3$

- $\eta_{CO_2}$ Carbon dioxide utilization efficiency

So the diesel consumed at day t is calculated as:

**Equation 13:** $$P_{Diesel/d} = \frac{P_{Diesel-CO_2/d}}{R_{Diesel-CO_2}}$$

- $P_{Diesel,t}$ Daily diesel consumption, Kg

- $R_{Diesel-CO_2}$ Carbon dioxide emission per diesel consumption,

  m$^3$ CO$_2$/ Kg diesel

$$R_{Diesel-CO_2} = \frac{2.68Kg-CO_2}{1Litre-diesel} \times \frac{1}{1.98Kg/m^3-CO_2} \times \frac{1}{0.85Kg/Litre-diesel} = 1.59m^3-CO_2/Kg-diesel$$

The total CO$_2$ produced during the whole process is the combination of CO$_2$ from anaerobic digestion and electricity generation

**Equation 14:**

$$C_d = \frac{P_{CO_2-ABD/d} + P_{diesel-CO_2/.d} + P_{CH_4/d}}{E_{el/d}} \times \frac{1.98Kg/m^3-CO_2}{1000Kg/Tonne} \times 1000kWh/MWh$$

- $C_d$ Carbon dioxide emission level, Tonne CO$_2$/MWh

| **Parameter** | **Value** |
|---|---:|
| Size of algae cultivation system | 100 ha |
| Productivity of algal biomass | 20 g/m$^2$-d |
| Productivity of methane in biogas | 1.3 m$^3$ CH$_4$/m$^3$ ABD |
| Methane content in biogas | 65% |
| Energy content of Methane | 9.77 kWh/ m$^3$ CH$_4$ |
| Energy content of Diesel | 10 kWh/kg diesel |
| Carbon dioxide emission from methane consumption | 1.143 m$^3$ CO$_2$/m$^3$ CH$_4$ |
| Carbon dioxide emission from diesel consumption | 1.59 m$^3$ CO$_2$/kg diesel |
| Energy conversion efficiency of electricity generation | 35% |
| Carbon transfer to biomass efficiency | 70% |
| Electricity production seasin | 365d/yr |
| Electricity production hours | 24h/d |

Table 1. Summary of adopted technical parameter values

## **Economic analysis**

The calculation of capital and operation cost for the algae cultivation system is based on the cost analysis from PETC report (Pittsburgh Energy Technology Center, now the Federal Energy Technology Center ) (Benemann J.R 1996). The report was originally developed to analyze microalgae systems for power plant flue gas utilization and carbon dioxide mitigation, so some of the contents are deleted to fit the scenario of this study[2]. The capital cost for each component is also adjusted to 2010 level using plant cost index (Chemical Magazine, 2010), and the operation cost using inorganic cost index and labor cost index (Chemical Magazine, 2010).

| Component | Cost /ha-yr |
|---|---:|
| Ponds | $10,089 |
| Mixing (paddle wheels) | $8,408 |
| CO2 Sumps | $14,692 |
| Harvesting/Flocculation | $14,335 |
| Water/Nutrient/Waste | $10,425 |
| Buildings, Roads, Electrical | $6,825 |
| Engineering (15% of above costs) | $9,716 |

Table 2. Summary of capital costs for algae cultivation system

| Component | Cost /ha-yr |
|---|---:|
| Nutrients (N,P,Fe) | $700 |
| Flocculant | $778 |
| Waste Disposal | $1,111 |
| Labor and Overheads | $3,782 |

Table 3. Summary of operation cost for algae cultivation system

Capital cost of biogas plant can be estimated at \$300-\$500/$m^3$ volume of anaerobic bio-digester (ABD), the smaller number is for large plants, and the higher number for small plants (Steinhauser 2008). An average value of \$400/$m^3$ ABD is assumed in this study. For the purpose of electricity generation, an additional \$650/$kW_{el}$ is required for the construction of CHP units and adjacent facilities. After adjusted to 2010 level, the costs are

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[2] The land capital is not depreciable so land cost is not considered in this study

\$405.71 /m$^3$ ABD and \$659.28/kW$_{el}$, respectively.

The specific operational costs for biogas plant maintenance shall be for concrete work 0.5% of the ABD investment costs (concrete work consists approximately 63% of ABD capital cost), for the technical equipment 3% of the ABD investment costs (technical equipment consists approximately 37% of ABD capital cost), and for the CHP units 4% of the CHP units investment costs. In addition to that, labor costs, transportation costs of substrates for digestion, and other unknown costs are assumed 20% of total maintenance costs. Diesel cost is subject to change and used as a variable in this study, thus not included in the section.

| **Component** | **Cost/m$^3$ABD** |
|---|---|
| ABD | \$405.71 |
| | **Cost /kW$_{el}$** |
| CHP units | \$659.28 |

Table4. Summary of capital costs for ABD and CHP

| **Component** | **Cost/m$^3$ABD-yr** |
|---|---|
| maintenance (concrete works) | \$1.28 |
| maintenance (technical) | \$4.50 |
| | **Cost /kW$_{el}$ -yr** |
| maintenance (CHP) | \$26.37 |

Table 5. Summary of operation costs for ABD and CHP

To estimate the annual operational costs for the complex system, the required revenue to support the investment should be determined. A fixed charge rate (FCR) allows for quick determinations of the targeted revenue. FCR is defined as the amount of revenue per dollar of investment that must be collected annually from the selling of products to pay the carrying charges on the investment (Short et al. 1995). For the purpose of the study, the revenue is calculated under a before tax requirement scenario, and the formula for FCR is:

**Equation 15:** $$FCR = \frac{UCRF[1-(b)(T)\sum_{n=1}^{M}\frac{V_n}{(1+d)^n}] + p}{1-T}$$

- UCRF uniform capital recovery factor,

defined as $$UCRF = \frac{1}{\sum_{n=1}^{M}\frac{1}{(1+d)^n}} = \frac{(1+d)^M - 1}{d(1+d)^M}$$

- M depreciation period in years

- b fraction of depreciation base ( depreciable fraction of capital cost)

- n analysis year

- T income tax rate of the investor (state and federal)

- $V_n$ fraction of depreciable base that can be depreciated in year n

- d nominal discount rate

- p annual insurance cost as a percentage of total investment

The discount rate is set to 6.6%, which is recommended if the primary purpose of the project includes renewables (Petersen 1994). Declining balance (DB) method is applied for measuring the depreciation, and a 20 years recovery period is assumed. The DB depreciation method is defined as:

**Equation 16:** $$D_n = B_{n-1} \times r$$

- $D_n$ annual depreciation allowance for year n

- r annual percentage rate of depreciation applied to the remaining book value

(Property cataloged 15- or 20- year class property, $r = \frac{150\%}{N} = \frac{150\%}{20} = 7.5\%$)

- n number of years the asset will be depreciated

- $B_{n-1}$ remaining book value of the asset

According to the definition equation of DB method, $V_n$ and b can be calculated as:

**Equation 17:** $V_n = \frac{D_n}{B_0} = \frac{B_{n-1} \times r}{B_0} = \frac{B_0 \times (1-r)^{n-1} \times r}{B_0} = (1-r)^{n-1} \times r$

**Equation 18:** $b = \sum_{n=1}^{M} V_n$

So the formula of FCR can be rewritten as

$$FCR = \frac{\frac{(1+d)^M - 1}{d(1+d)^M} \times [1 - \sum_{n=1}^{M}[(1-r)^{n-1} \times r] \times T \times \sum_{n=1}^{M} \frac{(1-r)^{n-1} \times r}{(1+d)^n}] + p}{1-T}$$

The discount rate used is in nominal value, so the FCR is calculated on a nominal basis. Therefore the electricity cost is in nominal value. Considering that the cost for diesel fuel is not included in operation cost, and the electricity is the only source of income, so the minimal electricity price should be:

$$Minimal\_electricity\_price = \frac{FCR \times Capital\_\mathrm{cost} + Annual\_Operation\_\mathrm{cost} + Annual\_diesel\_\mathrm{cost}}{Annual\_electricity\_productivity}$$

| Parameter | Value |
|---|---|
| Project life time | 20 yrs |
| Discount rate | 6.60% |
| Depreciation method | DB |
| Tax rate | 40% |
| Depreciation period | 20 yrs |
| Insurance rate | 0.50% |

Table 6. Summary of adopted economic parameters values

## Results and Potential Policy Implication

### Model outputs

The base analysis is conducted by running the model at different diesel prices and carbon dioxide recycle percentages, using the parameters listed in technical and economic sections above.

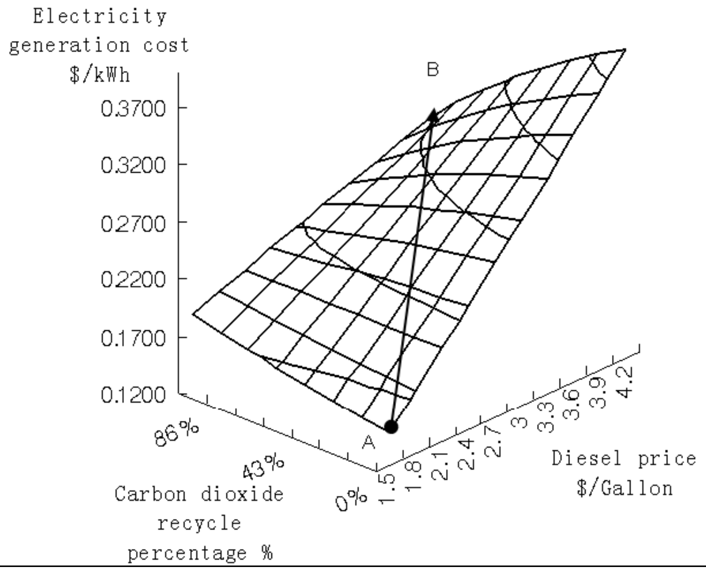

**Figure 4.** The model calculated electricity generation cost as a function of diesel price and carbon dioxide recycle percentage

Figure 4 shows that as diesel price increase, the lowest electricity generation cost scheme would move from no carbon dioxide recycling to 100% recycling (e.g. from A to B in Figure 4), indicates that the proposed carbon dioxide recycling scheme would became more economically feasible if the diesel price is high. Figure 5 shows the pathway of the transition from A to B, $2.10/gallon diesel price is the critical point where the most feasible scheme changes, and this change is achieved by shifting the scheme directly from no recycling to 100% recycling. A recycling scheme less than 100% would not be feasible under any circumstances.

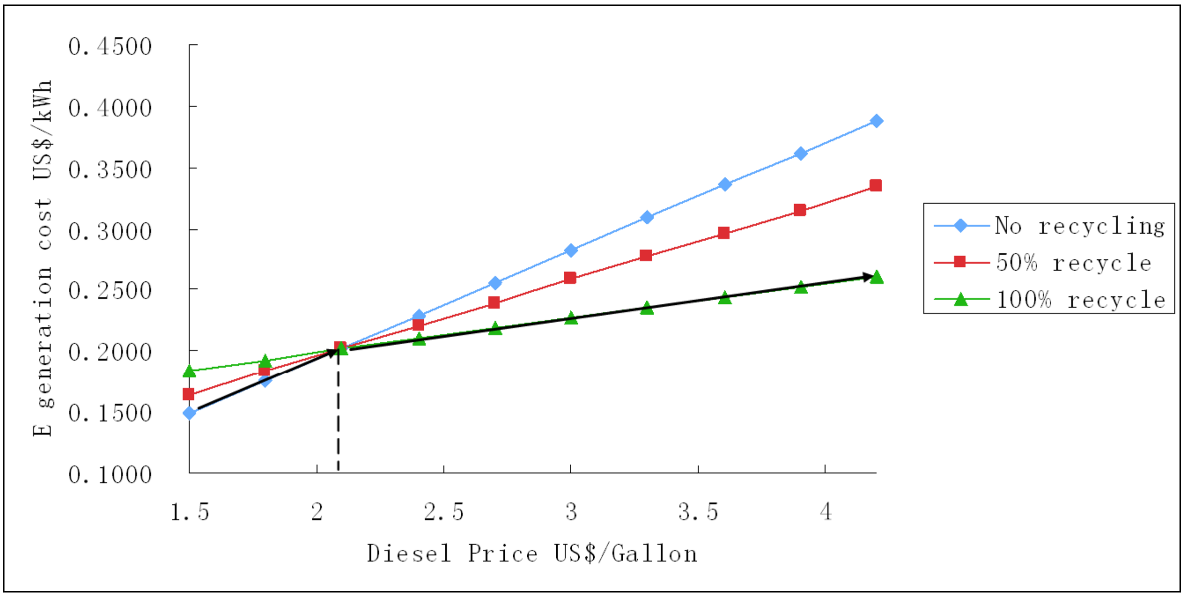

**Figure 5.** Comparison of model calculated electricity generation cost as a function of diesel price under different carbon dioxide recycling schemes

The general trend of such shifting remains the same under different scenarios in this study. However, the change in technical parameter may influence how the critical points are distributed. Take algal biomass productivities at 10, 20 ,and 30 VS g $m^2$ $d^{-1}$, the result that increase in biomass productivity leads to the decrease of critical diesel price, at which the electricity generation cost under no recycling scheme equals that under carbon dioxide recycling scheme (as shown in figure 7). Moreover, the increase of biomass productivity from 10 VS g $m^2$ $d^{-1}$ to 20 VS g $m^2$ $d^{-1}$ leads to the decrease of critical diesel price from $3.40/gallon to $2.10/gallon, about 3 fold of the magnitude of the decrease from $2.10/gallon to $1.65/gallon, which is resulted from the increase of biomass productivity from 20 VS g $m^2$ $d^{-1}$ to 30 VS g $m^2$ $d^{-1}$. The reason for the different magnitudes of critical diesel prices decrease caused by equally biomass productivities increase can be explained from two related aspects: On one hand, the increase of biomass productivity can break down the average capital cost on algae cultivation system, e.g. the capital cost per ton of biomass, but as the denominator increase continuously, the average capital cost decrease exponentially. On the other hand, the maintenance costs, i.e. mixing and harvesting costs, increase as the biomass productivity increase. In addition to that, the capital cost on infrastructures used to process the additional biomass increases simultaneously. As a result of these changes, the marginal benefit from the increasing biomass productivity decreases continuously.

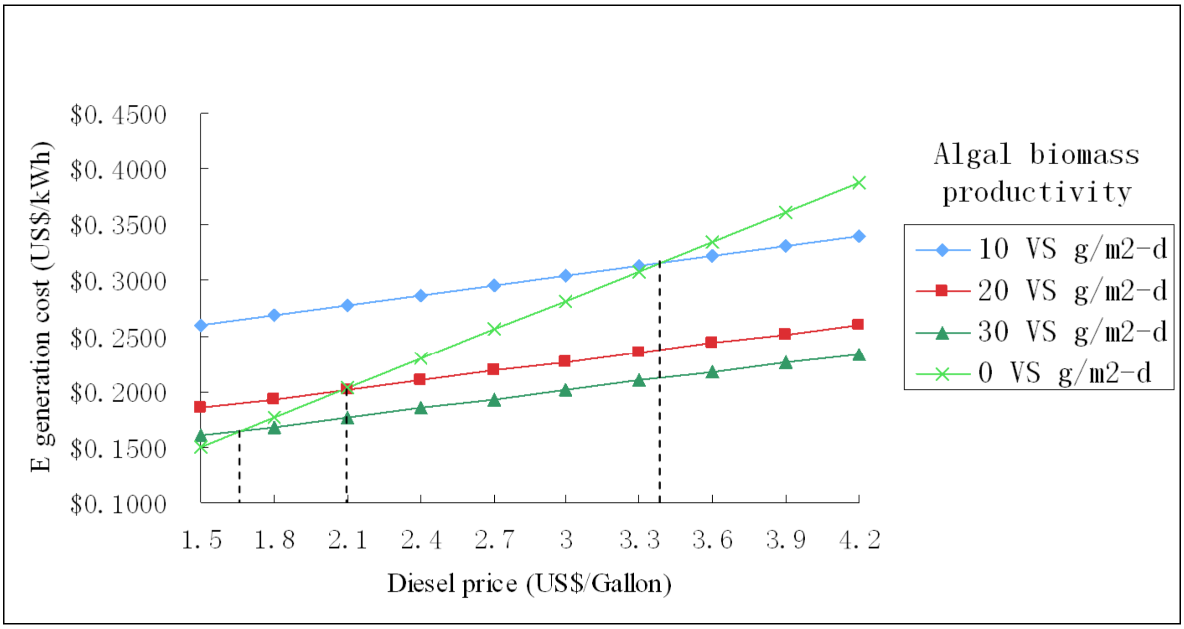

**Figure 6.** The model calculated electricity generation cost as a function of diesel price under different algal biomass productivity scenarios when 100% carbon dioxide is recycled

## Potential policy implications

In real world, the source of fuels can be diverse, and there are many unpredictable variables that may influence the outputs of proposed model. However, by applying the model to a relatively isolated system that has similar background to the proposed scenario, it is possible to find a niche for the application of such project, and potential policy implications that will incentivize the development of it.

Hawaii is chose as an example to discuss the feasibility of proposed project in real world scenario. The reason to choose it is because: first, as a group of islands, the generation of energy requires external energy sources being shipped to designated facilities; second, eight of the ten largest power plants in Hawaii use petroleum as their major energy source (DOE 2008).

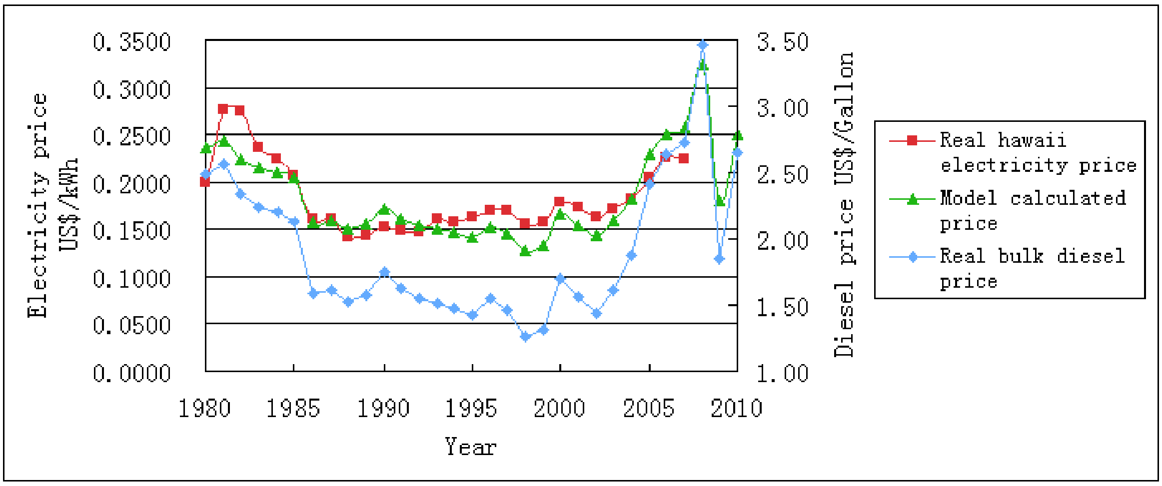

**Figure 7.** Comparison of historical Hawaii electricity retail price and electricity generation cost calculated from the model using historical pump diesel price as variables[3]

Historical diesel data are used as variables in the model, and electricity generation costs (minimal prices) are calculated under non carbon dioxide recycling scenario. The calculated prices are compared to historical Hawaii retail electricity, as shown in figure 7. The result suggests that the model calculated prices are more sensitive to the diesel prices fluctuation, while the historical retail prices response slower to the decline of fuel price, this is consisted with (Peltzman 2000) finding. Additionally, after the 1970s' oil crisis, the diesel price showed a declining trend until 1998 when the price started to increase, and by 2006 the real value of diesel has exceeded the historical highest value. Although the big

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3 The nominal price of historical Hawaii electricity retail price and nominal bulk diesel price have been adjusted to real price, using Consumer price index, and May 2010 CPI equals 1.000. The Bulk diesel price is calculated from retail diesel price. According to EIA, the cost on crude oil, refinery and transportation consist 90% of retail diesel price, so the bulk price is calculated as retail price times 90%.

bouncing in 2008 and 2009, it is very likely for the diesel price to grow in the future.

Policy makers can help industries adapting themselves to the fuel price change in the future and reduce the scale of potential electricity price increase, by subsidizing the reduction of carbon dioxide emission. The positive responses from industries may play an important in terms of fighting climate change and ocean acidification, so the actual influence could be a win-win situation for both economic development and ecosystem services.

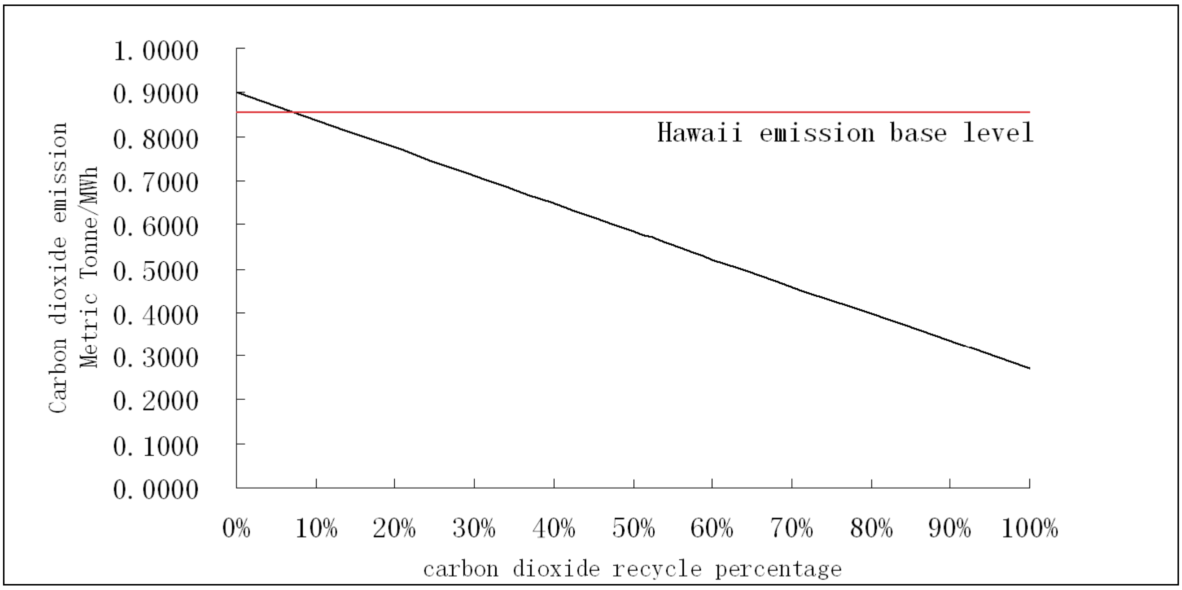

**Figure 7.** Carbon dioxide emissions as a function of carbon dioxide recycle percentage in proposed model

The baseline of carbon dioxide emission from electricity section in Hawaii is approximately 0.86 metric ton/ MWh. If all carbon dioxide emission can be recycled use the proposed recycling scheme, the emission level can be reduced to as low as 0.27 metric ton/MWh.

The productivity of algal biomass in the field may be not as high as expected, so it is important to figure out how much subsidy should be provided to ensure the electricity producers have the incentive to switch from traditional power generation scheme to the carbon dioxide recycling scheme. At current diesel price (About $3.00/gallon for retail, and $2.70/gallon for bulk sale), the required subsidy decreases as the average algal biomass productivity increases, and for example, a company would be encouraged to adopt the carbon dioxide recycling scheme, if the subsidy is more than $70/ton carbon dioxide reduced and they can achieve a 10 VS g m$^{-2}$d$^{-1}$ algal biomass productivity rate. More over, once the average biomass productivity exceed 14 VS g m$^{-2}$d$^{-1}$, even with out subsidy, the carbon recycling scheme would be more feasible.

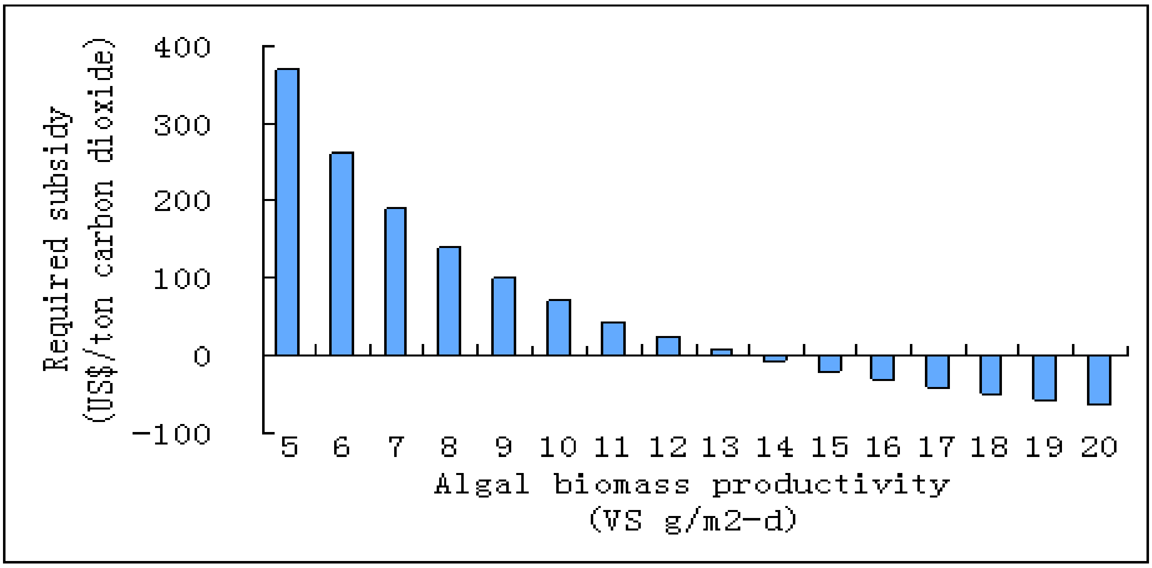

**Figure 8.** Subsidy required for the generation of electricity under different algal biomass productivity situations, when 100% carbon dioxide recycling scheme is adopted, and the diesel price is $2.70/gallon

## Conclusion

The proposed marine microalgae based biogas-diesel electricity generation combining carbon dioxide recycling scheme has the potential to slow down the electricity generation cost increase from diesel only scheme, once the increasing diesel price exceeded a threshold. The increase in algal biomass productivity can lower down the critical diesel price at which the electricity generation costs are equal for both schemes.

The application of proposed carbon dioxide recycling scheme can significantly reduce the carbon dioxide emission level. In Hawaii as example, government subsidizing carbon dioxide reduction can incentivize electricity generators to switch to the recycling scheme before the technical and economic preconditions fully mature. The benefits of such policy include potential ecosystem services and preparation of future challenges. Once the algal biomass productivity exceeds a critical level, even the diesel price doesn’t increase as expected; the recycling scheme can be preceded feasibly without subsidy.

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