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Photobiological Solar Energy Harvest

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1. Introduction

1.1 Background and motivation

In 2010, the United States consumed 36.96 quadrillion BTUs (39 quadrillion kJ) of liquid petroleum fuels (EIA, 2011). Even assuming the adoption of more stringent fuel economy standards and unconventional vehicle technologies, this number is expected to grow steadily with rising population and corresponding demand in the transportation sector. As the economies of developing countries strengthen, the global spread of industrialization and personal transportation will cause the demand for liquid fuel to rise dramatically in regions of historically low consumption. According to studies conducted by the Energy Information Administration, from 2007 to 2035, growth in the transportation sector accounts for 87 percent of the total increase in world liquid fuel consumption (EIA, 2010). Figure 1 displays this projected growth of liquid fuel consumption by various energy consuming sectors.

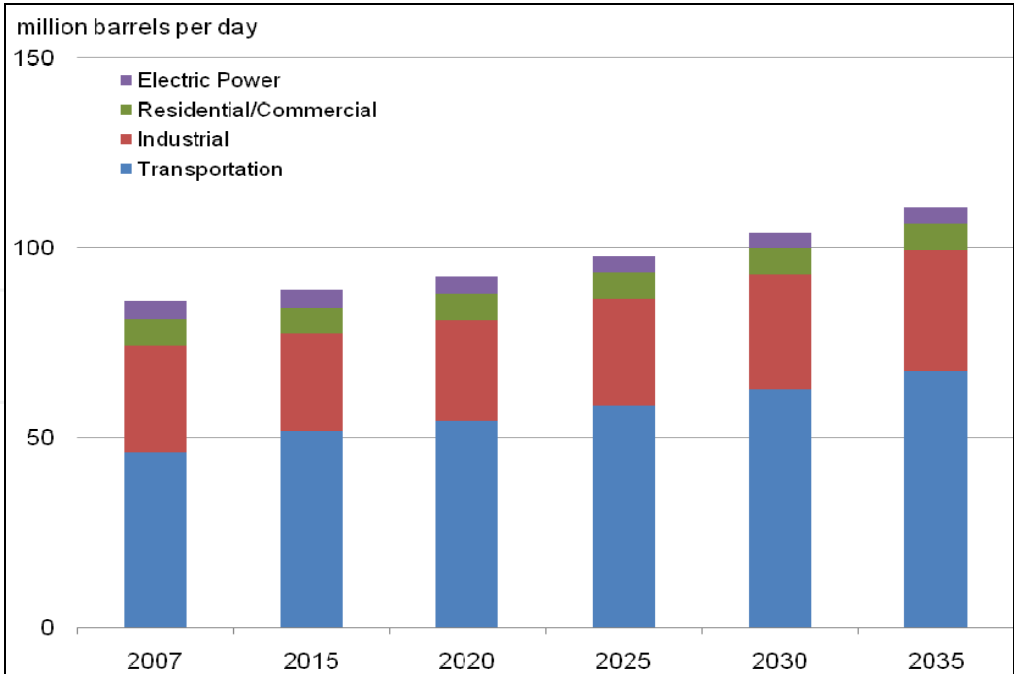


Fig. 1. World liquid fuels consumption by sector, 2007-2035 (EIA, 2010).

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The strength of the US economy depends heavily on its ability to transport goods and services from producers to consumers. The price of oil reached a record of \$145/barrel in the summer of 2008 (EIA, 2011), crippling business activities and marking the beginning of a global recession. Similar price spikes during the energy crises of 1973, 1979, and 1990 were followed by periods of economic distress. Taking these events as a whole, the price volatility of petroleum fuels presents a clear threat to economic stability and American prosperity.

In addition, concerns over climate change have put reducing fossil fuel combustion emissions at the forefront of environmental policy. Since the industrial revolution, the concentration of carbon dioxide in the atmosphere has increased by 36% to approximately 390 ppm in early 2011 (Conway & Tans, 2011). Human activities outpace the planet’s natural ability to remove the excess carbon, and the concentration of carbon dioxide continues to increase by approximately 1.9 ppmv each year. As atmospheric carbon dioxide concentration reaches its highest point in at least the last 650,000 years, it cannot be denied that industrialization has significantly altered the makeup of the Earth’s atmosphere (Soloman, et al., 2007). The global focus on limiting Greenhouse Gas Emissions (GHG) suggests impending environmental regulation and possible carbon taxes on industries consuming fossil fuels. These forthcoming policies will serve to raise already steep fuel prices and put further strain on the global economy.

To meet the expected demand for energy without threatening national security, the economy, or the environment, a new portfolio of fuels must be adopted that can be produced inexpensively, domestically, and in extremely large quantities. The United States transportation sector alone consumed 26.7×10^{15} BTUs of liquid petroleum fuel in 2010, equivalent to over 4.6 billion barrels of crude oil (731 million m³) (EIA, 2011). Based on energy content, over 205 billion gallons (776 million m³) of biodiesel must be produced each year to meet consumption. As most alternative fuels contain less combustible energy per unit volume, fuel from other unconventional sources would be required in even higher quantities. Figure 2 compares the most common alternative transportation fuels and their respective energy content as given by their higher heating value.

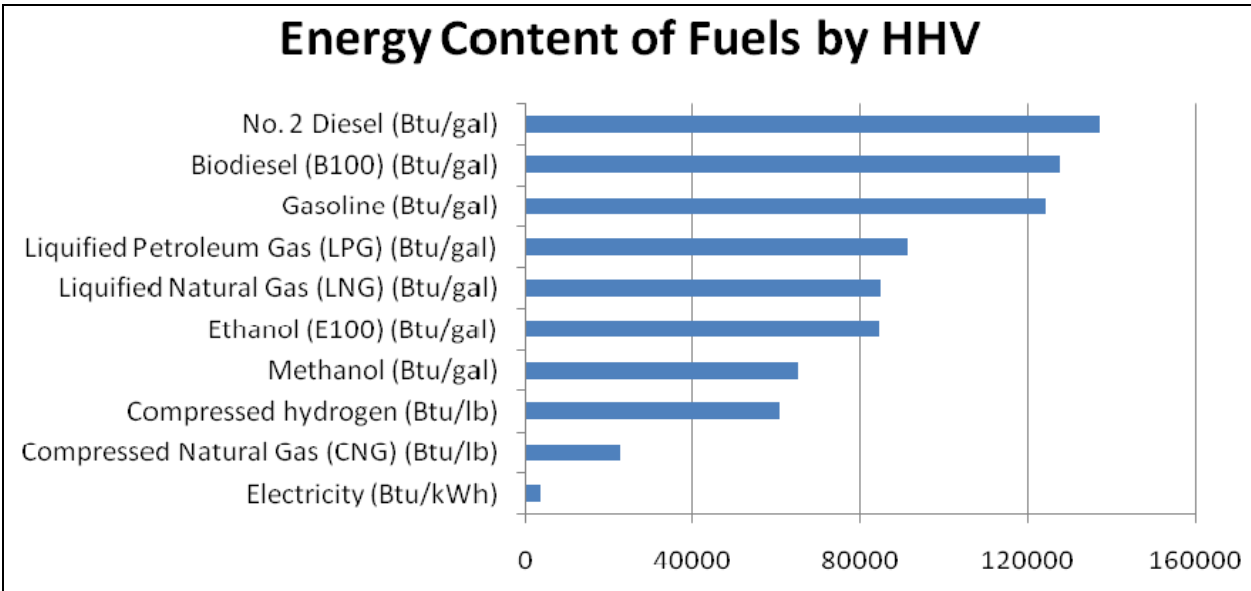


Fig. 2. Energy content of various fuels by Higher Heating Value (HHV) (EERE, 2011).

Recent innovations in electrically powered vehicles have led to a minority of drivers to consume less petroleum fuel. However, the low energy density of most batteries entails large battery packs, frequent recharging, and limited mileage. In addition, widespread adoption of this technology would put significant strain on the existing electric grid and potentially displace the demand for oil with that for the rare metals necessary for battery production, such as platinum, cadmium, and lithium (Hübner, 2010). Both the current infrastructure and the power requirements of heavy transportation, aviation, and maritime shipping necessitate a fuel that is both liquid and energy dense. Alternative fuels that meet these requirements include biodiesel, ethanol, methanol, and more recently, biobutanol, Fischer-Tropsch diesel, and hydrogenation-derived renewable diesel. However, the latter three fuels exist only in immature stages of development and will not likely be viable in the short to medium term (EERE, 2011).

The use of biodiesel in place of conventional petroleum diesel in compression ignition engines holds benefits for the economy, national security, and the environment. In 2000, biodiesel became the only commercially available alternative fuel to successfully pass the EPA-required Tier I and II health effects testing under the Clean Air Act. Burning biodiesel results in a significant reduction in the release of harmful emissions, such as sulfur oxides, carbon monoxide, and particulate matter. In addition, the US Department of Energy reported that replacing conventional diesel with biodiesel resulted in a 78.5% reduction in carbon dioxide emissions (National Biodiesel Board, 2009).

Biodiesel can be produced from any animal or vegetable oil, all of which are biodegradable, nontoxic, and renewable. Virgin soy bean oil and recycled cooking grease represent the most common domestic feedstock for biofuel production. However, current quantities of these readily available sources can provide only enough biodiesel to displace roughly 5% of the on-road diesel used in the United States (EERE, 2011). Increasing the cultivation of agricultural feedstock to meet the production of significantly more biodiesel would require unrealistic quantities of arable land, water, fertilizers, herbicides, and pesticides, all of which would be diverted from food production. To meet the current fuel demand, new feedstocks must be pursued.

1.2 Algal biofuel production history

In 1978, the National Renewable Energy Lab's landmark Aquatic Species Program began a twenty-five year investigation on the potential for microalgal biodiesel to solve the impending energy crisis. The program was motivated by the following: (i) lignocellulosic ethanol cannot substitute for energy dense diesel and aviation fuels; (ii) renewable oil sources are insufficient to meet the demand for diesel fuel; and (iii) the unprecedented environmental threat presented by global climate change. Over the course of twenty-five years, \$25 million was spent to collect and screen microalgae, study the physiological and biochemical aspects of various species and the role of genetic engineering to optimize desired characteristics, refine the process engineering aspects of cultivation, harvesting, and extraction, and finally, to develop outdoor mass culture systems with the intention of large scale biofuel production. Although the program ended in 1996, the NREL's analysis and the progress made in the phycology field, particularly in the area of genetic modification of the algae's metabolic pathways, laid the groundwork for future research (Sheehan, et al., 1998). The study's conclusions revealed that the Southwest United States holds ample resources in

the form of land, water, and CO₂ for the production of more than 30 billion gallons of biodiesel. However, challenges remained as the relatively low price of oil in 1996 made the high capital cost of the production process hard to justify. Biological productivity remains the most important factor for determining the final fuel cost. While open ponds on low cost land were deemed the most viable option for growth facilities, their low productivities presented a significant hurdle. Areas for improvement were identified as the need to find a market for the biomass residue after oil extraction, water and nutrients should be recycled, research should continue to search for an ideal strain, and a lower cost, easily accessible source of supplementary CO₂ must be found (Jarvis E. E., 2008).

In 2006, 10,000 dry tons of algal biomass were produced worldwide (Schulz, 2006). Although commercial production of nutritional supplements comprised the vast majority, private companies and research organizations around the world have been working to build on the findings of the NREL’s Aquatic Species Program to develop an economical method for the growth, harvesting, and processing of algae for fuel. In a significant strategy shift in 2009, ExxonMobil announced a partnership with Synthetic Genomics, a biotechnology company, that would allocate \$600 million over the course of five to six years for the development of biofuel from algae (Howell K., 2009). This accelerated research initiative and a renewed global interest in developing a viable alternative fuel suggest that the many obstacles identified by the Aquatic Species Program may soon be overcome.

1.3 Algal biofuel production portfolio

Several methods exist for the production of fuel from algae: (i) generation of hydrogen during the growth stage, (ii) fermentation of carbohydrates and sugars into alcohols, (iii) transesterification of intracellular lipids into biodiesel, and (iv) gasification of the residual biomass. Figure 3 illustrates these various pathways and their constituent metabolic precursors.

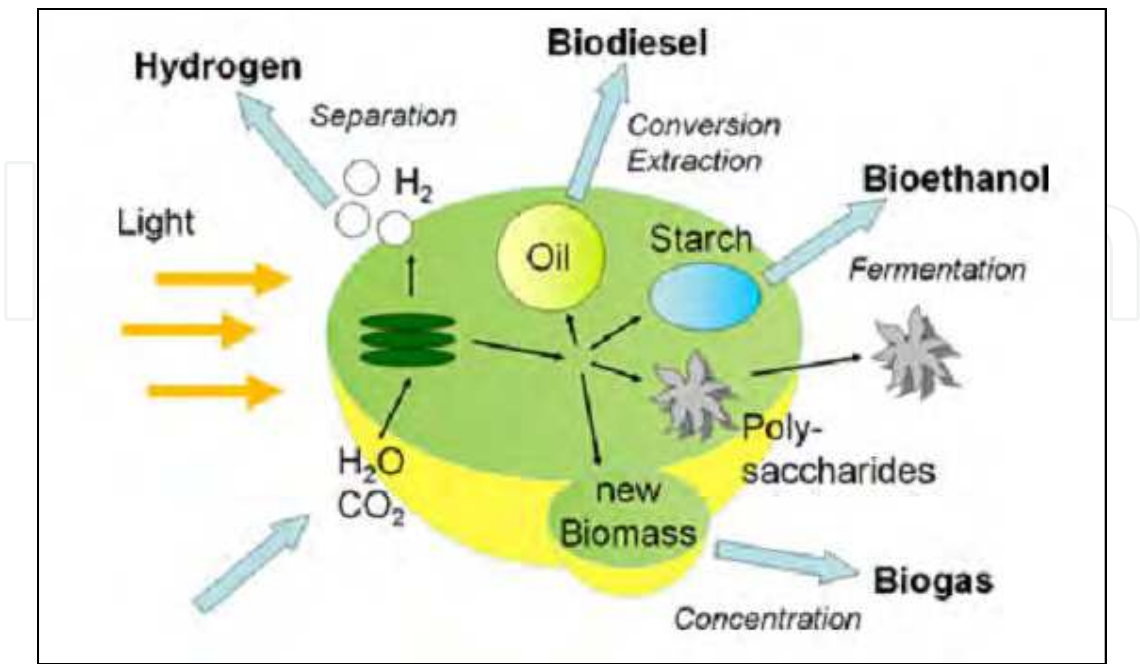


Fig. 3. Possible energy products from algae (Morweiser, et al., 2010).

1.3.1 Biohydrogen production

Biological hydrogen production has received attention in recent years as a safe and renewable energy source for a wide variety of applications, including the replacement of liquid fuel in the transportation sector. Remarkably, certain algal strains possess the ability to switch metabolic pathways and produce hydrogen during respiration. In a sealed, sulfur depleted environment, algae will stop oxidizing water, thus ending the supply of oxygen. When the remaining oxygen is consumed, the algae begin metabolizing stored compounds in an alternative respiration system from which hydrogen is evolved as the product (Melis & Melnicki, 2006). The catalysts for this reaction are either the hydrogenase or the nitrogenase enzymes, whose activities are inhibited by elevated oxygen levels in the environment. Moreover, the concentration of H^+ and electrons, which are obtained either directly from photosynthetic water splitting or indirectly through the degradation of starch, affects the productivity of this reaction (Kruse & Hankamer, 2010). While this process holds great promise for hydrogen production in general and fuel cell coupling in particular, research is still in its infancy and costs remain high.

1.3.2 Bioalcohol production

The Energy Policy Act of 2005 mandated an increase in the amount of biofuel blended into conventional gasoline, the vast majority of which has been met by corn ethanol (DOE, 2010). However, ethanol production from terrestrial plants such as corn, sugarcane, and lignocellulosic grasses requires large areas of arable land and huge volumes of potable water. Furthermore, the low energy density of ethanol cannot address the needs of the transportation sector in its entirety. Despite these issues, the market for ethanol remains large, as 23% of American the corn yield during the 2010/2011 growth season was diverted to ethanol production (USDA, 2011).

In the same way that carbohydrates generated by conventional ethanol feedstocks are broken down into sugar and fermented, the starches and cellulose in algae biomass can be used to produce ethanol. Depending on the strain of algae, the starch profile can include simple sugars or complex chains which must be broken before fermentation. The biomass can then be mixed with yeast or other fermentative microorganisms and fermented to produce alcohol (Bush & Hall, 2006). As the yeast consume sugar, they produce CO_2 which can be fed back into the growth system in a closed-loop process, as shown by Figure 4.

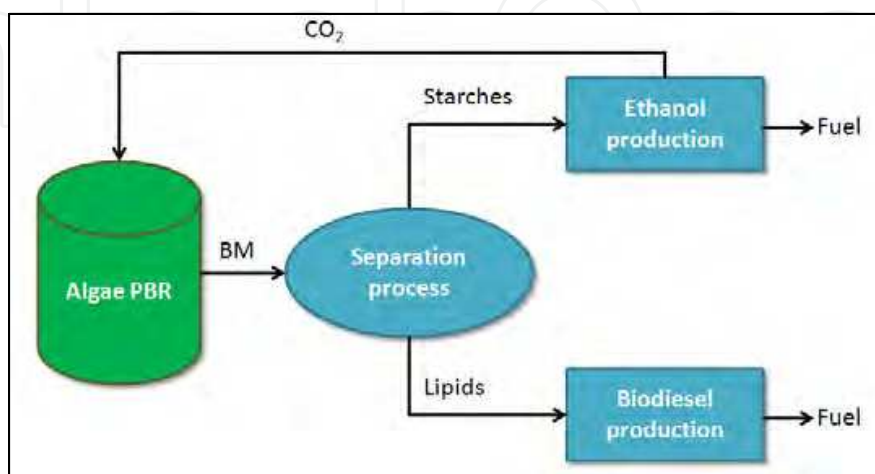


Fig. 4. Coproduction of ethanol and biodiesel from algae.

Although a combination biodiesel-ethanol plant is technically feasible, ethanol is a relatively inexpensive commodity and capital costs for such a facility are high. A more economically attractive approach to coproduction may be to convert the carbohydrate and protein dense biomass into a variety of high-value products, such as pigments, micronutrients, and omega-3 fatty acids in the form of EPA and DHA (Powell & Hill, 2009) (Singh & Gu, 2010). The chemical makeup of the algae biomass being cultivated dictates this co-product portfolio.

1.3.3 Biodiesel production

To produce biodiesel from algae, cell walls are ruptured and a solvent such as hexane is used to separate the intracellular lipids in the form of triacylglycerol (TAG) from the rest of the biomass. Methanol then acts as a catalyst to break these long TAG chains into smaller alkyl ester chains, commonly known as biodiesel (Scott S. A., et al., 2010). In addition, this reaction produces glycerol as a byproduct.

While biodiesel represents the most volumetrically energy dense fuel derived from algae, the separation process of the TAG lipids from the residual biomass presents a costly and inefficient bottleneck. Large amounts of solvent are needed for current techniques, while contamination of the lipids from other cellular components remains an obstacle (Scott S. A., et al., 2010). Active research in this area has suggested the possibility of selective decomposition of the cell wall using enzymes, electromagnetic waves, and sonic vibration (Cooney, et al., 2009) (Andrade, et al., 2011). These novel methods seek to minimize the quantity of solvent required and result in more complete extraction of the lipids.

Regardless of these process engineering challenges, the rapid growth rate, high lipid content, and unique cultivation conditions of microalgae suggest it to be the only feedstock with the potential to completely displace liquid fuels derived from petroleum (Chisti, 2007). For the production of biodiesel, microalgal systems hold significant advantages over other crops, including their higher photon conversion efficiency, their ability to be harvested batch-wise nearly year-round, their utilization of salt and wastewater streams (Park, et al., 2011), and their potential for CO₂ sequestration via flue gas coupling (Schenk, et al., 2008). In terms of arable land usage, no other oil crop could provide the quantities needed for the widespread adoption of biofuels without drastically altering the world's current agricultural landscape, as shown by Table 1.

Plant source	Biodiesel (L/ha/year)	Area to produce global oil demand (hectares x 10 ⁶)	Area required as percent global land mass	Area as percent global arable land
Soybean	446	10,932	73.4 %	551.6 %
Rapeseed/canola	1,190	4,097	27.5 %	206.7 %
Jatropha	1,892	2,577	17.3 %	130 %
Oil palm	5,950	819	5.5 %	41.3 %
Algae (10 g m ⁻² day ⁻¹ at 30 % TAG)	12,000	406	0.3 %	20.5 %
Algae (50 g m ⁻² day ⁻¹ at 50 % TAG)	98,500	49	0.3 %	2.5 %

Table 1. Comparison of crop-dependent biodiesel production from plant oils (Schenk, et al., 2008).

1.3.4 Biomethane production

Anaerobic digestion of organic waste produces a flammable gas mixture that can be burned for heat or used to power a gas engine. Once this biogas has been processed, it can be used in any conventional natural gas application. As the lipid fraction of algae ranges from 15-77% of total cell contents (Chisti, 2007), a large quantity of biomass remains after the extraction process. This organic biomass can be mixed with other forms of biowaste and anaerobically digested to produce biogas. In addition, the digested matter can be centrifuged and both the solid and liquid fraction used as fertilizers and soil conditioners. Figure 5 presents a basic schematic for a biogas production facility.

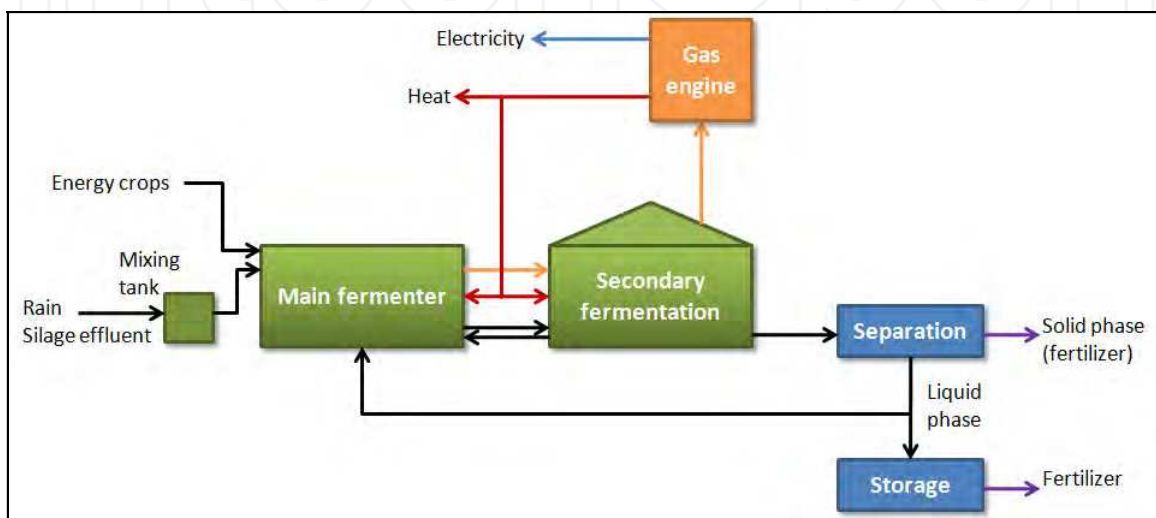


Fig. 5. Biogas production from energy crops, adapted from (Braun, et al., 2008).

The compaction of waste in landfills produces biogas naturally; however, if released freely into the atmosphere, this gas presents a significant pollution threat due to its methane content and combustibility when mixed with oxygen. Atmospheric methane is estimated to be more than twenty-one times as intense a greenhouse gas than carbon dioxide. However, when burned, biomethane is considered to be a relatively clean alternative fuel. Biomethane can be processed from biogas produced by the anaerobic digestion of animal waste, sewage, and crop waste from cellulosic and non-cellulosic plants. In the US, the potential annual production of biomethane from these sources could be equivalent to 10 billion gallons of gasoline. If this quantity of biomethane were substituted for conventional gasoline for fueling vehicles, greenhouse gas production could be reduced by 500 million metric tons of CO₂ per year (EERE, 2011). This reduction represents a 29% decrease in the rate of CO₂ emissions attributed to the American transportation sector in 2009 (EPA, 2011).

Despite this large breadth of activity seeking to realize algae's commercial potential, few comprehensive comparisons have been made to address the energetic and economic efficiency of these systems for biofuel production. The following sections analyze and compare methods for the cultivation, harvesting, and processing of microalgae for the production of biofuels. Particular emphasis is placed on the production of biodiesel due to its high energy density and compatibility with current transportation infrastructure and technology. A thermodynamic study identifies the most efficient production systems with regard to conversion of solar energy and utilization of auxiliary energy, and an economic

analysis highlights advantages of less efficient though potentially more profitable technologies. In this manner, current technology for algal biodiesel production can be assessed for its commercialization potential and utility to an energy consuming society.

2. Photobioreactor systems for biofuel production

Although the cultivation of algae began hundreds of years ago, only in recent decades have attempts been made to grow these organisms at an industrial scale. As with any agricultural system, as environmental control loosens, output becomes more erratic. Photobioreactors can be classified in two primary categories, closed and open systems. In closed systems, the algae are contained and culture conditions are highly regulated. In contrast, open systems dictate the algae grow exposed to the environment, permitting less control and increasing vulnerability to infection and invasion by predators. Although open systems present a higher risk of culture loss and generally produce less concentrated algae slurry, they are far less expensive to manufacture and operate than closed systems. Many have argued that open systems, particularly in the popular raceway pond configuration, currently represent the most economically viable method for producing algal biodiesel (Borowitzka, 2005) (Morweiser, et al., 2010) (Rodolfi, et al., 2009) (Stephens, et al., 2010). However, because these systems generate lower concentrations of biomass per liter, the concentration and extraction processes become more energy and cost intensive (Chisti, 2007). To analyze the photobioreactors both as singular units and part of the larger biofuel production system, this chapter examines closed and open reactors for their solar conversion and thermodynamic efficiencies with and without the inclusion of the harvesting and extraction processes.

2.1 Planktonic photobioreactors

Planktonic algae float or drift in a suspension of fresh or saline water. In the wild, these algae form large blooms at or near the surface and act as a vital food source for many fish and marine creatures. Planktonic photobioreactors serve to accommodate this type of algae by providing a slow moving current in which the culture can drift. As most cultivated algae strains exhibit this behavior, these photobioreactors have become extremely common while still assuming many different configurations.

2.1.1 Open pond raceways

Open pond systems generally consist of a lined or unlined shallow tank in which water is gently circulated via paddlewheels, as shown in Figure 6. The ponds are most commonly constructed out of earth, plastic, or concrete, and water depths range from 10-50 cm to optimize the absorption of light by the algae (Jorquera, et al., 2010). In the raceway configuration, algae inoculant is fed to the pond in front of a rotating paddlewheel. The algae mature as they circulate through the raceway and are harvested upon completing the path.

The relative technical simplicity and scalability compared to other PBR systems have made raceway ponds the most common method for commercial production of algae products. The largest algae growth system in the world utilizes this design, occupying over 440,000 m² in Southern California for the production of *Spirulina* sp., which is dried and sold as a nutritional supplement (Earthrise® Nutritional, LLC, 2009).

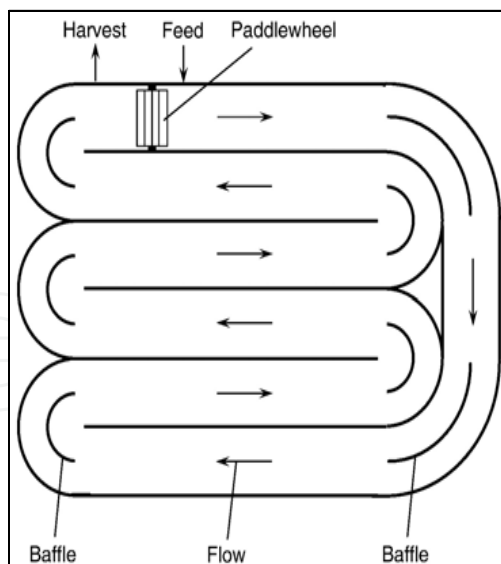


Fig. 6. Schematic of an open pond raceway system (Chisti, 2007).

Open ponds usually draw CO_2 from the atmosphere and receive unfiltered sunlight for photosynthesis. Because the pond is open to the ambient environment, evaporation off the surface helps to regulate its temperature. However, this evaporation also adds to the pond's high water consumption, and the exposure leaves the culture vulnerable to contamination and invasion by foreign species. In addition, because light conditions are not regulated, photoinhibition can be problematic. Finally, the large volumes of water required for these systems result in a much less concentrated product upon harvesting, requiring a more energy intensive dewatering processes. The cost of the final product ultimately depends on the amount of auxiliary energy required and the productivity of the photobioreactor, both of which are relatively low for open ponds in comparison to closed systems.

2.1.2 Tubular systems

Tubular systems can be oriented in horizontal, vertical, helical, or annular configurations and consist of series of small plastic or glass tubes through which planktonic algae gently circulate. In these systems, tubes are arranged parallel to each other and may be stacked to increase the yield per unit area. Highly turbulent flow is maintained by mechanical or airlift pumping to prevent algae sedimentation within the tubular array. Tubular photobioreactors operate as continuous culture systems in which a reservoir is used to remove dissolved oxygen and add CO_2 to the fluid before continuing the loop and repeating the process. Additional carbon dioxide may be supplied at intervals along the tubes to maintain a constant pH and ensure that photosynthesis is not interrupted by lack of carbon (Chisti, 2007). Figure 7 displays a basic schematic of a tubular photobioreactor.

Closed systems can achieve more than thirteen times the volumetric productivity than raceway ponds systems as they allow better capture of incident radiation, protection from contamination, more effective gas/liquid mass transfer, and a higher degree of control over pond conditions (Chisti, 2007) (Jorquera, et al., 2010). In addition, closed systems have much smaller areal footprints and require smaller volumes of water than open ponds, resulting in more productive facilities and higher biomass concentrations at harvest (Chisti, 2007). As

biomass concentration can be nearly 30 times greater than algae slurry harvested from raceway systems, biomass recovery from tubular systems is generally less labor intensive. However, tubular reactors can become expensive due to high power requirements for mixing and gas/liquid transfer. While open pond systems may consume as little as 4 W/m^3 , horizontal tubular systems of similar scale have been reported to require as much as $2000\text{--}3000 \text{ W/m}^3$ (Jorquera, et al., 2010) (Sierra, et al., 2008). Depending on the cost of processing the harvested biomass and the market value of the final product, highly productive tubular systems may be economically justified (Chisti, 2007).

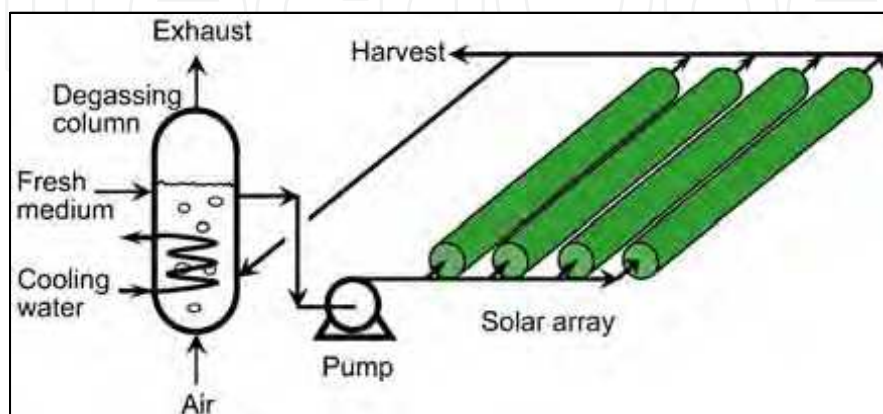


Fig. 7. Schematic of a tubular photobioreactor (Chisti, 2007).

2.1.3 Flat plate systems

Flat plate photobioreactors cultivate planktonic algae in vertical, translucent panels which are illuminated from both sides and mixed by aeration (Sierra, et al., 2008). As in all photobioreactors, these systems are developed in concert with the unique physiology of the algae species under cultivation. In particular, light regime, temperature regulation, and mass transfer represent important design parameters in the construction of these systems. Flat plate systems have been in use since the 1950's, and modern reactors have both reduced the areal footprint of the cultivation system (Pulz, et al., 1995) and facilitated the guidance of any desired light path through the use of laminated glass sheets (Hu & Richmond, 1996). Figure 8 displays a schematic for a flat plate photobioreactor system. Flat plate systems are usually constructed from glass or plastic panels held together by steel frames. Innovative systems have utilized plastic bags within a wire netting support system, resulting in a simpler construction than other designs (Tredici & Rodolfi, 2004).

In addition to the plate's material transmissivity, location and orientation of flat plate reactors largely determine the quantity and quality of incident solar radiation (Duffie & Beckman, 1980). For plates oriented in an East-West configuration at locations within 40° of the equator, the quantity of intercepted global radiation becomes similar to that of horizontal surfaces such as raceway ponds but with better homogenization of light reception over the course of a year (Sierra, et al., 2008). To minimize light saturation, panels can be placed in a North-South configuration to encourage a degree of mutual shading and dilute high intensity light during the afternoon, reducing photoinhibition (Morweiser, et al., 2010) (Carlozzi, 2003). Like tubular systems, the high surface area to volume ratio of flat plate systems results in shorter light paths, high photosynthetic efficiencies, and

consequently high productivities. Similar to their tubular counterparts, the energy requirements of flat plate photobioreactors makes them more expensive than the more technically crude open systems (Morweiser, et al., 2010).

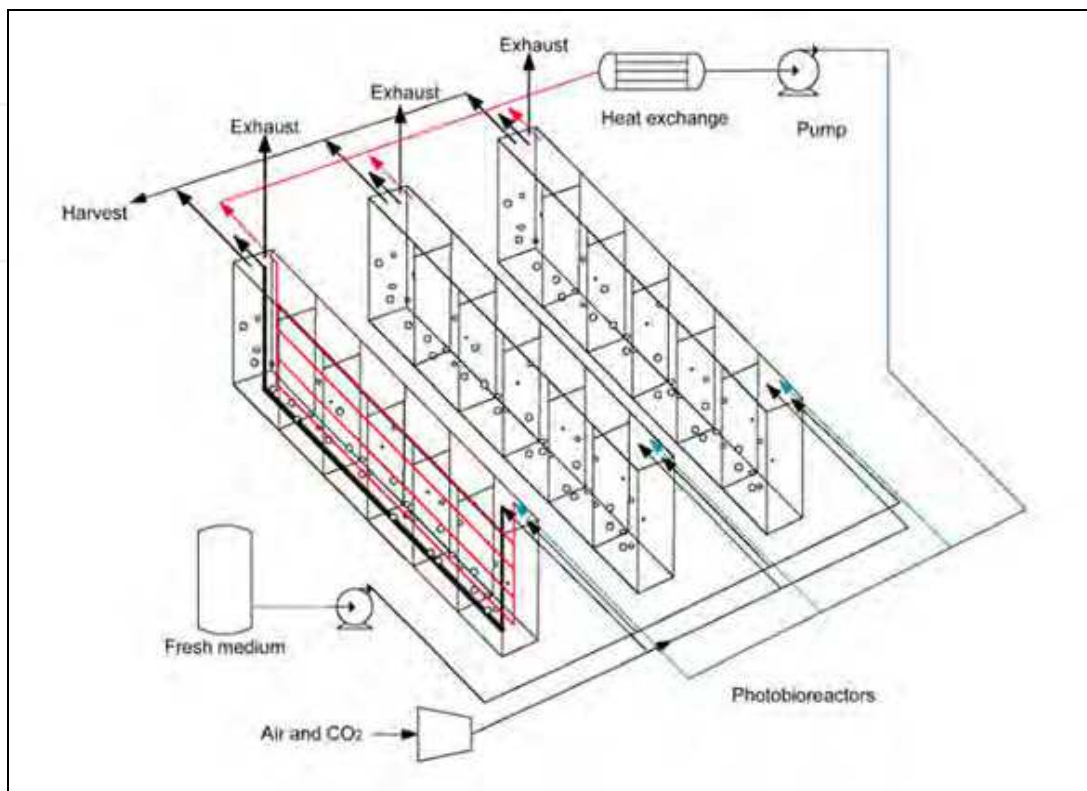


Fig. 8. Schematic of a flat plate photobioreactor (Jorquera, et al., 2010).

Flat plate reactors hold an advantage over tubular systems in that oxygen molecules generally have a much shorter distance to travel before reaching a degassing station. If the design of any closed system does not adequately account for this mass transfer, dissolved oxygen released during photosynthesis can accumulate and potentially damage the algae cells (Sierra, et al., 2008). Flat plate systems typically require approximately 40-50 W/m³ for mixing, pumping, and mass transfer (Morweiser, et al., 2010). As discussed in the context of the open pond system, this consumption is orders of magnitude lower than that for tubular reactors of similar capacity, resulting in less costly operation. This lower power requirement for flat plate systems also becomes advantageous as many algae species are damaged by high levels of shear.

2.2 Benthic photobioreactors

Unlike planktonic organisms, benthic algae grow immobilized in a biofilm attached to a substrate. Benthic photobioreactors accommodate these species by providing a large surface upon which the algae can settle. These novel systems represent an alternative to the more commonly available planktonic photobioreactors and serve to expand culture options to include species that were once limited by cultivation method. Benthic photobioreactors have taken many different forms, all of which seek to maximize the substrate surface area and minimize water and auxiliary energy consumption and nutrient waste. In most systems,

water is gently circulated over the biofilm, and drip systems are employed to deliver nutrients. Figure 9 illustrates a novel benthic photobioreactor developed in The University of Texas' Solar Energy and Biofuels lab for the production of *Botryococcus braunii* sp. This lab scale system utilizes a carbonated concrete surface as the algae substrate and has demonstrated productivities of up to 30.73 kg/m³ with a lipid content of 26.8%. In addition, this particular photobioreactor was shown to reduce the water requirement for cultivation by up to 42 times that of raceway pond systems (Ozkan, et al., 2011).

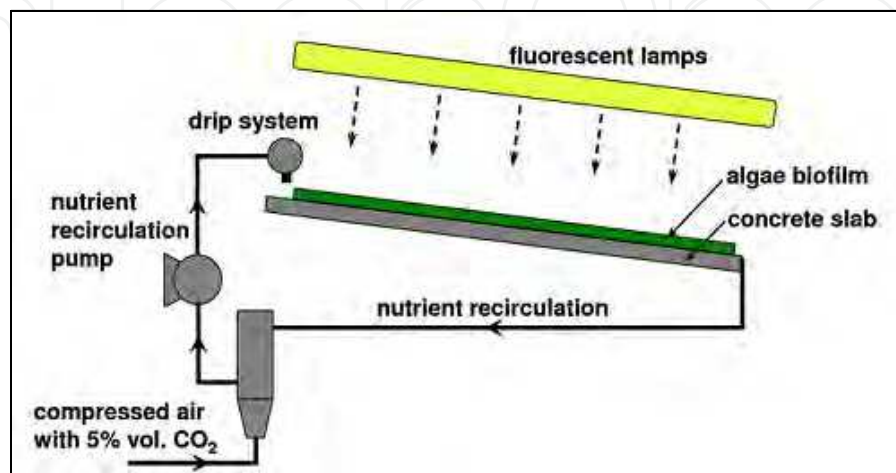


Fig. 9. Schematic of an algae biofilm photobioreactor (Ozkan, et al., 2011).

In addition to this carbonated concrete system, researchers have successfully immobilized benthic algae on a wide variety of substrates, including calcium alginate gels (Baillez, et al., 1985), agitated polystyrene foams (Johnson & Wen, 2010), and PVC bristle combs (Silva-Aciares & Riquelme, 2008). Membrane systems have been coupled with fossil-fired power plants in order to mitigate CO₂ emissions (Kremer, et al., 2006), and biofilms grown on corrugated raceways and algal turf scrubbers have been tested for the removal and recovery of nutrients from wastewater and animal waste effluent, respectively (Cragges, et al., 1997) (Kebede-Westhead, et al., 2006) (Mulbry, et al., 2008) (Park, et al., 2011). Many of these systems hold great promise for reducing the water, nutrient, and energy requirements of cultivation that plague planktonic photobioreactors. However, productivities vary widely between systems, and maximizing irradiance remains challenging. Further research will continue investigating these issues, especially with regard to the technology's potential coupling with waste stream treatment.

3. Algal biodiesel production and energy usage

3.1 Photobioreactors as solar energy conversion systems

When comparing the energy conversion efficiency of any technology, analyses must examine the utilization of freely available resources in addition to the auxiliary energy supplied by manmade systems. In this section, the relative merit of different methods for algal biodiesel production is determined based on their thermodynamic and solar energy conversion efficiencies. The overall efficiency of a system, η , can be defined as the net energy out of the system in kilowatts, P_{net} , relative to the energy input across the system boundary, P_{in} . Equation (1) illustrates this concept.

$$\eta = \frac{P_{net}}{P_{in}} \quad (1)$$

The sun represents the primary energy source provided to the algae cultivation systems and is supplemented by auxiliary power in the form of electricity for pumping and mixing. Energy utilization is examined during algae growth, harvesting, and extraction, i.e., during all processes up to the state known as “biocrude,” at which the raw lipids can be refined into biodiesel. Figure 10 defines the system’s control volume, with accompanying inputs and outputs. Unfortunately, reliable data could not be found for all consecutive stages of growth, harvesting, and processing for each photobioreactor system under study. Comprehensive energy input information could only be obtained for the open pond system. However, because the open pond demonstrated a lower biomass concentration in the harvested slurry, larger volumes must be processed for the same biomass yield. Thus, extraction and harvesting are expected to be more energy intensive. If the efficiency including harvesting and extraction for the open pond are positive, it can be assumed that the efficiencies of systems generating more highly concentrated slurries will be even more favorable.

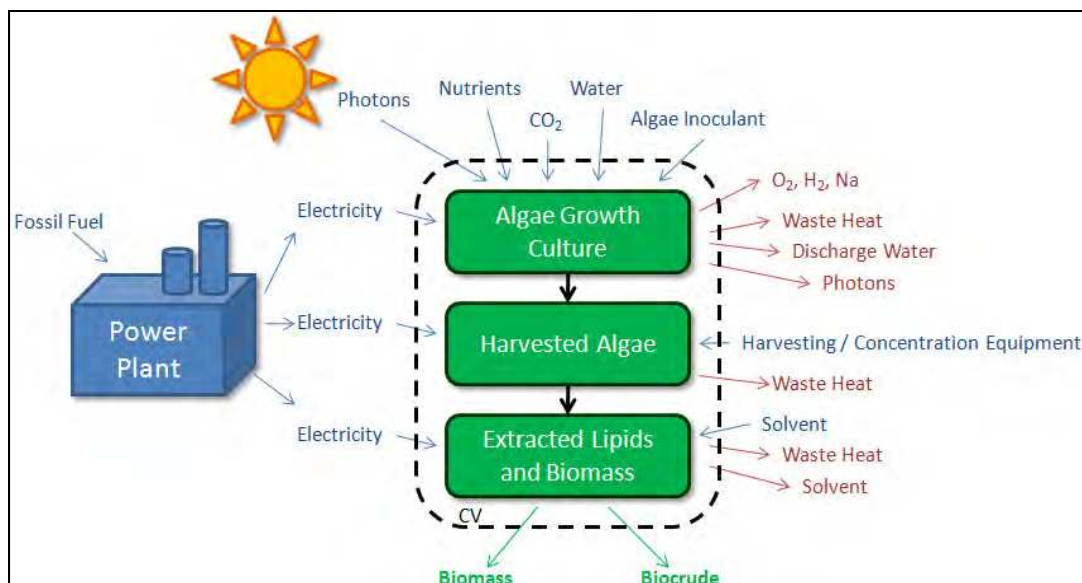


Fig. 10. Algae biofuel production process, adapted from (Beal, 2011).

P_{out} is defined as energy available within the biocrude produced by the system in kilowatts. This is calculated as:

$$P_{out} = x_{oil} \dot{m}_{algae} E_{oil} \quad (2)$$

Where \dot{m}_{algae} represents the rate of algae production by mass in kilograms per second, x_{oil} is the mass fraction of lipids within the algae cell, and E_{oil} is the energy content of the produced lipid, equivalent to 37.6 megajoules per kilogram (Reboloso-Fuentes, et al., 2001).

The net power produced by the system, P_{net} , considers only the useful energy that crosses the system boundary. Because the sun is widely available at no cost, P_{net} disregards this input, but takes into account auxiliary power, P_{aux} , supplied to the system in the form of electricity as:

$$P_{net} = P_{out} - P_{aux}$$

(3)

Furthermore, the closure bounds of what constitutes input power can be elaborated. To assess the solar energy conversion efficiency, P_{in} is equivalent to the full-spectrum of incident solar energy ($P_{solar, full}$). This enables a comparison to photovoltaic and solar thermal technologies in illustrating total solar resource utilization.

This efficiency will be markedly low, as green plants only utilize the photosynthetically active portion of the solar energy incident on Earth. Photosynthetically active radiation consists of light with a wavelength from 400 – 700 nm, a range which comprises approximately 46% of the full-spectrum (Larkum, 2003). Limiting the energy input to only that part of the solar spectrum which is photosynthetically active gives a more representative value of efficiency based on the organisms’ natural abilities. Thus, a second calculation is considered with regard to the algae’s utilization of only photosynthetically active radiation (PAR). In this calculation, P_{in} is redefined as $P_{solar, PAR}$ to represent only that fraction of the spectrum that is photosynthetically active (x_{PAR}), as:

$$P_{solar, PAR} = P_{solar, full}x_{PAR}$$

(4)

Moreover, the technology must be analyzed with sole regard to auxiliary inputs to the system. Because sunlight is free, abundant, and renewable, the production of fuel from this primary energy source can be merited as long as auxiliary inputs do not outweigh the net energy available in the final product. In this calculation, P_{in} is equivalent to P_{aux} . If this auxiliary power utilization effectiveness (ϵ_{aux}) is found to be less than unity, the system consumes more fuel than it produces and should not be implemented.

Finally, the thermodynamic efficiency is calculated based on the total energy input and useful energy output. In this calculation, input energy includes both the auxiliary energy supplied to the system and the full spectrum of incident solar energy. Table 2 summarizes these efficiencies.

Solar Energy Conversion Efficiency, Full Spectrum	$\eta_{solar} = \frac{P_{out}}{P_{solar, full}}$	(5)
Solar Energy Conversion Efficiency, PAR	$\eta_{PAR} = \frac{P_{out}}{P_{solar, PAR}}$	(6)
Auxiliary Power Utilization Effectiveness	$\epsilon_{aux} = \frac{P_{out} - P_{aux}}{P_{aux}}$	(7)
Thermodynamic Efficiency	$\eta_{th} = \frac{P_{out} - P_{aux}}{P_{solar, full} + P_{aux}}$	(8)

Table 2. Energy conversion efficiency calculation methodology.

3.2 Parameters influencing energy output

To better understand the factors affecting photobioreactor productivity, a formulation was put forth by Weyer et al. to determine the theoretical maximum and best case productivity for open pond photobioreactors based on reactor design and the biochemical aspects of

photosynthesis (Weyer, et al., 2010). While their study does not provide clear information about energy consumption and thus cannot be used in a complete thermodynamic efficiency calculation, their breakdown of losses in the conversion of solar energy to chemical energy helps identify areas for potential design optimization. This section explains Weyer et al.'s eleven term formulation in order to clarify why biomass output varies with design choice and which factors limit productivity regardless of design.

3.2.1 Incident solar energy

The laws of thermodynamics represent the governing principles behind any efficiency analyses, stating that the energy flux into a system is at all times greater than or equal to that which can be stored within the system. Thus, for photobioreactor technologies, solar irradiance represents the primary limitation to the generation of algae biomass.

The energy available from the full spectrum of light incident on Earth's surface (E_{solar}) varies as a function of latitude and atmospheric conditions of the particular location under study. Weyer et al. employed the NREL's Blue Clear Sky Model (Bird & Hulstrom, 1981) to approximate atmospheric absorption assuming cloudless skies. Although this provided a theoretical maximum annual solar irradiance of 11,616 MJ/m², the model does not account for realistic climate conditions. For a more representative approximation of solar irradiance at a given location, historical meteorological data was collected. A survey of six sites with latitudes within 40 degrees of the equator gave values for annual solar irradiance of 5,623-7,349 MJ/m² (Weyer, et al., 2010). For the purposes of this paper, the location of the photobioreactor was taken to be located in Eliat, Israel for better comparison to the experimental systems described in Section 3.3. The average annual solar irradiance for this location was found to be 7,301 MJ/m², as documented by US Department of Energy (EERE, 2011).

More than 99% of the radiation entering the atmosphere have a wavelength less than 4000 nm. However, photosynthesizing organisms can only utilize the portion of this spectrum commonly known as Photosynthetically Active Radiation (PAR), which ranges from approximately 400 – 700 nm (Szeicz, 1974). Figure 11 shows the incident solar radiation at the top of the atmosphere, at sea level, and at 10 m below ocean surface. To accurately determine the usable energy available to photosynthetic organisms, this reduction must be accounted for.

The second term in Weyer et al.'s study calculated the photosynthetically active fraction of the solar spectrum. Terrestrial solar energy as a function of wavelength, $E_{solar}(\lambda)$, is taken proportional to the full spectrum (approximated by zero to 4000 nm wavelengths) as:

$$x_{PAR} = \frac{\int_{400nm}^{700nm} E_{solar}(\lambda) d\lambda}{\int_0^{4000nm} E_{solar}(\lambda) d\lambda} \quad (9)$$

By this measure, the percentage of photosynthetically active radiation comes to approximately 45.8% of the full spectrum (E_{solar}). However, while this percentage is technically classified as photosynthetically active, chlorophyll better utilize the red and blue light on the far ends of the spectrum. Thus, treating the entire spectrum of visible light equally results in an overestimation of the energy input to the organic system (Larkum, 2003). A more accurate calculation can be made based on the light action spectra of the particular microalgae under study.

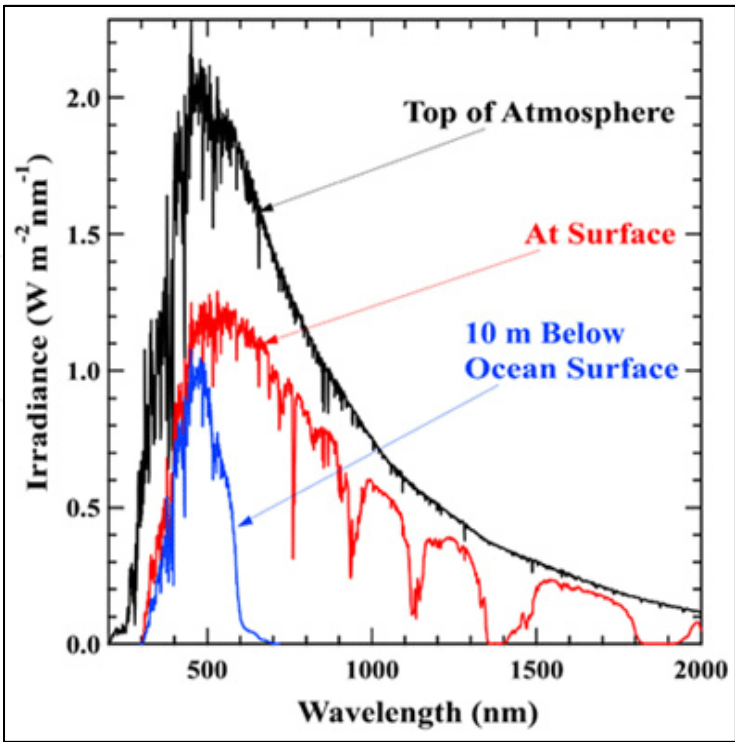


Fig. 11. Global solar irradiance (Spectral Irradiance Monitor)

The usable incident radiation can then be analyzed for its energy density by examining the number of photons within the PAR range incident on the surface and their associated energy content. The wavelength-weighted average photon energy (\bar{E}_{photon}) can be found using the calculation of $E_{\text{solar}}(\lambda)$ and Planck’s Law, which states that the energy associated with a wave is inversely proportional to its wavelength, given by Equation (10) where h represents Planck’s constant (6.63×10^{-34} J/s) and c represents the speed of light (2.998×10^8 m/s).

$$\bar{E}_{\text{photon}} = \frac{1}{3 \times 10^{-11}} \int_{400\text{nm}}^{700\text{nm}} \frac{hc}{\lambda} d\lambda \tag{10}$$

Using the wavelength-weighted average photon energy, the Photon Flux Density (PFD) incident on a surface can be calculated as:

$$\text{PFD} = \frac{E_{\text{solar}} x_{\text{PAR}}}{\bar{E}_{\text{photon}}} \tag{11}$$

3.2.2 Design specific losses

The first design-specific reduction in productive potential relates the losses in incident solar energy to the construction and geometry of the photobioreactor. The following two variables comprise this reduction: (i) reflection off the surface and (ii) the magnitude of radiation depending on the latitude, time of day, and day of the year. To determine this Photon Transmission Efficiency (η_{PT}), these two variables are multiplied and summed (Weyer, et al., 2010).

In the case of flat systems such as ponds or panels, the magnitude of radiation and the reflection off the surface of the photobioreactor can be calculated from the angle of incidence, which is based on the location of the surface and the solar time. These can be calculated based on the methodologies outlined by Duffie and Beckman (Duffie & Beckman, 1980).

Reflective losses take place when (i) there is an appreciable difference between the indices of refraction and (ii) the angle of incidence on the interface is large. Using the angle of incidence and Fresnel’s equations for reflection of unpolarized radiation passing through a medium, the reflective losses can be calculated. By combining the magnitude of incident radiation with the reflected losses and integrating over the course of a day, the losses in photon transmission due to reflection can be found. Equation (12) illustrates this concept, where $r(t_s)$ represents reflectivity as a function of solar time in hours, and $G_r(t_s)$ represents the magnitude of global solar irradiance in MJ/m² per day.

$$\eta_{PT} = \frac{\int_0^{24hrs} r(t_s)G_r(t_s)dt_s}{\int_0^{24hrs} G_r(t_s)dt_s} \tag{12}$$

Figure 12 displays the reflected incident solar radiation for an open pond as it varies by latitude and time of year. For the best case scenario, losses due to reflection average about 5% of the total incident solar radiation, with increased losses during winter at locations far from the equator. If production is to continue year-round, losses due to reflection can be minimized by choosing an appropriate location nearer to the equator or inclining the systems with respect to the angle of the latitude. Although for pond systems this is not possible, for flat plate and benthic systems the angle of inclination can be adjusted to minimize reflection losses. The calculation for photon transmission efficiency becomes more complicated with flat plate, tubular, and bagged systems as the reflectivity and transmissivity of the container material must be accounted for.

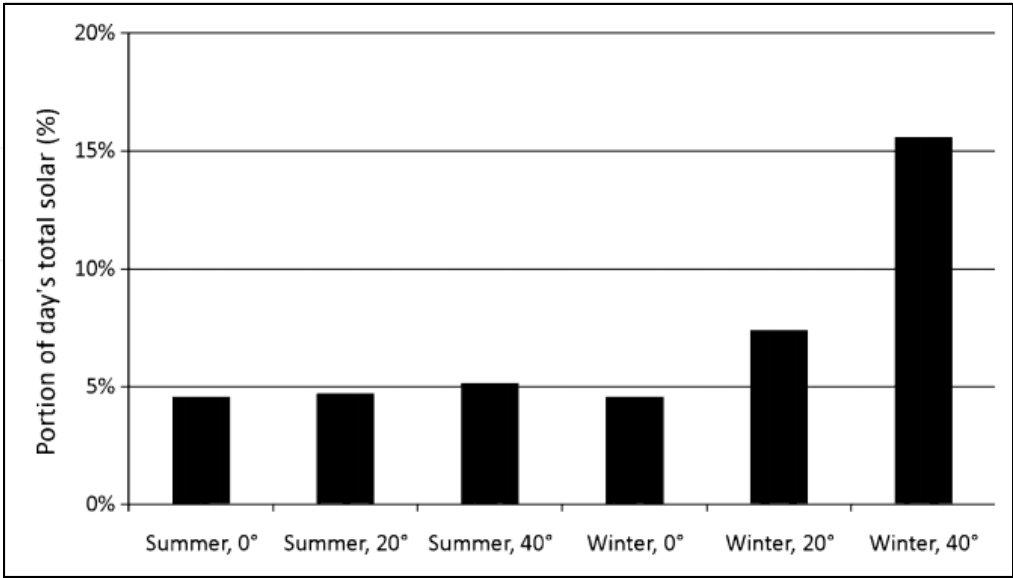
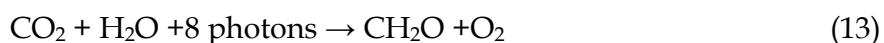


Fig. 12. Reflected solar radiation in an open pond by latitude and solstice (Weyer, et al., 2010).

The photon utilization efficiency (η_{PU}) represents the second photobioreactor design-specific reduction in energy output. Although an adequate quantity of photons may be incident upon the photobioreactor's surface, sub-optimal culture conditions will limit the cells' ability to utilize these photons. In particular, temperature and irradiance have significant effect on photosynthetic efficiency. Photoinhibition occurs under high irradiance, slowing photosynthesis and potentially damaging cells. This can be particularly troublesome for horizontal systems exposed to unfiltered sunlight, such as in open ponds (Franklin, et al., 2003). Photon utilization efficiency can range from 50-90% under low light conditions; in a high light environment with photoinhibition occurring, efficiency drops to as low as 10-30% (Goldman, 1979). A median value of 50% was used by Weyer et al. to represent a best-case scenario for photon utilization efficiency. However, this may be high due to the almost unavoidable effects of photoinhibition in uncovered raceway systems (Weyer, et al., 2010).

3.2.3 Chemical conversion and biological process losses

Inevitable losses occur in the conversion of photons into chemical energy in the form of sugar. The overall chemical reaction for the photosynthetic conversion of carbon dioxide and water into sugar can be given as:



The eight photons needed for this reaction represent the "quantum requirement" (QR) for one mole of carbon dioxide and one mol of water to be converted into sugar and oxygen. This general formulation for photosynthesis represents the combination of two chemical reactions: light reactions where photons are converted to ATP and electron carriers in the two photosystems, and dark reactions where carbon dioxide is fixed in the Calvin cycle (Weyer, et al., 2010). Under ideal conditions, this process would require three photons at the lowest usable energy level (700 nm), as dictated by the energy requirement for the formation of sugar, CH_2O . However, due to the high energy levels required to split water molecules, plants have adapted two photosystems through which to transfer electrons. The combination of these systems divides the potential energy requirement, facilitating the conversion by using more photons at lower energies. In this process, commonly known as the Z-scheme for the characteristic shape of the electron transfer path, researchers have generally accepted that eight moles of photons are required per mole of CO_2 fixed. However, this may be conservative under realistic conditions. In Equation (13), CH_2O represents the simplest form of carbohydrate energy produced by photosynthesis, whose energy content of 482.5 kJ/mol is accounted for in the term E_{carb} .

The biomass accumulation efficiency (η_{BMA}) represents the loss in biomass production in exchange for other cellular functions. This "cost of living" efficiency varies drastically between different species and environments. Manipulating culture conditions to stress the cells has shown to increase lipid production in some species. In others, varying the nitrogen input and temperature have shown to affect biomass production. The general principles governing this phenomenon are not well understood, but a median value of 50% was estimated for a best-case scenario in which culture conditions are optimized to reduce the loss in biomass due to respiration (Weyer, et al., 2010).

Combining these terms with the energy content of the biomass produced (E_{BM}), which is taken as the heat of combustion as a weighted average based on the cellular composition, the biomass growth rate (\dot{m}_{BM}) can be obtained, as demonstrated in Equation (14). In Weyer et al.'s calculation, E_{BM} was taken to be 21.9 MJ/kg biomass to represent the median value of the energy content during the growth stage rather than in the oil laden state just before harvest. This may be an underestimate, as the biomass energy content for *Nannochloropsis* sp. has been reported to contain up to 33.5 MJ/kg biomass (Jorquera, et al., 2010). However, for this theoretical calculation, the algae species is not specified and 21.9 MJ/kg represents a conservative estimate.

$$\dot{m}_{BM} = \eta_{PT} \eta_{PU} \eta_{BMA} \frac{E_{carb} PFD}{E_{BM} QR} \quad (14)$$

The percent oil content of the cell is used to determine the rate of lipid production in the algae culture. A theoretical maximum for percentage oil has yet to be determined, with experimental values ranging from 15-77% of total cell contents (Chisti, 2007). However, the values were likely obtained using gravimetric analysis, which accounts for the total lipid quantity within the cell rather than that which is usable. Thus, these experimental values may be optimistic (Weyer, et al., 2010). In addition, cells which produce large quantities of lipids often grow at slower rates. Pursuit of a natural or genetically engineered algae strain must continue to balance these trade-offs. Using the lipid fraction (x_{oil}) and the algal oil's density (ρ_{oil}), the volumetric lipid production rate can be calculated as:

$$\dot{V}_{oil} = \frac{x_{oil} \dot{m}_{BM}}{\rho_{oil}} \quad (15)$$

The density of algal oil was taken to be similar to that of soybean oil, which is approximately 918 kg/m³ (Weyer, et al., 2010). Using the mass rate of biomass production and the energy content of the oil, the energy output of the algal biofuel production system can be obtained. Equation (2) shows this calculation for P_{out} . This value can then be inserted into Equations (5) thru (8) to determine the system's solar conversion and thermodynamic efficiency. The energy content of lipids extracted from *Nannochloropsis* sp. was taken to contain 37.6 MJ/kg, which is assumed to be representative of oil from most algae strains (Rebollosa-Fuentes, et al., 2001).

$$P_{out} = x_{oil} \dot{m}_{BM} E_{oil} \quad (16)$$

Table 3 summarizes the assumptions made in the calculation of theoretical best case oil productivity for an open pond system.

3.3 Survey of actual energy output

To compare realistic productivity to the theoretical formulation proposed by Weyer et al., data was collected from three operating facilities. A 2010 study by Jorquera et al. compiled literature data from an open raceway pond (Richmond & Cheng-Wu, 2001), a vertical flat plate system (Cheng-Wu, et al., 2001) (Richmond & Cheng-Wu, 2001), and a horizontal tubular system (Chini Zittelli, et al., 1999). Baseline productivity was taken as uniform at 100,000 kg of

biomass per year to facilitate comparisons. Each photobioreactor cultivated the algal strain *Nannochloropsis* sp., whose oil content was assumed to be 29.6% dw, an average value based on reported ranges of 20-40% depending on culture conditions and maturity (Rodolfi, et al., 2009). Table 4 summarizes the relevant productivity data for each of these systems.

Term	Value	
1. Full-spectrum solar energy, E_{solar}	7301.13	MJ/m ² -yr
2. Photosynthetic portion of spectrum, x_{PAR}	45.8%	
3. Average photon energy, E_{photon}	225.3E-3	MJ/mol
4. Photon transmission efficiency, η_{PT}	95%	
5. Photon utilization efficiency, η_{PU}	50%	
6. Quantum requirement, QR	8	
7. Carbohydrate energy content, E_{carb}	482.5	kJ/mol
8. Biomass accumulation efficiency, η_{BMA}	50%	
9. Biomass energy content, E_{BM}	21.9E-3	kJ/kg
10. Cell oil content, x_{oil}	29.6%	
11. Oil density, ρ_{oil}	918	kg/m ³
Best case areal biomass productivity	97,078	kg/ha-yr
Best case areal oil productivity	31,302	L/ha-yr
Best-case areal energy production from lipids	1080.44	MJ/ha-yr
Area required to produce 100,000 kg biomass	10,301	m ²

Table 3. Best case assumptions and productivities for a raceway pond (Weyer, et al., 2010).

	Open Raceway	Flat Plate	Tubular
Annual biomass productivity (kg/yr)	100,000	100,000	100,000
Areal footprint (m ²)	25,988	10,147	10,763
Biomass concentration (g/l or kg/m ³)	0.35	2.7	1.02
Areal biomass productivity (kg/ha-yr)	38,479	98,551	92,909
Areal oil productivity (L/ha-yr)	12,407	31,777	29,958
Areal energy productivity from lipids (MJ/ha-yr)	428.26	1,096.83	1,034.04

Table 4. Production data for photobioreactors (Jorquera, Kiperstock, Sales, Embirucu, & Ghirardi, 2010).

3.4 Solar energy input

The calculation for solar energy supplied to the systems was based on the respective location of each photobioreactor. These included Eilat, Israel for the raceway pond and flat plate photobioreactor and Florence, Italy for the tubular system. Historical meteorological averages for global solar radiation were used for the full spectrum solar power input (P_{solar} ,

full spectrum), which was then used to calculate the photosynthetically active portion of the incident radiation ($P_{solar, PAR}$), as discussed in Section 3.2.1. Global solar radiation includes both direct beam and diffuse radiation. Table 5 lists values for average global irradiance by location.

	Average global irradiance (full spectrum)	Average global irradiance (PAR)
Eilat, Israel (29°32'N, 34°57'E)	231.5 W/m ² (7301 MJ/yr)	108.3 W/m ² (3417 MJ/yr)
Florence, Italy (43°47'N, 11°11'E)	130.3 W/m ² (4110 MJ/yr)	61.0 W/m ² (1923 MJ/yr)

Table 5. Average global solar irradiance by photobioreactor location (EERE, 2011).

3.5 Auxiliary power inputs

Operational data was compiled for the systems under study by Jorquera et al. in order to compare each facility’s Net Energy Ratio (NER) in its utilization of supplied auxiliary power. For this analysis, the data for total energy consumption for each system is used for P_{aux} in the calculation of auxiliary power utilization effectiveness and thermodynamic and solar efficiencies. Energy consumption data in the photobioreactor systems includes only that for air pumping, mixing, and liquid/gas mass transfer (Jorquera, et al., 2010). As consumption data for the tubular system was not reported by the operators, the power required for air pumping was assumed to be similar to that of other tubular facilities at 2500 W/m³ (Sierra, et al., 2008). Table 6 summarizes the auxiliary energy required on a volumetric and total annual consumption basis.

	Open Raceway	Flat Plate	Tubular
Volumetric energy consumption (W/m ³)	3.72	53	2500
Total energy consumption (MJ/yr)	378,450	698,940	15,895,800

Table 6. Comparative energy consumption for photobioreactor systems (Jorquera, et al., 2010).

4. Efficiency results and other considerations

4.1 Solar conversion and thermodynamic efficiencies

Applying the data shown in Tables 4 thru 6 to Equations (5) thru (8), thermodynamic and solar efficiencies and auxiliary power utilization effectiveness for the systems can be found. The results of these calculations are summarized in Table 7.

	Raceway	Flat Plate	Tubular
Solar energy conversion efficiency, full spectrum	0.59%	1.50%	2.52%
Solar energy conversion efficiency, PAR	1.28%	3.28%	5.49%
Thermodynamic efficiency	0.39%	0.55%	-24.58%
Auxiliary power utilization effectiveness	1.94	0.59	-0.93

Table 7. Solar conversion and thermodynamic efficiencies and auxiliary power utilization effectiveness for photobioreactor systems.

The efficiency calculations presented in Table 7 assumed the energy out of the system only included that available in the extracted lipids. However, as was mentioned in Section 1.3’s discussion of algal fuels, the residual biomass may be fermented into ethanol or processed as biogas. The total energy content of the generated biomass is taken to be 31.55 MJ/kg (Jorquera, et al., 2010). Table 8 recalculates the solar conversion and thermodynamic efficiencies and auxiliary energy utilization effectiveness to include the total energy available from the biomass and lipids generated by the system.

	Raceway	Flat Plate	Tubular
Solar conversion efficiency, full spectrum	1.66%	4.26%	7.13%
Solar conversion efficiency, PAR	3.63%	9.30%	15.57%
Thermodynamic efficiency	1.46%	3.28%	-21.19%
Auxiliary power utilization effectiveness	7.34	3.51	-0.80

Table 8. Solar conversion and thermodynamic efficiencies and auxiliary power utilization effectiveness including the total energy available in the biomass.

Of the three photobioreactors, the tubular system utilized incident solar energy most efficiently. As singular systems, perfectly efficient organisms can theoretically convert photosynthetically active solar energy into biomass at an efficiency of about 26.7% (Weyer, et al., 2010). However, due to losses also observed in the photobioreactor systems, photon transmission, photon utilization, and biomass accumulation reduce this photosynthetic conversion efficiency of solar energy into biomass to an approximate maximum of only 1-4% (Jorquera, et al., 2010). When including the total recoverable energy available in the biomass, the efficiency values in Table 8 are consistent with those for terrestrial plants, with distinctly higher efficiencies in the case of the flat plate reactor and tubular reactors.

The thermodynamic efficiency for each system was found to be low, and became highly negative in the case of the closed tubular reactor. However, as solar energy is assumed to be free, renewable, and abundant, a more economically important factor for the successful adoption of these technologies examines how well the facilities utilize auxiliary energy supplied to the system. Of the three photobioreactors, the energetic output from the raceway pond almost doubled the required auxiliary energy when solely accounting for lipid production, increasing to more than seven fold when including the energy available in the biomass. Though not as productive, the flat plate system had a positive thermodynamic efficiencies and high auxiliary energy utilization effectiveness as well. The tubular system, however, proved in both cases to require far too much auxiliary energy to justify large scale implementation.

The theoretical best case production for a raceway pond described in Section 3.2 would have the same efficiencies for the thermodynamic system if baseline production was taken to be 100,000 kg and similar auxiliary energy inputs were assumed. However, the areal productivity shown by the theoretical production calculation for a raceway pond was close to that of a flat plate or tubular system, as can be seen in Tables 3 and 4. This implies that raceway ponds can achieve productivities similar to that of closed systems, with better land utilization and potentially lower construction and operational costs. However, values used for photon utilization and biomass utilization efficiencies in the theoretical best case scenario

may be unrealistically high with regards to current technology for industrial production. Maintaining precise culture conditions in an open order to minimize losses in photon utilization and biomass accumulation efficiencies remains difficult.

4.2 Harvesting and processing energy costs

While the efficiency values for the raceway and flat plate systems appear encouraging, they account only for the growth phase of the biofuel production cycle, as was shown in Figure 11 in Section 3.1. Biomass harvest, lipid extraction, and processing require significant amounts of energy, which generally scales with the biomass concentration of the harvested liquid. The high volumes of water required by open raceway systems result in a significantly lower concentration of biomass in the harvested algae slurry than apparent in either of the closed systems, as shown in Table 4 of Section 3.3. Based on biomass concentration, the flat plate system produced the most favorable harvested product in terms of ease of extraction and processing. Although the data compiled for these systems did not include energy consumption during either of these phases, the energetic costs of harvesting and processing have been extensively documented for the more common cultivation method of raceway ponds. As the biomass concentration in the harvested slurry is reported to be lower for open ponds than for closed systems, raceway pond production can be judged as the most energetically and economically expensive method in terms of downstream processing.

Although many methods of harvesting and lipid separation exist, most can be classified as sedimentation or filtration based processes. Sedimentation processes depend on differences in the specific density of algae particles, while filtration methods exploit algae size and surface properties (Morweiser, et al., 2010). Centrifugation has proved popular for small scale algae cultivation operations and consumes roughly 5 kWh/m³ at flow rates of 1 m³/hr. Scaling up may reduce the energy consumption of centrifugation to approximately 1-3 kWh/m³ (Morweiser, et al., 2010) (Molina Grima, et al., 2003). Although membrane filtration requires significantly less power than centrifugation methods, its success primarily relies on the algae strain's physiological properties and thus is not suitable in all algae cultivation scenarios (Schenk, et al., 2008). In addition, fouling of the membrane and pressure drops across the interface pose problems (Gregor & Gregor, 1978).

Data compiled for the energetic cost of harvesting and processing algae from a raceway pond cultivation system is listed in Table 9. The study in question was undertaken by Dr. Yusuf Chisti, and assumed a lipid fraction of 20% dw, biomass productivity of 0.025 kg/m²-day, and biomass concentration of 1 kg/m³. These energy costs can be applied to the open raceway pond system described in Section 3.3 to achieve a more comprehensive representation of the thermodynamic efficiency and auxiliary power utilization efficiency for the biofuel production process. However, it should be noted that Chisti's analysis assumes a much higher biomass concentration than that cited by Jorquera et al., and thus harvesting costs are likely underestimated when applied to the open pond production scenario. For construction, 80.4 MJ/m² was assumed for the facility area, divided by a 20 year productive life of the facility and by the mass of annual oil production. Energy costs of equipment, including that required for biogas production, were estimated to be 27.2 MJ/ton of machinery required, also divided by a 20 year lifespan and the mass of annual oil production. Table 10 displays these recalculated efficiencies including the energy

consumption of harvesting and processing, as well as the co-production of biogas from residual biomass.

Input	Energy (MJ/kg oil produced)
Harvesting	0.30
Oil recovery	3.17
Biogas production	0.88
Facility construction (including maintenance)	4.00
Energy embodied in equipment (including maintenance)	62.8 x 10 ⁻⁶

Table 9. Harvesting and biofuel production energy costs (Chisti, 2008).

	Cultivation only	Complete process
Thermodynamic efficiency	1.46%	1.33%
Auxiliary power utilization	7.34	4.04

Table 10. Thermodynamic efficiency and auxiliary power utilization effectiveness for an open raceway pond during the growth stage compared to those for the complete biofuel production process.

While the inclusion of energy costs from downstream processing lowers the thermodynamic efficiency and auxiliary power utilization effectiveness, calculated values still suggest the process to be energetically positive. Energy consumption by harvesting and processing may be minimized by scaling the operation; however, increases in biomass concentration would have more dramatic effects on downstream costs (Stephens, et al., 2010). In the near term, the co-production of biogas or high value products from the residual biomass is likely as oil commodity prices remain low. With this in mind, biomass concentration plays an important role in both decreasing processing costs and increasing the production of profitable commodities more so than any substantial increase in the strain’s lipid fraction (Stephens, et al., 2010). If auxiliary power requirements for closed system cultivation can be reduced, their generation of high concentration algal slurry could result in a commercially viable production process.

4.3 Water and nutrient usage

Facility and operation costs often scale with water and nutrient consumption. In an ideal system, water consumption would be kept to a minimum and losses due to evaporation would be negligible. However, open pond systems generally are located in hot, arid climates where incident solar energy levels are high and culture temperature can be maintained. Depending on pond composition, wind speed, ambient temperature, and relative humidity, evaporative losses in open ponds can reach levels of 1 cm/day (Sheehan, et al., 1998). For a large production facility, this daily loss in water depth would have to be compensated for by the continued addition of new culture medium. Fortunately, algae can utilize water that would not be suitable for human consumption or agriculture due to high salinity or waste contamination. However, these large volumes of water imply intensive pumping, which translates into higher costs. Table 11 reviews the biomass concentrations cited by Jorquera et

al.’s study and the corresponding water volume required by each facility, assuming no evaporation or water recycling.

	Raceway	Flat Plate	Tubular
Biomass concentration (kg/m ³)	0.035	0.27	0.56
Water required (m ³)	2,857,142	370,370	178,571
Water required (gal)	754,777,142	97,841,481	47,173,571

Table 11. Water requirements based on biomass concentration from each photobioreactor system (Jorquera, et al., 2010)

As shown in each photobioreactor system, water consumption scales directly with biomass concentration. The raceway pond demonstrates the lowest concentration and thus the highest corresponding water consumption. Although empirical data was not available, it can be assumed that water consumption in the open pond would be even greater due to high rates of evaporation. Closed systems hold a significant advantage in terms of water consumption and lower rates of evaporation, in addition to having the capability to recycle 70-80% of the water used in each growth cycle (Subhadra, 2010).

A study by Clarens et al. found that biodiesel production from microalgae in an open pond system consumed up to 12 times the water required by biodiesel production from canola on the same scale. However, by coupling production to wastewater treatment, the water consumed by the algal biodiesel production process can be reduced by 89% (Clarens, et al., 2010). In addition, coupling algae cultivation to wastewater treatment plants allows the algae to remove and recover nutrients that must otherwise be supplied via fertilizer.

Finally, the benthic photobioreactors discussed in Section 2.2 hold the potential to greatly reduce the water required for algae cultivation. As the algae are immobilized on a substrate, a relatively small volume of water circulates over the biofilm to enhance mass transfer of nutrients and CO₂. Lab scale operation of a carbonated concrete system has shown to consume up to 42 times less water than algae cultivation in conventional systems (Ozkan, et al., 2011).

4.4 Economics

A comprehensive study of the economic feasibility of the algal production process was conducted by Gao et al. in 2009. In this report, a formulation devised by Molina Grima in 2003 for cost estimation based on direct experience with a closed, tubular system and vendor quotes was refined and examined with a discount rate of 7% over ten years. Molina Grima’s 100 hectare facility produced approximately 26.2 tons of biomass per hectare each year for the purpose of extracting a high value product. Using a conservative co-production estimate of 10% oil yield, costs of Molina Grima’s tubular system were compared to those of a facility employing 192 hectares of open ponds on 384 hectares of land, as documented by the U.S. Department of Energy. The total cost breakdown included the capital and operating costs required to build a processing facility in which separation of lipids and transesterification of TAGs would transform the raw extracted material into biodiesel. While this study did not examine the energetic costs as documented by Jorquera’s 2010 or Chisti’s 2008 analyses, it provides a detailed representation of the economic costs of industrial scale biodiesel production operations. Table 12 contains a summary of this analysis.

	Closed System	Open System
Areal biomass production rate	26.2 tons/ha-yr	112 tons/ha-yr
Capital investment	> \$3 million/ha	~\$100,000/ha
Total annual operating cost	\$933,995/yr	\$147,769/yr
Biomass cost*	\$35,649/ton	\$1,319/ton
Biodiesel cost*	\$49.39/gal	\$5.46/gal

*Biomass and biodiesel costs accounts for expenditures associated with growth, harvesting, extraction, and refining.

Table 12. Cost comparison for a tubular and open pond system in 2003 dollars (Gao, et al., 2009, Molina Grima, et al., 2003).

With the cost of conventional diesel at approximately \$1.51 for 2011/12, these numbers do not encourage potential investors to fund algae based operations (Radich, 2004). However, a closer examination can be made for advancements in closed and open cultivation system and processing technologies. Table 13 contains the recalculated production costs per gallon of biodiesel with oil yield improvements, reductions in the price of solvents and CO₂, and the application of existing U.S. tax credits made available by the American Recovery and Reinvestment Act of 2008.

System	Scenario	EE \$/gal
Closed Tubular	Yield increased to 60%	\$33.13
	Total capital + fixed cost of production reduced by 50%	\$26.18
	60% yield; 50% capital/fixed cost reduction	\$17.65
	50% hexane recovery	\$49.28
	60% yield; 50% capital/fixed cost reduction; 50% hexane recovery	\$17.54
	Tax credits; 60% yield; 50% Capital costs; 50% Hexane recovery	\$16.54
Open Raceway	Yield increased to 20%	\$4.24
	Yield increased to 30%	\$3.02
	CO ₂ price of \$0.2/kg (from \$0.47/kg)	\$3.29
	CO ₂ price of \$0.035/kg (from \$0.47/kg)	\$1.96
	50% Hexane recovery	\$5.34
	20% yield; \$0.2/kg CO ₂ price	\$2.61
	30% yield; \$0.2 kg CO ₂ price	\$1.94
	Tax credits; yield increased to 20%	\$3.24
	Tax credits; yield increased to 30%	\$2.02
	Tax credits; CO ₂ price of \$0.2/kg (from \$0.47/kg)	\$2.29
	Tax credits; 20% yield; \$0.2/kg CO ₂ price	\$1.61
	Tax credits; 30% yield; \$0.2 kg CO₂ price	\$0.94

Table 13. Costs for tubular and raceway systems with potential economic improvements and tax incentives (Gao, et al., 2009).

According to this study, cultivation of algae in closed tubular systems for biodiesel purposes is prohibitively expensive, and technical progress to lower the capital cost and/or increase oil yields, although making a significant difference, cannot come near competing economically with other biodiesel sources. However, similar advances in open pond technology can bring the costs of production down to only \$1.94/gallon biodiesel.

Despite these challenges, provisions for research in the American Recovery and Reinvestment Act have strengthened the potential for commercialization of algal biodiesel. With the passage of this act, \$61 billion were earmarked for energy generation, of which \$800 million was specifically provided for biofuels (Voegelé, 2009). In addition, existing tax credits for producers range from \$1/gallon for “agro-diesel,” \$0.50/gallon for diesel made from recycled cooking oil, and an additional \$0.10/gallon credit for small producers of biodiesel. An annual budget of \$150 million has also been authorized for the FY2009 – FY2012 to be used for loan guarantees and grants for the construction of biorefineries. Import duties on ethanol also protect domestic producers of biofuels (Yacobucci, 2006). While all of this demonstrates the government is interested in protecting domestic producers of alternative fuels, none of the provisions specifically target to algal biofuels. If the “agri-biodiesel” tax credits are applied to the study conducted by Gao et al. for open ponds, the economic outlook becomes much more favorable.

5. Conclusions and outlook

The steady increase in liquid fuel consumption and the eventual depletion of petroleum reserves necessitates the adoption of alternative fuels. Biodiesel from algae feedstock holds a realistic potential to displace petroleum as the United States’ transportation fuel due to algae’s rapid growth rate and high oil content. Relative to other alternative fuels, biodiesel has a high energy density and can be used in a wide variety of transportation applications. Algae cultivation does not require the diversion of large portions of arable land from food production and can be grown without the consumption of potable water. Finally, algae cultivation with open pond and flat plate systems holds a positive energy balance in its favorable solar conversion and thermodynamic efficiencies. All of these facts have been recognized by industry and academia, and the research gaps identified by the NREL’s historic Aquatic Species Program are quickly being filled. With this renewed interest, technical improvements and existing government incentives can make the production of biodiesel from algae economically justified.

By comparing Weyer et al.’s theoretical best case formulation with experimental data, the parameters causing the discrepancy in productivity for open pond systems can be identified. The land required by the best case scenario comes close to matching productivities achieved in the closed systems. By concentrating on incorporating the design advantages of each system, the best case scenario for open ponds described by Weyer et al. may be achieved. In particular, photon transmission efficiency and photon utilization efficiency represent important design parameters whose manipulation significantly affects the system’s biomass output. Although photon transmission efficiency and photon utilization efficiency were taken to be 95% and 50% respectively, realistic values are likely much lower for open pond systems. Of the two parameters, photon utilization efficiency had a much more negative effect on the final biomass productivity, indicating the significance of maintaining optimal culture conditions. This control over the algae’s

environment can also be translated into the losses in biomass accumulation efficiency, as biomass losses due to respiration may be mitigated in certain species by applying different environmental constraints. Both configurations of closed systems allow this variability, but the current auxiliary energy costs outweigh the potential benefits of this technical sophistication. Further research requires the development of a hybrid system in which aspects of both closed and open designs can be featured. Passive temperature control and use of atmospheric CO₂ must be combined with the lower water consumption and areal footprint of closed systems in order to generate an algae slurry with a high biomass concentration.

In addition to these design challenges, the theoretical study identified areas of biological constraint that could potentially be resolved through strain selection or genetic modification. In particular, expanding the portion of the solar spectrum usable for photosynthesis can increase the solar conversion efficiency while pigment reduction in the organisms can help reduce instances of photoinhibition, accelerating the biomass growth rate and resulting in a more productive culture. Likewise, reducing the quantum requirement through the modification of photosystems would allow for more efficient use of incident PAR energy. While the fraction of usable lipids remains important for the production of biodiesel from algae, biomass growth rate ultimately determines profitability, particularly when incorporating the production of a portfolio of high value products with a variety of algal fuels. In the short term, the coproduction of these high value products is necessary to overcome the economic and energetic obstacles of this relatively immature technology. However, as oil commodity prices continue to rise, the economics of algal biodiesel are expected to strengthen. Algae biodiesel's energy density and compatibility with infrastructure provide significant advantages to current alternative fuels. As research advances and production processes become less capital, energy, and water intensive, algae biodiesel will surpass its competitors as the most viable alternative to petroleum fuel.

6. References

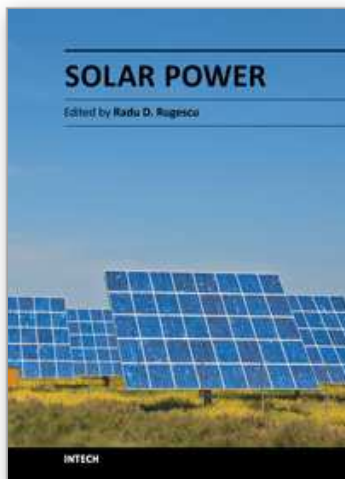
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