Summary

GreenFuel Technologies (www.greenfuelonline.com/) has recently generated positive publicity for their technology, which converts CO_2-containing emissions from power plants into valuable biofuels using proprietary algal photobioreactors (PBRs).

This report shows that GreenFuel's method will not be economically feasible, even if the company achieves spectacular progress in development of its technology. Fundamental thermodynamic constrains make it impossible for such approach to be commercially viable for fuel prices below **$800/bbl,** even if flawless technological implementation is assumed. Since other technologies offer alternative options at substantially lower costs, GreenFuel's approach cannot be expected to have a significant place in our future energy supply or carbon mitigation strategy.

Introduction

At the core of GreenFuel's proposed process is the generation of algal biomass using the flue gases from a fossil fuel-based power plant and solar energy as inputs. The idea is extremely attractive as flue gases are CO_2-containing pollutants that need to be dealt with and sunlight is free and abundant. The resulting biomass can be monetized via the following mechanisms:

1. converting it to biodiesel via transesterification;
2. converting it to bio-ethanol via fermentation;
3. converting it to liquid/gas fuels via pyrolysis;
4. generating heat/electricity by burning it (with or without gasification);
5. selling it as feed protein;
6. disposing it in a landfill and receiving credits for avoided emissions;

Production of biofuels will also have carbon mitigation potential by the virtue of avoided fossil fuel use, and thus will benefit from future carbon credits. In contrast, production of animal feed will not be carbon beneficial: since the displaced feeds are also of photosynthetic origin, there is no net emission avoidance

Looking at these options, there is a very clear winner as to what is the most economically effective way to monetize the process, namely, conversion of algal lipids into biodiesel. Biodiesel is a clean-burning biofuel that enjoys generous subsidies and can be sold wholesale for as high as $2.50 per gallon [1]. With gross heating value of 126,200BTU per gallon, that would equate to **$18.80** per **GJ**, which compares very favourably with:

- coal at **$1-1.5/GJ**,
- natural gas at **$7-8/GJ**,
- gasoline at **$11.40/GJ** (assuming $1.50/gal wholesale)
- corn ethanol at **$16.82/GJ** (assuming $1.50/gal, incl. subsidy).

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[1] Providing full background information on biodiesel is not the scope of this report; there are good resources on biodiesel available on the Web, for example: http://www.eia.doe.gov/oiaf/analysispaper/biodiesel/index.html, or http://en.wikipedia.org/wiki/Biodiesel

The allure of the biodiesel route comes not only from its high selling prices, but also from its easy and efficient manufacturing method. The vast majority of biodisel cost is in the feedstock – oils or fats from plant origin; the transesterification process is becoming well established, has low capital costs and is highly efficient. Algae are thought capable of providing high lipid content. Some species of algae, grown in specific conditions, can accumulate 30-60% (mass) and in some cases higher lipid contents. Thus, generating large amounts of biolipids using only flue emissions and sunlight is a very attractive proposition.

One may argue that producing bioethanol is a very lucrative option too, considering its high selling prices above. Production of ethanol from corn or sucrose by fermentation is an established process, however, it is significantly more exothermic (losses energy) than biodiesel production from lipids, and in addition, it has not been proven commercially with algal feedstock.

Liquid fuels or biogas can potentially be generated from biomass by pyrolytic, non-fermentative processes. Research on such technologies has been going on for more than 80 years, as it would allow the use of much cheaper feedstocks (grassy and woody residues, municipal solid waste, etc.), however, so far no significant commercial installations have been established. A major disadvantage of pyrolysis, when compared to transesterification and fermentation, is the high energy needs of the process. It requires external heating to 300-800^{o}C, making it obvious that the energy ratios would be much worse than for fermentation or transesterification (we have not been able to find a study on pyrolysis with a credible energy balance in it).

The lack of major commercial pyrolytic installations for biomass means that the processes that have been tried so far are so inefficient that they are not commercially feasible even if much cheaper (or free as would be the case with MSW) feedstocks are used. It should be noted that some reports mention that algal biomass will be better than lignocellulosic feedstock for pyrolytic conversion into volatiles, however, it is not clear by how much and whether it would provide for economic viability.

Using the algal biomass for generation of electricity or heat is not lucrative by itself, considering the very low prices of coal; however, when combined with future carbon credits it may make sense. For a gas-powered plant the biomass can be gasified, however the gasification technologies are still very immature and with low energy ratios (high biomass inputs, low gas outputs). In any case, electricity generation is a much less lucrative option than biodiesel, even with future carbon credits. Biodiesel enjoys subsidies now that are likely higher than any future carbon credits[2], in addition to the higher value of liquid fuels in general. Electricity generation may be an option for the non-lipid portion of the algal biomass.

Producing algae purely for animal feedstock is also a worse option than biodiesel: the market is highly competitive and no carbon credits can be claimed (as the displaced feeds are also of photosynthetic origin, there is no net emission avoidance). Protein, however can be a valuable byproduct of a biodiesel production process that uses the

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[2] The current tax credit for agriculturally-derived biodiesel is $1/gal, which roughly equals $100 per ton of CO_2 avoided

lipid fraction of the biomass. Similar protein by-products are generated in the corn ethanol process (distillers-dried-grains, DDG) and in the production of biodiesel from soybeans.

The problem with making protein in conjunction with substantial amounts of biofuels is that it will be produced in such large amounts that will likely saturate the potential markets[3]. Regardless, just based on selling prices, protein may be a better option (as a byproduct of biodiesel production) than electricity-generation, regardless of the lack of carbon credits[4]. The challenge will be to certify the algal protein for animal use, to market it to farmers, and to transport it to customers. No such logistical hurdles exist for electricity generation, which can take place at the very power plant where the flue gases are generated.

Finally, sequestering the biomass in a landfill will likely not be a valuable option due to the lack of large landfill capacity.

For the purposes of this report we assume that the algal biomass generated by GreenFuels is converted into biodiesel via lipid extraction and transesterification. For the remaining biomass, we assume that it is converted into a by-product and will represent its net value (revenues minus costs) as a fraction of the biodiesel value, without specifying what that by-product is.
The by-product options are summarized below:

1. **Protein-based animal feed:** medium value product, low production costs; no carbon credit potential, danger of market saturation from DDG and processed soybeans; issues with certification, market-acceptance, and distribution.
2. **Electricity generation as a coal substitute**: low value, low production costs; coal is <$2/GJ, carbon credits/taxes in excess of 100% are needed.
3. **Liquid/gas fuels:** high value products, high production costs; technology unproven and inefficient; competition from low-cost cellulosic feedstocks, such as MSW.

Upper Efficiency Limit for GreenFuel's Process

GreenFuel Technologies is developing a process for algal biomass production in photobioreactors. The company has a pending patent application that is published and can be found on USPTO's website.

The patent describes sophisticated technological solutions to some problems associated with growing biomass in PBRs. While the implementation of these solutions in a commercially robust and reliable manner, and on a large scale will not be easy, this report assumes that the company will be 100% successful in achieving it. No assessment of the technological risks associated with the process is presented here.

Assuming such flawless technological execution, there are basic thermodynamic and other technical limitations that make such setup economically unfeasible.

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[3] p256 of NREL's report on biodiesel from algae.

[4] Assuming carbon credits of $50/ton of CO_2 or less.

Basic thermodynamic principles of photosynthetic energy collection.

Photosynthetic organisms (PO), such as algae, transform visible light in the 400-700 nm part of the spectrum - called photosynthetically active radiation (PAR) - into the chemical energy of carbon-containing compounds. PAR varies with latitude, seasonality and geographical factors. An excellent resource for mean annual PAR levels can be found here.

The energy - in the form of biomass - that can be obtained via photosynthesis thus depends on the level of PAR and the efficiency of the conversion process ***Q***.

$$\mathbf{E_{biomass} = PAR \times Q}$$

Photosynthetic organisms use eight photons to capture one molecule of CO_2 into carbohydrate $(CH_2O)_n$ Given that one mole of CH_2O has a heating value of **468kJ** and that the mean energy of a mole of PAR photons is **217.4kJ**, then the maximum theoretical conversion efficiency of PAR energy into carbohydrates is:

$$\mathbf{468kJ/(8 \times 217.4kJ) = 27\%}$$

This is the ideal yield on PAR energy that is: (i) actually absorbed by the photosynthetic organism, (ii) in conditions where this organism operates with 100% photosynthetic efficiency (every photon that is absorbed is effectively used in photosynthetic reactions), and (iii) the organism does not waste any energy on any life-support functions, other than building biomass. We will call this efficiency $\boldsymbol{Q_{theo}}$.

In addition, there are other fundamental limitations affecting ***Q***, these are discussed in detail in Appendix ***A***. Based on these the maximum value for ***Q*** can safely be assumed to be around **10%.**

A scaled-up plant working at **10%** efficient PAR conversion into useful energy will be a remarkable feat, where everything must go right and all of the efficiency components (the ***Q***s in Appendix ***A***) must assume their maximum values. If achieved, it will represent a ten-fold improvement on solar energy yield per surface area as compared to the best recorded agricultural yields, and approximately 30-fold improvement over more normal agricultural yields.

Unfortunately, this 10-30 fold improvement over existing land yields does not justify the capital and operational costs associated with building PBR plants.

Maximum Monetization and Carbon Mitigation Potential Assuming Upper Efficiency Limit

Monetization Stream

So what will a **10%** PAR conversion get you? Let’s go back to the formula:

$$\mathbf{E_{biomass} = PAR \times Q}$$

As can be seen from the PAR maps, annual PAR levels vary with latitude and geographical factors. In the Southwest USA it can reach **105W/m^2**, the rest of the USA it is between **80-90 W/m^2**, while in the U.K it is around **65 W/m^2** [5]. The energy captured in biomass will thus be on the order of **6.5** to **10.5 W/m^2**, which compares with maximum terrestrial yields of **0.3** to **1W/m^2**

A very important question is what the form of this captured energy is. For the high value biodiesel production, one would like a very high lipid fraction. There are some species of algae that can produce biomass with very high lipid content (30-50%, up to 80%) under certain physiological conditions. As early as in the 1940s these have been discussed as possible biofuel feedstocks, and in the 1980s the governments of the USA and Japan invested heavily in algal lipid research. All of the evidence to date, however, shows that the high lipid contents can only be achieved in conditions of physiological stress, most notably nitrogen starvation. It has been thus concluded[6] that there are no conditions in which the microorganism would reallocate energy into lipids production, there are only conditions in which the fraction of other components (mostly proteins) is suppressed. This makes a lot of physiological sense as cells need protein to grow efficiently, not lipids.

In GreenFuel's case, nitrogen starvation is out of the question, as the flue gases are rich in NOx. Further research will be required to optimize other stress factors that may be introduced to increase the lipid content. The benefit of higher lipid content will be an easier extraction process, however, it will happen at the expense of growth rate and photosynthetic efficiency, so it is not likely to be pursued.

We will optimistically assume that the maximum achievable lipid content in a GreenFuel process - while maintaining the very high overall ***Q*** of **10%** - is between **33%** and **50%** on energy basis (roughly 15-25% on weight basis).

Given such yields of lipid and by-product biomass, we calculated several monetization scenarios assuming:

- sale price of **$18.80/GJ** of biodiesel ($2.50/gal), and
- net value for the by-product (by-product revenues minus additional costs needed for its production) that equals to
    - **0.2** of the biodiesel value with equivalent energy content in the high-lipid case, and
    - **0.25** in the low lipid case, reflecting the higher level of by-product.

The results for three different locations are presented in Table 1.

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[5] It is likely that insolation of the land that is immediately adjacent to a power-plant will be attenuated by the smoke (aerosols, soot, condensed vapour, etc.) coming from the smokestack. If 100% of the flue gas is piped into the PBRs, this will likely be a non-issue.

[6] see, for example, p97 of NREL's report on biodiesel from algae.

	S.W. USA		N.E. USA		U.K	
lipid content	50%	33%	50%	33%	50%	33%
biodiesel, gal/m^2/yr	1.24	0.82	1.06	0.71	0.77	0.52
biodiesel, \$/m^2/yr	\$3.10	\$2.05	\$2.65	\$1.78	\$1.93	\$1.30
by-product, \$/m^2/yr	\$0.62	\$0.51	\$0.53	\$0.44	\$0.39	\$0.33
Total, \$/m^2/yr	\$3.72	\$2.56	\$3.18	\$2.22	\$2.31	\$1.63

Table1. Biodiesel yields and revenue flows from a square meter for three different locales and for two different lipid concentrations.

As can be seen from Table 1, the maximum biodiesel yield from the S.W. USA is less than **1.5 gal/yr/m^2**. According to a construed example in GreenFuel's patent application, an algal plant generates 342,000 bbl of biodiesel per year in a 1.3km^2 area, which would translate into **11 gal/m^2/yr**. Given biodiesel's energy content of 126,200BTU per gallon, this would equal to energy capture of **46.6W/m^2** for a region with mean annual PAR levels of **105W/m^2**, or in other words a ***Q*** of **44.4%**! Considering that the theoretical efficiency of photosynthesis is **27%**, this claim is an unconscionable exaggeration that may get GreenFuel in trouble with the patent office.

It is quite obvious from Table 1 that cash yield per m^2 is dependent on mean annual PAR values, however, water availability may be a serious constraint for building an algal plant in the sunny but dry S.W. USA. This can be extended to the rest of the world: regions with high insolation are generally very dry, while regions with ample water supplies have high level of cloudiness and reduced insolation.

Finally, looking at the dollar flows per m^2, it is obvious that they are very low. According to a study on the greenhouse industry in New York State for the year 2000, the average sales for all greenhouses (p. 4) were **\$161.77/m^2/yr**, which resulted in gross profits of **$\$_{2000}$38.82/m^2/yr** (24% gross margins). Thus, the gross **profit** per **m^2** from a simple hothouse was more than **10x** higher than our best-case projected gross **revenue** from a PBR plant.

Carbon Mitigation Potential

Photosynthesis captures CO_2 to produce carbohydrates. The most efficient biochemical route for carbon capture, therefore, is to avoid further energy penalties and to store the carbon as carbohydrates. Terrestrial plants do, in fact, consist mainly of carbohydrates, such as cellulose.

If 100% of the energy captured is stored as carbohydrates, the carbon capture will use **39kJ/gC**, equal to **0.0000256gC/s** for each **1W** of energy captured. For example, in the case of the S.W. USA where one can expect maximum solar capture density of **10.5W/m^2** , the effective carbon capture density will be around **8kgC/m^2**/yr, or **30kgCO$_2$/m^2/yr**.

Algae, however, are not known to store large quantities of carbohydrates, and thus expend additional energy to convert them into proteins and lipids. For our discussion, where we assume that the primary product of a GreenFuel-based process is biodiesel, we also assumed that 33-50% of the captured energy will be in the form of biolipids. It is reasonable to expect that the majority of the remaining biomass will be in the form of proteins, which have higher biosynthetic energy requirements than carbohydrates and thus lower yield of captured carbon per unit of captured energy. Nevertheless, we will assume that all of the remaining biomass is, in fact carbohydrate, in order to estimate the absolute upper limit of the technology for carbon mitigation. In that case the total carbon-mitigating potential of the technology - for different locales and biomass lipid fraction - is given in Table 2:

	S.W. USA		N.E. USA		U.K.	
lipid content	*50%*	*33%*	*50%*	*33%*	*50%*	*33%*
captured energy in by-prod., W/m^2	5.25	7	4.5	6	3.25	4.3
kgCO$_2$/m^2/yr of byproduct	15.57	20.75	13.34	17.79	9.64	12.75
captured energy in biodiesel, W/m^2	5.25	3.5	4.5	3	3.25	2.2
kgCO$_2$/m^2/yr of biodiesel	11.82	7.88	10.13	6.76	7.32	4.50
Total carbon mitigation, kgCO$_2$/m^2/yr	**27.39**	**28.64**	**23.47**	**24.54**	**16.95**	**17.25**

Table 2. Carbon mitigation potential for the scenarios listed in Table 1

There are several conclusions that stem from Table 2. First, one can see how the higher the fraction of biodiesel (lipids) in the final product mix is, the lower the carbon mitigating potential is. This is simply due to the fact that lipids contain 32% more energy per gram of carbon fixed than carbohydrates[7].

Second, Table 2 shows that the carbon mitigation density of the process is much lower than what GreenFuel's patent application claims. In their construed example, the company claims 244,000 tons/yr of CO_2 mitigation for a 1.3km^2 field. From Table 2 one can see that even in the best carbon mitigation case (not the best economical case, compare Table 1 to Table 2), a 1.3km^2 field can sequester at most **37,232 tCO_2**, which for the hypothetical small 250MW coal-fired plan is only **2.2%** mitigation.

Finally, it is interesting to note that our by-product values from Table 1 can be achieved by simply sequestering the by-product biomass at carbon credit prices of **\$40/tCO_2** for the 50% lipid scenario and **\$25/tCO_2** for the **33%** lipid scenario, assuming no costs associated with sequestration, and again, that 100% of it is carbohydrates. If the carbon credit prices are lower than that, then additional value must be derived from the by-products to compensate accordingly.

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[7] Assuming ethyl-oleate with energy content of 39kJ/g and MW of 284

Low Boundary Estimate of GreenFuel’s Costs

Capital Costs

There is no way to predict with certainty how much it will cost to build out a square meter with GreenFuel’s photobioreactors, however, we can put some low limit constrains by looking into comparable examples and making some assumptions.

The first comparable example of a somewhat industrialized, photosynthetic system is the greenhouse. A detailed budget for a polyethylene greenhouse is given at **\$81/ m**^{2} in 1990 dollars (**\$129/m**^{2}in today’s dollars). A more recent detailed budget (Table 1 in the .pdf) for a polyethylene greenhouse business comes to **\$190/m**^{2}**,** however it includes a number of overhead facilities.

Other, less detailed estimates that we found on the Web, range from **\$80/m**^{2} for simple inflatable constructions to over **\$200/m**^{2} for more industrialized installations like the gutter-connected greenhouses in Figure 1. Just the material costs for the simplest polyethylene Quonset designs approximate **\$25/m**^{2} (cost of polyethylene and galvanized steel tube bows). In contrast to polyethylene - a soft and highly nondurable material - greenhouses built with polycarbonate glazing (GreenFuel’s preferred material) have capital costs at the higher end of the range.

The second example is a solar non-photosynthetic installation: sun-tracking heliostats, such as the ones used in concentrated solar power (CSP) installations. A detailed report on CSP heliostat costs done by Sargent & Lundy LLC (S&L) is available on NREL’s website. In 2003 capital costs were on the order of **\$160/m**^{2} (S&L, page 5-14) and were expected to come down to **\$117m**^{2} in around 2020. As passive sun-collecting elements, the heliostats are simpler than the proposed PBRs, with the exception of their sun-tracking drives, which constitute 25% of the total cost. The heliostat costs are broken down in figure **E-5** of the S&L report.

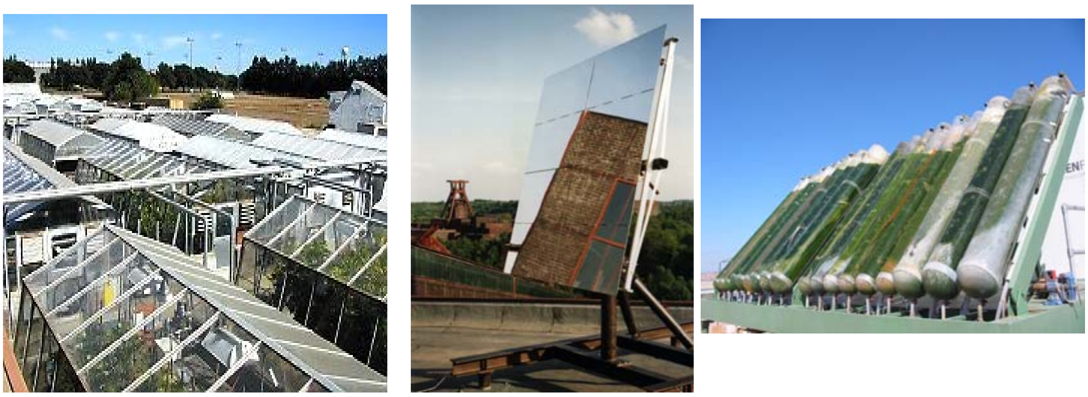

Figure 1. From left to right: a greenhouse; a heliostat; a prototype GreenFuel reactor

It can be assumed that site preparation costs, structural costs, labour, and installation will be comparable between the heliostat field and the PBR field. The communication and wiring costs will likely be higher for the PBR case as it will require more sophisticated control signal flow, however, it is not expected to influence dramatically the total cost.

For surface coverage, the heliostats use glass mirrors at **~$15/m^2**. As can be seen from Figure 4 in GreenFuel's patent application, reproduced here as Figure 2, their PBR design requires more than four-fold coverage of the land area with material: two walls for the sun-panel compartment and two walls for the "dark" compartment. In addition these compartments will most likely require dividing into tracks or tubes, as the proposed annular design will not be stable over extended lengths, thus requiring more material.

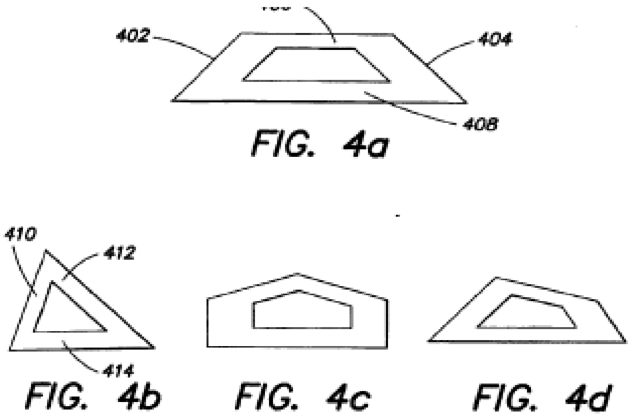

Figure 2. Side-views of proposed PBR's showing the requirement for redundant surface coverage with material.

Therefore, at least 5m^2 of material will be required for each square meter of land surface. Such high degree of surface coverage with material (**5x**, compared to **1x** for the heliostat) will greatly exceed the mirror costs in our CSP reference.

The heliostat drive accounts for ¼ of its cost and will be missing from the PBR. Instead, gas and liquid handling systems will be present, with spargers, valves, pumps, and compressors. The tubing and piping that is required for the field is a significant cost that grows exponentially with the size of the plant, as each additional m^2 is more and more separated from the source. In addition pH and temperature sensors will also have to be installed. On balance it is likely that the sum of these elements will be at least equal to the cost of the heliostat drive, most likely significantly higher.

Based on these assumptions, the low limit of the PBR field is estimated at around **$180/m^2**, by taking the heliostat cost (**$160**) and adding **$20** for the extra surface coverage with material. It should be noted that the heliostat costs in the S&L report are in 2003 dollars, while all our assumptions are in current dollars. (The 2003 to 2007 deflator is **11.4%**)

The PBR costs per square meter are not variable with plant size, with the exception of tubing and piping costs, which grow with plant size. The balance of plant (BOP) capital costs will consist of:

- facilities for harvesting the biomass,
- lipid extraction facilities,
- transesterification plant,
- inoculators,
- storage facilities,
- testing labs,

- media preparation facilities,
- administration offices,
- control equipment,

and will be scalable: they will go down per unit of output as the plant gets bigger in size. Because of that, it is difficult to estimate how much they will contribute per square meter, without knowing the size of the PBR field and the output. As a conservative approach, we will assume that BOP cost will be **$10/m^2**, or **~5%** of the total cost, which is probably the case for a very large plant. In the CSP case the non-heliostat costs are 57% of the entire plant, however, CSP is much more efficient in collecting solar energy than the PBRs, thus requiring smaller solar-capture area for the same amount of energy post-processing. In addition, the bioenergy post-processing infrastructure is not directly comparable to the CSP reference case.

Adding everything up, we come up with a low boundary for the capital cost of **$190/m^2**, consisting of **$180/m^2** of PBR field and **$10/m^2** for BOP. Assuming the best-case scenario from Table 1 and Table 2, where **5.25W/m^2** are captured into biodiesel, then the capital costs for the plant will equal to **$36,190/kW$_{\mathbf{biodiesel,}}$.**

Such capital costs compare highly unfavourably with a CSP electricity generation plant with capital costs[8] of **~$6.424/kW$_e$.** The solar power plant in question will have projected LECs of ~$0.14/kWh and will not be commercially viable without subsidies from the Spanish government and the EU. On energy equivalent basis such LECs would equal to **$5.17/gal ($217/bbl, $38.90/GJ)** of biodiesel. Looking at it from another angle, a solar plant with capital costs (per unit of useful energy converted from sunlight) equalling just 17% of the PBR capital costs will still result in non-competitive energy prices.

Prospects for Lowering the Capital Costs of a PBR Plant

It is often assumed that technological improvements will result in time in lower costs per unit built. In some cases such cost declines can be quite dramatic, with the most extreme example being the semiconductor industry. It is not surprising that Draper-Fischer-Jurvetson (DFJ) – a Silicon Valley venture-capital firm – is one of GreenFuel’s main backers. One only needs to see the walls of DFJ’s main office, adorned with stunning images of integrated circuits from companies backed by the firm, to understand their long standings involvement in the semi industry. Perhaps the logic of ever-racing cost reductions has enticed DFJ to invest in GreenFuel.

The reality, however, is completely different for structures that are highly intensive in basic materials and low in technical complexity. In our analysis we have used two examples of highly unsophisticated structures: greenhouses and sun-tracking mirrors. One would assume that all the efficiencies have been wrung out of hothouse manufacturing and the prices are about as efficient as they can get. As for the heliostat mirrors, S&L have provided a very detailed analysis in their report as to where they expect costs will be in the next decade. While the firm expects reductions to $117/m^2 by 2020, the majority of the technological advances are projected in relation to the helio-drive, which is the most technically sophisticated element, and where there is the highest potential for efficiency gains.

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[8] p5-10 of S&L report, relates to projected direct costs for Solar Tres in Spain..

The rest of S&L's estimated cost reductions are expected to come from increased deployment which would bring about efficiencies from volume discounts and learning. As pointed out, however, in a critique on the report done by the National Research Council, it is not clear how increased deployment can solve the cost issues, if the base case is not attractive enough for initial deployments to take place.

We do not know what the costs of a GreenFuel PBR currently are; undoubtedly, they will go down with time, as it is the case with every new technology. In our estimates, however, we have focused on what we believe are the bottom achievable costs, after all of the efficiency gains have taken place. In effect, what our costs represent is mostly the sum of the materials and low-tech components in a PBR system: basic material costs for structures and surface coverage, pipes, spargers, compressors, pumps, labor and installation. The components that are more sophisticated, such as pH and temperature sensors, electronic valves, etc. have also been highly optimized for bioreactors and other chemical processes, so it is unrealistic to expect dramatic decreases in the future.

Another factor for consideration on capital cost is the sheer magnitude of the buildout that will be required to achieve any noticeable effect on our fuel supplies, as well as meaningful return on the current investments in the technology. For the **1.3km^2** example given by GreenFuel to the USPTO we can calculate that the maximum volume of biodiesel that it can produce is **1.6M gal/yr**, which will equal to only **0.0028%** of domestic diesel fuel consumption for the year 2002. At the same time the *entire* U.S. vegetable greenhouse industry in 2001 consisted of 850 acres, or less than **3.5km^2.** Thus, it is obvious that if we are to "grow" fuels in a meaningful way using GreenFuel PBRs, the required buildout will surpass in magnitude anything that has been contemplated before, which will raise the issue of whether the corresponding demand for parts, materials, and labor can be met and on what terms and timetables.

Finally, as much as high energy prices are beneficial to GreenFuels prospects, they are also detrimental to the capital costs of construction. Basic materials are energy-intensive and their prices usually fluctuate in step with energy prices. This is especially the case for plastics and other petrochemicals that are also dependent on hydrocarbons as feedstock.

Economic Life of the Plant

The economic life of the plant is important to estimate the rate at which its capital costs must be paid off. It is our view that the durability of the sunlit material will be the limiting factor in estimating the plant life. Polycarbonate glazing for greenhouses usually comes with a 10-year warranty, however it has been reported that significant yellowing starts to occur before that. Low-iron glass is much more durable to UV damage.

The biggest concern that we have is the fouling of the internal surface of the sunlit panel. Cultivating microorganisms for prolonged time in near saturated cultures generates cell debris with propensity to stick to and pollute the walls of the vessel. Even in the photo of GreenFuel's prototype (see Figure 1) one can clearly see spots and smears on the PBR walls. Such contamination requires scrubbing for removal, however after a few years of use the scrubbing damages the surface, thus affecting the optical properties of even the highest grade glass. Another possible contaminant in GreeFuel's case may be soot particles from the flue gas, which could be particularly troublesome due to their high absorptivity.

Maintaining the optical clarity of the inner surface will, in our view, severely limit the economic life of the plant. For our model we will use 20 years, however, we remain sceptical that such length can be achieved while maintaining performance.

Land

The land costs are an interesting component when discussing algal bioplants. The whole concept of industrial photosynthesis is based on the premise that it is more efficient than agricultural and forestry cultivation and as such it requires less land.

We have argued here that the maximum possible yields of PAR capture in a PBR-based plant are 10 times higher than the maximum agricultural yields (achieved in sugarcane cultivation) and up to 30 times higher than more normal terrestrial yields.

It should be further noted that this estimate is based on comparing the solar aperture of the PBR plant to gross agricultural acreage. The actual footprint of a PBR plant is likely to be higher than its solar aperture, as it is impractical to install adjacent PBRs too tightly. Looking again at the CSP example (S&L), a heliostat-based power plant with a 1.3 km^2 aperture is modelled to have a 6.5 km^2 footprint. Assuming the same density of solar-capture elements, the yield advantage over agriculture - based on gross acreage - is only two- to six-fold. A more conservative ratio of two m^2 of gross land per m^2 of solar aperture would result in 5-15-fold advantage over agricultural yields.

Such yield advantages are not sufficient to offset the capital costs of the PBR buildout. As can be seen in Appendix ***B,*** agricultural prices in the USA range between **$0.07/m^2** (New Mexico) and **$2.77/m^2** (Rhode Island). Thus, the yields per square meter of gross acreage will have to be between **75x** and **2,700x** higher in the PBR to achieve capital cost parity with the price of land, even if the land for the PBR plant is free.

A PBR plant does not need to be situated on agricultural land, however, this does not mean that it can be built anywhere. The land requirements are:

- proximity to a fossil-fuel emission source (power plant)
- proximity to process water
- good insolation level

Most power plants are situated in proximity to urban areas where the land is at premium. As discussed elsewhere, water availability is geographically divorced from high insolation areas.

In an article available here, GreenFuel claims that there are more than 1,000 power plants in the U.S. with sufficient water and land availability to host a commercial installation (it makes no mention of insolation levels at these sites). It is hard to evaluate, based on this brief mention, what is considered land availability. In their patent application, GreenFuel cites an example of a 1.3 km^2 PBR plant connected to a 250MW coal-fired power plant. Even assuming that this land area refers to solar aperture and not to footprint as the Example claims, it is evident from Table 1 and Table 2 that such installation will have a very limited biodiesel output as well as very limited carbon mitigation potential.

Despite the company's claims, it is argued here that land availability will be a difficult factor in deployment of the technology. A GreenFuel installation will either require substantial amounts of land near power plants to achieve significant production rates, or it will be a small-scale installation, which will not benefit from economies of scale and will lead to high BOP capital costs.

Nevertheless, because the land factor is so highly uncertain and so dependent on geographical location, we will assume in our model that there is no land cost associated with a PBR plant buildout.

Operation and Maintenance (O&M) Costs

O&M costs include:

- personnel cost for washing, repairs, and maintaining the PBR field
- personnel for repairs and maintenance of BOP
- administrative personnel
- control systems and computers service contracts
- weed control
- road maintenance
- vehicle maintenance
- parts and materials for the PBR field
- parts and materials for BOP
- miscellaneous (travel, phones, office supplies, etc.)

Going back to the heliostat reference example, the costs associated with maintaining and washing the solar field are 0.03 FTE per 1000m^2(S&L). Assuming fully burdened employee costs of $40,000/year, this translates into **$1.20/m^2/y**r (S&L uses $50,000/yr for an FTE, 2003 dollars). It should be noted that the heliostat field has a single washable surface, while PBRs will have to be periodically cleaned from the inside as well, since there will likely be cell debris sticking to the inner surface of the sunlit panel. Nevertheless, we will stick to the **$1.20** figure for our model.

For all other personnel costs we will assume a 9:1 split between PBR and BOP. This is slightly higher than what we assumed for the capital cost split between PBR and BOP, in view that the administration overhead does not figure heavily in the capital structure, yet it will affect the BOP personnel costs.

In terms of replacement parts and materials for the PBR, as well as the BOP, we will use a very conservative **0.26%** of the capital cost, which would result in **$0.50/m^2/yr**. For comparison, S&L uses 0.5% for the heliostat field and 0.3%-0.4% for the BOP.

For the purposes of this report we will ignore all other O&M costs.

CATEGORY	**COST, $/m^2/yr**
personnel cost for PBR field maintenance, washing, repairs	$1.20
personnel cost for BOP, incl. administrative	$0.13
Parts and Materials	$0.50
All Other	$0.00
TOTAL	**$1.83**

Table 3. Simplified O&M costs

Other Fixed and Variable Costs

The algal media costs are variable with respect to the plant capacity and output. These costs consist mainly of water, trace elements, and pH buffer. The latter is needed because CO_2 dissolved in water raises its acidity and must be neutralized. The least expensive buffering agent – lime – is likely not an option here due to the prospect of precipitating calcium carbonates. Costlier sodium based buffer will likely be the next best option.

It has been mentioned in the press by GreenFuel that algae can grow on brackish water from saline aquifers or in sea water. While this may solve some of the water availability problems, it will result in other undesirable side effects: salt precipitation on the bioreactor walls; precipitates on pumps and valves leading to reduced lifecycle; presence of salts in the final biomass, which will likely have to be purged with steam.

Pumps and compressors for delivery of media and flue gas to the PBRs will require electric power. Curiously, this cost is fixed with respect to output and scales up **exponentially** with plant capacity. This is due to the fact that a larger plant will require transport of gas and media to locations that are further from the source than in a small plant.

The only truly variable costs are the ones associated with biomass processing. These include:

- primary dewatering
- compacting (final dewatering)
- drying
- lipid extraction
- transesterification
- by-product processing

For our model we use net value for the by-product revenue (by-product costs are already subtracted there). With respect to the biodiesel part we will assume that any methanol and ethanol volumes that are needed for transesterification will be offset by corresponding sales of glycerine. The caveat here is that with large volume production it is likely that the glycerine markets will be fully saturated, and these sales will not be able to fully offset the ethanol/methanol costs.

As mentioned in the introduction, the biodiesel refineries are efficient and low-cost installations, albeit far from no-cost. A biodiesel feasibility study from 2004 estimates incremental ***transesterification only*** costs at **$$_{2004}$0.073/gal[9],** which will

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[9] see Table 5B there; only labor, utilities and misc. expenses are added up, net of feedstock and depreciation.

result in **$0.09/m^2/yr** in the best productivity scenario from Table 1. For the other costs in this category we were unable to find good reference cases, so we conservatively set them at zero.

CATEGORY	**COST, $/m^2/yr**
water	$0.00
trace elements	$0.00
pH control	$0.00
piping/compression	$0.00
dewatering, drying	$0.00
lipid extraction	$0.00
transesterification	$0.09
TOTAL	**$0.09**

Table 4. Simplified Other Costs

Energy costs are hidden in all categories *highlighted* in Table 4 and deserve a special mention. According to statements from GreenFuel, their technology will require “single-digit percentages of parasitic power”. It is not clear to what level of CO_2 conversion these references were being made. If they refer to the aforementioned 250MW-power-plant/1.3km^2-PBR-field case - which as we saw is expected to have a very limited capacity for CO_2 conversion - then even 1% parasitic power will be an awfully high requirement. In any case, energy costs are likely to fluctuate in step with the prices of final fuel, making them more variable with revenue than with physical output, and thus reducing the operational leverage of the process in conditions of rising energy prices.

Economic Viability of a GreenFuel Plant

Summarized here are all of the assumptions from above that we will use to evaluate the economic viability of a GreenFuel plant by calculating the minimum biodiesel price needed for an NPV value of 0 by the end of the plant’s economic life.

CATEGORY	**VALUE**
Capital Cost, $/m^2	$190
Economic Life, yrs	20 yrs
Construction Duration, yrs	1 yr
Internal Rate of Return, IRR, %	14%
Land, $/m^2	$0
Simplified O&M costs, $/m^2/yr	$1.83
Simplified Other Costs, $/m^2/yr	$0.09
Best Case Biodiesel Output (column1, Table 1), gal/m^2/yr	1.24 gal
Revenues from by-products, net of cost, as fraction of biodiesel revenues	0.20
Biodiesel price for NPV=0 at EOY20, $/bbl	**$853/bbl**

Table 5. Economic Assessment of a GreenFuel Process Plant

While a price per barrel of **$853** (**$20.31/gal**) may sound unsettling, it is even more troubling in view of what lies behind the assumptions used in its calculation:

- Upper boundary for solar-to-product conversion efficiency;
- Location with highest insolation level in the USA, which may present difficulties with process water availability;
- Upper boundary for lipid content;
- Free Land;
- Conservative assumptions for capital costs;
- No budgeted contingencies
- Conservative assumptions for repairs, maintenance, washing, and administrative O&M costs;
- No budget for other O&M costs;
- No budget for fixed and variable costs, other than for transesterification;
- Practically zero allowance for parasitic energy costs, which are expected to be substantial if fuel prices are ever to reach such levels;
- No tax allowance;
- Zero return on current venture capital investments in the development of the technology (the IRR used relates to the return on capital outlays for the plant buildout).

This **$20.31/gal** figure can be looked upon from another angle. According to our optimistic model, such price will result in gross *revenues* of **$30.22/m^2/yr.** Incidentally, such *revenues* are still significantly less than the **$38.82 m^2/yr** gross *profits* achieved by the New York State greenhouse industry in 2000. Thus at first approximation it can be assumed that even at fuel prices of **$853/bbl** a greenhouse will be a better investment than a GreenFuel plant.

Comparison to Other Alternative Fuel Technologies

The worldwide peak in conventional oil production will occur within this or the next decade: there is not enough time to divert the world's transportation fleet to non-liquid fuels. Is it possible, then, that the impending oil shortage will result in fuel prices reaching and exceeding **$800/bbl**? It is an extremely unlikely scenario. As conventional oil dries up, other liquid fuel options will be economic long before the prices reach such stratospheric levels.

A good summary of these liquid fuel options has been written by Farrell and Brandt at UC-Berkeley. As can be seen, gas-to-liquid and unconventional oil resources have production costs in the **$20-30** per bbl (2000 dollars), which makes them economical even at today's prices[10].

With respect to climate change, carbon capture and geological sequestration (CCS) is expected to be economical in the EUR20/tCO$_2$ range by the year 2015. It is true that these estimates are not done in the context of retrofitting existing plants, however, the

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[10] The cost ranges in the article are likely based on theoretical models like this one. Recent large costs overruns on GTL projects in Qatar underscore the difficult learning curves that lie ahead for new technologies adoption

barriers for that are more economical than technological. GreenFuel's claim that their technology can be used for retrofitting may be semantically correct, however, it makes no economic sense either. We saw that GreenFuel's Example to the Patent Office, for a 250MW coal-fired plant with a 1.3km^2 PBR field attached to it, only mitigates **2.2%** of carbon emissions, while at the same time the conservative costs for the PBR plant are on the order of **$260M**. Considering that coal-fired plants cost ~2,000/kW to build, "retrofitting" the 250MW plant to mitigate only 2% of its carbon emissions would cost 50% of the price of a new coal plant with similar capacity.

Combining the GTL process with carbon capture and sequestration at coal-fired power plants will produce end-results (clean-burning liquid fuels and carbon mitigation) that are equivalent to what GreenFuel is trying to accomplish, at much lower cost. Let's assume that costs of **$30/tCO$_2$** (higher than Stromberg's estimate of 20EUR/tCO$_2$) for CCS are added to the GTL synfuel costs. Furthermore, let's assume that a barrel of GTL synfuel costs **$40** (higher than Farrel and Brandt's estimate of **$20-30/bbl**) and has the same carbon content as crude oil (**~118kgC/bbl**). In such a scenario, a barrel of clean burning synfuel will only cost **$53** ($40 production costs + $13 CCS fee), which is lower than the current price of biodiesel (**$105/bbl**).

For a longer term solution (40-50 years), the CSP systems referenced here offer a clean solar energy source, with minimal water requirements. Estimates for the near-term LEC using CSP systems are around $0.08/kWh, which equals to **$22/GJ$_e$**. These systems do not produce liquid fuels, however, they may become relevant for transportation in the context of electric vehicles or plug-in hybrids. A price of **$22/GJ** would translate into a wholesale price of **$3/gal** for gasoline at energy content parity. It is important to note that electric motors have much higher efficiency coefficients than internal-combustion engines (ICE), so we need to look at the energy costs to the wheels, and not the costs to the tank/battery. If we assume a two-fold efficiency advantage for the electric motor over the ICE, then the CSP power in the context of electric or plug-in hybrid vehicles is competitive to current prices of gasoline.

These examples show that we have much better options for both, post-oil energy sources and carbon mitigation, than the proposed algal PBR technology.

Conclusions

1. Maximum achievable density of solar capture with industrial photobioreactors is on the order of **6.5-10.5 W/m^2**, which compares with terrestrial yields of **0.3-1W/m^2** Such densities of solar conversion do not justify even the most inexpensive capital and operational outlays for PBR buildout and operation.

2. Algal microorganisms operating with maximum photosynthetic efficiency allocate only a limited fraction of the captured solar energy into lipid production. Only this limited fraction can be processed via the lucrative biodiesel pathway and the rest of the biomass will have to be allocated to less profitable products.

3. A PBR-based biodiesel plant operating at maximum efficiency is not economically feasible at fuel prices below **$800/bbl.**

4. A PBR-based biodiesel plant will have a maximum carbon mitigation potential of less than **30 kgCO$_2$/m^2/yr**

5. Biofuel production in PBR-based plants compares unfavourably with other alternative technologies for liquid fuel production, carbon mitigation and solar energy.

6. Hype surrounding some alternative energy startups sometimes disregards the laws of physics and other fundamental principles.

GreenFuel Technologies: A Case Study for Industrial Photosynthetic Energy Capture

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March, 2007

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Preface

In early 1998, while finishing my Ph.D. work on yeast genetics in Houston, I was soul-searching what to do next with my career. Renewable energy and biofuels was something that intrigued me a lot and I also wanted to employ my skills in eukaryotic microbial genetics as well as some emerging genomic technologies. One obvious route was to work on yeast strain improvement for the corn-ethanol process. After looking at the potential impact, I was disappointed to find out that it wasn't that great: the conversion yields and productivity of existing strains were quite strong, the major bottleneck was availability and cost of the corn feedstock.

What about lignocellulosic feedstocks? NREL was doing some breakthrough work with *Zymomonas* and I visited them on a ski-trip to Colorado. I met there with Steve Picataggio, who was the lead scientist and just had a paper published in Science. *Zymomonas* strain improvement was full of promise and Golden, CO looked like a very attractive proposition, after spending six years in Houston's heat and humidity. Unfortunately, in 1998 oil prices were at multi-decade lows and Steve simply had no funding support and backing from above to expand his group in these conditions.

I also looked at the possibilities to work on algal strains as an alternative, hyperproductive feedstock. I talked to my advisor and she looked at me as if I was an alien (she often looked at me this way). Algal genetics was pretty much an obscure field back then and you could not publish in any place of significance. Nevertheless, I spent an afternoon tackling the fundamental parameters and doing the calculations that are contained in this report. The numbers just didn't work: solar energy is too dilute and photosynthesis has fundamental limitations. Designing even a super-efficient strain would not be economical without completely rewiring the photosynthetic machine.

I ended up in Lee Hood's lab in Seattle, which is probably the best thing that happened in my career, as within a year we started the Institute for Systems Biology – the first systems biology initiative in the world. Lee's lab was heavily into microrarrays and genomic technologies, so I embarked on some fascinating studies of yeast physiology using microarrays. Pursuing my interests in biofuels, I wrote to COPPERSUCAR in Brazil and they sent me some of the strains used in their sugarcane-to-ethanol plants, to look at them with microarrays.

One major issue with industrial strains is the ability for genetic manipulation. For lab strains people use something called auxotrophic markers to track the success of any genetic transformation, however, these are unusable for highly-polyploid industrial microbes. Together with my talented Research Assistant, Allison Golden, we initiated a project to track genetic modifications by photonic means, where a would-be transformed cell will also become transiently fluorescent and sorted with a FACS machine.

Meanwhile, realizing the importance of feedstock availability and cost, I focused my interest into municipal solid waste (MSW). I was able to obtain a grant and get an extremely talented postdoctoral candidate to come for an interview. Everything was falling in place and I couldn't be more excited. Right then though, as often happens in life, within a couple of months Allison decided to go back to school (she got accepted in the prestigious Bioengineering program at UW) and the postdoctoral candidate accepted an offer from M.I.T. As I was overloaded with many other things - running the microarray lab at ISB, working on a new nanotechnology for genomic analysis, participating in a major project on genetics of juvenile diabetics – I decided to end my direct involvement with bioenergy.

Nevertheless, the field still intrigues me and I try to keep up with the latest developments. As the energy prices have gone way up and the climate change issue is becoming more and more pressing, bioenergy is hotter than ever. In times like these it is important keep cool heads and to stay grounded in the laws of physics and thermodynamics. While this report may go into more detail than needed, its main conclusions could have been reached by investing in a calculator and a few hours on Google Scholar. (It took me an afternoon in the dark pre-Google ages of the late1990s to basically reach the same conclusions.) Had this been done, millions of dollars and human effort could have been saved and potentially allocated to more promising endeavours.

Krassen Dimitrov, Ph.D.

Appendix A

Factors Affecting Q and Their Upper Limits

Photosynthetic organisms (PO) can approach the theoretical photosynthesis limit in conditions of low light; when the light levels are higher the processes of photosaturation and photoinhibition take place and reduce the photosynthetic efficiency down to 20% or less of the theoretical maximum. The energy conversion efficiency will thus be:

$$\boldsymbol{Q_1} = \boldsymbol{Q_{theo}} \text{ x } \boldsymbol{Q_{ps\text{-}eff}},$$

Where $\boldsymbol{Q_{ps\text{-}eff}}$, or photosynthetic efficiency, is a measure of how well the PO is avoiding photosaturation and photoinhibition. Dealing with this photosaturation effects has been a major challenge and an area of active research. It is in this area where GreenFuel claims to have made significant contribution. We will assume that the GreenFuel's process brings $\boldsymbol{Q_{ps\text{-}eff}}$ to an average of 90% (**0.9**) with their clever reactor designs and protocols; or in other words nine out of every ten photons that are absorbed by the PO are used in photosynthetic reactions and one photon is lost due to fluorescence or heat dissipation. This will be a truly remarkable accomplishment, even for a PO that is permanently adjusted to low-light conditions, not to speak about an algae cell that is intermittently exposed to light of low and high intensity as the GreenFuel patent proposes.

POs do not absorb 100% of the PAR that falls on the surface of Earth because of reflection of green photons, as well as other factors. For terrestrial plants that maximum observed fraction of absorbed PAR (generally known as fAPAR, called here $\boldsymbol{Q_{abs}}$) is 0.85. Such high $\boldsymbol{Q_{abs}}$ are found in the rainforest, where the surface coverage with leafs of tightly packed photosynthetic cells (Leaf Area Index, LAI) is $5m^2/m^2$. For an algal suspension bioreactor with limited depth, this may be a challenge, especially considering that there is an extensive stream of light-reflecting gas bubbles flowing through it. Nevertheless we will assume a $\boldsymbol{Q_{abs}}$ of **0.85**. Thus the maximum efficiency with which the POs will absorb and convert the PAR energy is given by:

$$\boldsymbol{Q_2} = \boldsymbol{Q_1} \text{ x } \boldsymbol{Q_{abs}}$$

$\boldsymbol{Q_2}$ does not take into account that PO use some of the captured energy for purposes other than biomass generation. We will call this $\boldsymbol{Q_{life}}$, or the efficiency with which the algae support their life functions. This in turn is split into $\boldsymbol{Q_{life\text{-}light}}$ and $\boldsymbol{Q_{life\text{-}dark}}$. During the day the cells can utilize ATP energy that is generated by photosynthesis system II (PSII) and which is not subject to the 27% $\boldsymbol{Q_{theo}}$ requirement for CO_2 fixation, but in fact has a higher energy conversion coefficient. At night, when the ATP is depleted, the PO will break down carbohydrates to provide energy for its living needs.[1] Here we will assume $\boldsymbol{Q_{life\text{-}light}}$ of **0.9** and $\boldsymbol{Q_{life\text{-}dark}}$ of **0.8** for a total ***Q***life

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[1] The same is true for the harvested biomass during its processing, therefore quick killing is needed to assure minimal energy losses. In experimental conditions, the biomass is quickly collected and then placed in a 105°C oven for determination of dry weight. In a scaled-up plant this is obviously not an option; it will be a challenge that has been ignored so far.

of **0.72**. This compares favourably with terrestrial plants, where values of 0.6-0.65 are generally accepted. Comparison of the energy requirements for terrestrial plants and algae are omitted here for brevity. In general, it is expected that the algal culture will be more efficient in some aspects, while in others the terrestrial plants will have an advantage; on balance we believe that the algal culture could achieve slightly higher efficiency for life support.

$$\boldsymbol{Q}_3 = \boldsymbol{Q}_2 \times \boldsymbol{Q}_{\mathbf{life}}$$
$$\boldsymbol{Q}_{\mathbf{life}} = \boldsymbol{Q}_{\mathbf{life\text{-}light}} \times \boldsymbol{Q}_{\mathbf{life\text{-}dark}}$$

Before the solar energy is absorbed by algae in a PBR-based plant, the light has actually to get into the reactor. This is defined as the optical efficiency of the process and will be called $\boldsymbol{Q}_{\mathbf{opt}}$.

$$\boldsymbol{Q}_4 = \boldsymbol{Q}_3 \times \boldsymbol{Q}_{\mathbf{opt}}$$

$\boldsymbol{Q}_{\mathbf{opt}}$ has four components:

$$\boldsymbol{Q}_{\mathbf{opt}} = \boldsymbol{Q}_{\mathbf{tr}} \times \boldsymbol{Q}_{\mathbf{clean}} \times \boldsymbol{Q}_{\mathbf{shade}} \times \boldsymbol{Q}_{\mathbf{refl}}$$

$\boldsymbol{Q}_{\mathbf{tr}}$ is the transmission coefficient of the wall of the reactor that is sunlit. It appears that GreenFuel's choice is polycarbonate, with transmission in the visible spectrum of ~**0.9**. It will be hard to find a material with better transmission properties. Regular glass is worse; low-iron glass is slightly better but more expensive.

$\boldsymbol{Q}_{\mathbf{clean}}$ is the cleanliness of the bioreactor wall. For large scale solar collectors the maximum cleanliness approaches **0.95** and it is unlikely that it can get better than that[2].

$\boldsymbol{Q}_{\mathbf{shade}}$ is a measure of the shading effects in the solar field. Collectors with a flat surface will collect all of the PAR that falls down, however, as can be seen from GreeFuel's patent their reactors are not flat which has important and beneficial implications for their process. We will assume here shading efficiency of **0.93**. $\boldsymbol{Q}_{\mathbf{shade}}$ will be affected by how densely the PBRs are placed. Low density of PBRs will result in higher shade efficiency, at the expense of higher land requirements.

$\boldsymbol{Q}_{\mathbf{refl}}$ is a measure of how much light is reflected by the wall of the PBR at various angles. This is not to be confused with $\boldsymbol{Q}_{\mathbf{tr}}$ which only measures transmission of light that is directly orthogonal to the surface. At various angles the air-wall and wall-water interfaces will reflect different amounts of light. For example, polycarbonate and glass have a refractive index of around 1.585. When light comes at an angle larger than 72o all of it will be reflected by the wall-water interface via total internal reflection. Here we assume $\boldsymbol{Q}_{\mathbf{refl}}$ of **0.88**

$\boldsymbol{Q}_4$ should give a measure of the efficiency with which the PAR enters the PBR, gets absorbed by the algae, and gets converted into useful biomass.

The last part of the efficiency discussion has to deal with post-synthetic and plant efficiency, $\boldsymbol{Q}_{\mathbf{plant}}$, with the following components:

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[2] See S&L

$$Q_{plant} = Q_{process} \times Q_{av} \times Q_{tech}$$

$Q_{process}$ is the efficiency with which the biomass is collected, dried, the lipid fraction is extracted and processed into biodiesel. We will assume a heroic **0.98**. Such yield would be considered good for just the transeesterification part of the process and requires very low moisture contents of the biomass, as higher moisture contents result in hydrolysis over transesterification.

Q_{av} is the maximum availability of the plant, net of scheduled and unscheduled maintenance. We will assume **0.98**

Q_{tech} is a measure of technology execution, or how reliably and reproducibly the PBRs will operate. As pointed in the beginning, we will assume **100%** for this measure, as this report only discusses the fundamental thermodynamic and technical limitations, and not the risks associated with developing a new and unproven technology.

Total Maximum Efficiency Achievable

Based on the previous section, the total efficiency of the process is given by:

$$Q = Q_{theo} \times Q_{ps\text{-}eff} \times Q_{abs} \times Q_{life\text{-}light} \times Q_{life\text{-}dark} \times Q_{tr} \times Q_{clean} \times Q_{shade} \times Q_{refl} \times Q_{process} \times Q_{av} \times Q_{tech},$$

or

$$Q = 0.27 \times 0.9 \times 0.85 \times 0.9 \times 0.8 \times 0.9 \times 0.95 \times 0.93 \times 0.88 \times 0.98 \times 0.98 \times 1.00 = 0.10$$

What will an efficiency of **10%** mean? Let’s introduce a measure of

$$F = Q/Q_{theo},$$

which measures what fraction of the theoretical efficiency is achieved in converting solar PAR into biodiesel energy.

A **10%** overall efficiency will have an ***F*** value of **0.37**, or 37% of the theoretical efficiency. For comparison, the highest productivity in the ocean, observed near the Equator, is 1-2g of carbon per m^2, which corresponds to **0.36-0.72%** of PAR, for an ***F*** factor of **0.013**, (**1.3%** of the theoretical efficiency). As another comparison, sugarcane is considered the terrestrial plant with most efficient photosynthetic conversion. The maximum yields of sugarcane achieved would correspond to **1.1%** PAR conversion, or an ***F*** factor of **3.7%** - an order of magnitude less than our best case PBR scenario above.

Thus, converting sunlight into biodiesel with a ***Q*** of **0.1** means that the process is ten to thirty times more efficient than the best terrestrial and marine efficiencies, respectively. It is important to note that these figures do not compare photosynthetic efficiencies, but rather the efficiency of the entire process – from PAR to product. Just looking at the photosynthetic efficiency in our estimate, it is assumed to be significantly more than 10-30x higher in the PBR than in the open systems. The latter get light directly from the Sun with no air-wall/wall-water interfaces, so they are expected to have higher $\boldsymbol{Q_{opt}}$ values. In addition there are no losses from biomass-to-biofuel conversion ($\boldsymbol{Q_{plant}}$ = **1.00**). Finally, in the case of sugarcane, it produces mostly sugar, which as a carbohydrate, is the immediate product of photosynthesis - there are no losses from further bioconversion.

There are a few reports in the literature that claim photosynthetic yields in excess of 10% of PAR. In GreenFuel's patent application the company claims that in an experimental example 20% solar efficiency was achieved. Based on the above discussion, these reports should be taken with a block of salt. Apart from sloppiness or outright deceit, what other factors can lead to exaggeration of photosynthetic yields:

- Quoting only peak efficiency: the yield achieved in a short period during a light phase.
- Not accounting for diffuse light: only direct light is measured as the energy input in an experiment. While an isolated experimental PBR will receive substantial amounts of diffuse light; in a tightly paved field of PBRs there will be no sources of diffuse light.
- Not accounting for vitamins and other growth factors in the media. In most experiments the researchers supplement the media with vitamins and other compounds, thus alleviating the biosynthetic requirements on the cell. Vitamin supplementation will be uneconomical for large scale production
- Supplying ammonia as nitrogen source, thus not requiring the cell to use energy for nitrogen fixation. In GreenFuel's case nitrogen is supplied as NOx from the flue gas, so the cells will require expending energy for its reduction. This requirement is reflected in my estimate of $\boldsymbol{Q_{life}}$ above.
- Representing the yield as based on absorbed light, rather than on total available light, by adjusting the insolating light flux downwards in accordance.
- Using wrong conversions for photon flux. If the insolating light is measured as PPF it needs to be converted into irradiance. This has been a common source of error.

The detailed discussion of the efficiency limits serves academic purposes only. Even assuming an ***F*** factor of **100%** - in other words, if a GreenFuel plant works at theoretical photosynthetic efficiency - it will still not make economic sense.

APENDIX B

U.S. Farm Prices

State	2005 avg. land value (in dollars per acre)	Pct. change from 2004
Alabama	$2,050	10.2%
Arizona	$1,750	9.4%
Arkansas	$1,820	10.3%
California	$4,160	9.5%
Colorado	$845	9.0%
Connecticut	$10,800	5.9%
Delaware	$8,400	40.0%
Florida	$3,700	19.4%
Georgia	$2,590	10.2%
Idaho	$1,480	8.8%
Illinois	$2,900	11.1%
Indiana	$3,050	10.1%
Iowa	$2,490	13.2%
Kansas	$800	11.9%
Kentucky	$2,200	10.0%
Louisiana	$1,680	6.3%
Maine	$1,950	5.4%
Maryland	$7,900	38.6%
Massachusetts	$10,500	6.1%
Michigan	$3,150	7.9%
Minnesota	$2,030	12.8%
Mississippi	$1,580	6.8%
Missouri	$1,740	10.1%
Montana	$445	8.5%
Nebraska	$910	10.3%
Nevada	$550	10.0%
New Hampshire	$3,450	6.2%
New Jersey	$10,300	5.6%
New Mexico	$290	9.4%
New York	$1,880	5.6%
North Carolina	$3,570	8.2%
North Dakota	$500	9.9%
Ohio	$3,180	8.5%
Oklahoma	$805	8.1%
Oregon	$1,350	8.0%
Pennsylvania	$4,000	9.6%
Rhode Island	$11,200	9.8%

South Carolina	$2,330	8.4%
South Dakota	$570	14.0%
Tennessee	$2,700	8.0%
Texas	$925	8.2%
Utah	$1,230	7.0%
Vermont	$2,300	7.0%
Virginia	$3,900	21.9%
Washington	$1,650	7.8%
West Virginia	$1,600	6.7%
Wisconsin	$2,850	14.0%
Wyoming	$350	11.1%

Source: Department of Agriculture's National Agricultural Statistics Service