A Value Chain and Life-Cycle Assessment Approach to Identify Technological Innovation Opportunities in Algae Biodiesel

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ABSTRACT

Algae biodiesel is an opportunity space that has gained renewed interest for venture investment. As with any new opportunity space, determining where the greatest value capturing potential resides has important implications for directing investment and research. This paper presents a value chain analysis of algae biodiesel and maps current industry players against similar segments in the biofuels and petroleum value chains. Using margin analysis and life-cycle analysis of one of the market pains (energy use in algae harvesting and biomass processing to biodiesel), a technology opportunity was identified. The identification of potentially high value companies using semi-quantitative analysis provides a useful tool for investors and entrepreneurs in the algae biodiesel space.

Keywords: biofuel, algae, biodiesel, life-cycle analysis

1. BACKGROUND

Today there is broad scientific consensus that human activities have altered our climate. Experts are more certain than ever that increases in anthropogenic greenhouse gas (GHG) concentrations have caused a rise in global average temperatures, leading to substantial environmental, social, and economic consequences. Given the substantial impact of liquid petroleum combustion, which accounts for approximately 39% of energy-related CO_2 emissions in the US, it is not surprising that biofuels, such as ethanol and biodiesel, have become increasingly popular as governments, producers, and consumers alike seek to reduce their carbon footprints [4]. When produced from food grains, these biofuels may reduce direct-effect GHG emissions compared to their fossil fuel analogs [8; 11], but global land-use changes may actually result in greater emissions from their production [14]. In an effort to develop a new biodiesel feedstock that does not use food grains or arable farmland for fuel production, over 50 start-up companies and numerous university and national laboratories are investigating how microalgae can meet these requirements while providing attractive, scalable solutions for investors and entrepreneurs.

1.1 Algae-to-energy

Algae are photosynthetic organisms found in a variety of aquatic and terrestrial environments. Algae can range in size from microscopic single cells on the order of 0.2-2.0 μm in diameter to giant kelp that can reach 60 m in length [1]. To date, the majority of research on algae-to-energy pathways has focused on microalgae and the unique ability of some species to accumulate lipids as a large proportion of their body mass. In general, algae demonstrate higher biomass and lipid productivities than terrestrial plants and can be grown on salt water and wastewater, providing essential treatment services and reducing freshwater requirements for feedstock production. Though most research has targeted phototrophic algae growth in hopes of using waste CO_2 from plant power flue gases, algae grown heterotrophically on carbon sources like glucose and glycerol are being investigated to achieve higher biomass densities and productivities.

Algae are generally grown in open ponds or closed bioreactors and must be harvested to obtain a biomass suitable for processing into liquid biofuels. When grown in sunlight, algae rarely achieve densities greater than 5 g dry weight/L, necessitating flocculation and dewatering steps that can be energy intensive and expensive. Today there is no single process established for cost effective harvesting, oil extraction, and conversion into biodiesel. In fact, this is an area of active research and a significant part of the intellectual property claimed by many companies in the space. Although anaerobic digestion and gasification of algal biomass are other processing strategies being investigated, here we focus on lipid production as a feedstock for biodiesel.

From 1978 to 1995, the US Department of Energy's Aquatic Species Program (ASP) spent roughly US$25M to identify algae species appropriate for biodiesel production, understand lipid biosynthesis in hopes of discovering ways to increase productivity, and assess the economic viability of fuel production [15]. The data indicated that although the technology held great promise, the cost of algae-based biodiesel could not be compete with low-cost petroleum diesel. Likewise, the Japanese invested about $117M through the Research Institute of Innovative Technology for the Earth (RITE) to develop enclosed bioreactors for CO_2 sequestering algae, but the project also ended with disappointing cost projections. These conclusions create opportunity for technological innovations that reduce cost and increase efficiency, thereby enabling scalable solutions for algae-to-biodiesel in the marketplace. Recently, Huntley *et al*. (2003) published results from their US$20M investment (1998-2001) in Aquasearch, a Hawaiian marine biotechnology company successfully producing astaxanthin from *Haematococcus pluvialis* [9]. Their economic analysis contrasts sharply with previous estimates and indicates that per barrel oil prices could range from US$84 to US$50 dollars when using a unique hybrid cultivation system that incorporates both closed photobioreactors and open ponds.

Over the past three years, over US$240M of venture capital (VC) and other investment support has gone into start-up companies attempting to commercialize algae-to-energy products. With this significant investment, a careful assessment of where opportunity lies along the value chain can help guide development of this nascent industry towards where technological innovation has the greatest value capturing potential. Although intellectual property protection makes it difficult to determine what companies have achieved and what remains hypothetical, we can categorize basic process distinctions at each segment of the value chain to determine its likelihood for success and its contribution to the product's life cycle energy balance.

1.2 Value Chain Analysis

A value chain describes value-creating activities along a supply chain and represents both material (primary) and information (supporting) flows. Like any industry, algae-to-energy production is comprised of a set of activities that can be segmented and analyzed individually to determine where the potential for value capture is highest. Segments can be quantified by determining the operating or net profit margins of companies performing that value-adding activity, with higher margins potentially indicating a more difficult, costly, time sensitive, or essential segment. A company operating in only one segment is termed a pure player, and its profit margins are considered indicative of the value captured by the segment. If a pure player does not exist, margins from a proxy company with a parallel role and business model in a related industry can be used. A value chain analysis informs where potentially profitable entry points exist or where existing companies can increase their portion of the value capture through creating a substitute or alternative solution, eliminating segments, or by addressing an emerging market.

1.3 Life-Cycle Assessment

The idea that biofuel feedstock production from microalgae reduces net GHG emissions relative to petroleum diesel is widely assumed to be true but almost entirely unsubstantiated. A thorough life-cycle assessment (LCA) has not been completed on algae cultivation for liquid biofuel feedstock production, and it remains unclear whether a positive net energy balance is possible given the requirements of cultivation, harvesting, oil extraction, and transesterification to biodiesel. Here we outline several major factors affecting the net energy balance and begin compiling the data necessary for a more complete LCA. Ultimately, such an analysis will be site and process specific, but some basic calculations can reveal strategies that are unlikely to yield positive results. Furthermore, combining biodiesel feedstock production with wastewater treatment, as has been proposed [2], may significantly improve the economics and energy balance attributed to both processes. We intend for our analysis to be a basis for discussion within the industry as to where opportunity lies for both investment returns and long-term environmental sustainability.

2. METHODS

2.1 Value Chain Analysis

Information presented at the 2008 Algae Biomass Summit in Seattle, Washington, in addition to published, peer-reviewed literature and company websites, was used to construct a value chain that reflects the algae-to-biodiesel opportunity space. Segments were assessed based on known pure player profit margins and approximated values from proxy companies in parallel industries such as crop-based biofuels and petroleum production and refining. Operating margin analysis and venture investment were assessed and incorporated into an analysis aimed at identifying segments of highest value capture.

2.2 Life-Cycle Assessment

In an initial analysis of market pains for technology scaling, we have focused on net energy production across the value chain. Several economic models of large-scale algae cultivation have been published, each with unique assumptions that directly impact projections for energy use and related GHG emissions. An updated version of Oswald & Benemann's 1996 assessment [3; 12] was chosen as the basis for a simplified energy balance evaluation of algae cultivation and a recent LCA on soy-based biodiesel completed by Argonne National Laboratory provided data for biodiesel processing inputs [10]. Given the process-specific nature of any LCA, here we present only very preliminary data that should be verified by companies as they develop their processes.

3. VALUE CHAIN ANALYSIS

Market and company analysis of industries indicates diversity in positioning and product development across the value chain. The value chain used here was based on analogies with the crop-based biodiesel and oil industries, including: (1) algae selection and cultivation; (2) grow out; (3) harvesting, extraction, and conversion; (4) storage and distribution; and (5) retail.

The CleanTech group indicated in their Q3 investment report that algae biodiesel companies with products across the entire value chain received investment. For example, Sapphire Energy, the largest algae fuel start-up in terms of funds raised, is focusing on producing a "renewable gasoline" and has emphasized the grow out of photosynthetic microorganisms. Solazyme synthetically evolves marine microbes for biosynthetic manufacture of fuel as well as nutraceuticals, cosmetics, and other industrial and specialty chemicals. They are partnered with Chevron and are the only company to have produced certified biodiesel from algae thus far. They own patents on multiple technologies, including for algae grown from CO_2 and sunlight or with organic materials. Solix Biofuels uses a patented open bioreactor design and recently raised $5M to build a pilot plant near Durango, CO. The following section exemplifies the value chain and uses proxy companies in the petroleum and agriculture industries to map value-capturing segments.

Table 1. Leading algae start-up by investment totals

Company	Defining innovation/strategy	Investment to date
Sapphire Energy	renewable gasoline, grow out	+100M
Solazyme	engineering synthetic marine microbes, certified biodiesel	+70M
Solix Biofuels	patented bioreactor	15.5M

3.1 Algae selection and cultivation

Algae for large-scale cultivation can be purchased from private culture collections, isolated from natural water bodies or waste treatment facilities, or genetically engineered for desired characteristics, such as increased lipid content or enhanced photosynthetic efficiency. The choice of algae strain can affect everything from necessary growing conditions and nutrient inputs to later choices of harvesting and processing methods.

Some companies have already protected genetically engineered algae while others suggest such genetically modified organisms (GMO) are unnecessary, potentially dangerous if accidently released to the environment, and unlikely to maintain dominance in outdoor ponds thought to be the least expensive method for cultivation. Solazyme, along with biotech companies like Honolulu-based Keuhnle AgroSystems and Seattle-based Targeted Growth, Inc., specialize in creating customized strains of algae for prospective growers. A few companies bypass this segment by collecting already existing unwanted algal blooms in natural waters for conversion to biofuel and other products (i.e. Blue Marble, Seattle, WA).

Firms in this segment can be compared with both oil field exploration firms and agricultural seed stock databanks. ION Geophysical Corporation is a pure player in the oil field exploration segment of the petroleum value chain that uses seismic data acquisition to identify and model potential oil fields. In the same way, an algal biotech company has a databank of algae strains, their pertinent characteristics, and will be able to sell this information or characterize new strains as needed by clients.

3.2 Grow Out

The next segment of the value chain is producing algal biomass on a commercial scale. Algae can be grown in open ponds, closed bioreactors, or in the open ocean. Nutrients must be obtained from waste streams or added chemicals. A carbon source is also necessary, which can take the form of CO_2 from the atmosphere or flue gas or various types of cellulosic waste and organic matter if growing algae heterotrophically.

Companies like Vertigro and Washington-based Bionavitas sell patented photobioreactors designed to increase productivity and photosynthetic efficiency. Likewise, Bodega Algae is focusing on modular bioreactors that can be installed on-site to mitigate CO_2 emissions from industrial plants.

Some companies avoid regional and climatic constraints important for photosynthetic growth by feeding algae organic compounds that allow them to grow without sunlight. Though much higher productivities can be achieved like this, the source of the carbon compound must be carefully considered. For example, if sugar derived from corn was used to grow algae which was then converted into fuel, the overall conversion of sunlight energy into fuel energy would be lower than had the algae been grown photosynthetically. However, if the carbon source were truly a waste product destined to be land filled (i.e. excess glycerin from biodiesel production), even if it was originally plant derived, such a negative accounting would be inappropriate. This type of life-cycle consideration is necessary to understand the wider implications of fuel production.

This segment of the algae biodiesel value chain is comparable to the farming and harvesting portion of the agriculture industry and the drilling and production section of the petroleum industry. Syncrude Canada Ltd. manages oil reserves and produces crude oil, though they don't manufacture their own equipment. Schlumberger plays in both oil field exploration and drilling and production. By combining segments of the value chain, they capture more value for themselves.

3.3 Harvesting, Extraction and Conversion

The dilute nature of algae cultivation presents unique challenges to companies in this segment. Unlike biodiesel production from soybeans, which involves solvent extraction from a mostly dry (<10% moisture) oilseed containing 18-20% oil, oil production from algae must contend with a wet biomass feedstock (>90% moisture) or expend energy and money to dry the biomass. Though some strategies for harvesting and conversion are well known, many are proprietary and few companies have been willing to divulge how this part of their process works. It is likely that extracted oil would be sent to existing biodiesel processing facilities (which are in need of inexpensive feedstock) or processed on-site (depending on scale).

The harvesting and conversion segment is analogous to the refining stage of petroleum processing. Western Refining, Inc. focuses on refining petroleum into mainly light transportation fuels like diesel and gasoline.

Table 2. Margin Analysis of Companies Along the Value Chain

Company	Operating Margin		
	2007	2006	2005
1) ION Geophysical Corporation	9.00%	7.90%	6.80%
1+2) Schlumberger	29.10%	25.50%	21.50%
2) SUNCOR Energy	17.4%	24.2%	17.6%
3) Western Refining	5.30%	7.20%	X
4) Enbridge Energy	4.4%	5.9%	3.0%
6) Travel Centers of America[a]	-2.7%	X	X

Note. All data from www.hoovers.com (2-20-09). [a] 2008 margin was +0.86 %.

3.4 Storage and Distribution

Like most liquid fuels, algae biodiesel must be stored in tanks and distributed to where it is sold to consumers. Today, there are no algae companies producing enough biodiesel to warrant a significant investment in this segment. However, placement of infrastructure for algae grow-out should consider the cost and energy involved with transporting the product to market. Most algae startups plan to utilize the existing fuel distribution infrastructure. We compare this segment with Enbridge Energy, a company which transports, stores and markets refined petroleum products.

3.5 Retail

Algae biodiesel will be sold just as biodiesel or petroleum diesel is sold to consumers at a filling station. Alternatively, large commercial buyers (i.e. the Army, large fleets) could absorb a significant fraction (if not all) of the algae biodiesel produced within the next few years. We model this segment on Petro Stopping Centers, which sells petroleum products to consumers.

3.6. Summary and Analysis

In the biofuel and petroleum value chains, most of the value is created in the exploration and processing segments, with lesser margins in the refining, distribution and retail segments. The value is created in identifying the sources (e.g. seeds for crops, and oil reserves) and harvesting/production at scale (requiring specialized infrastructure). The equivalent for algae would be companies involved in screening and identification of algae with high oil content, and those involved in the grow out and extraction of the lipids. The competitive differentiation here involves screening tools and equipment/process design for scaled production and extraction. One of the main challenges in these early segments of the value chain is the energy input-to-output ratio of the process.

4. LIFE CYCLE ANALYSIS

Several options for the conversion of algal biomass into usable forms of energy have been researched, along with several direct uses for algae biomass or conversion process waste products. Conversion processes are considered on the basis of the condition of the biomass starting material, both in terms of biochemical composition and moisture content, the energy ratio and conversion efficiency technically achievable, and the overall economic feasibility of the process. When comparing algae species known to produce biomass with given proportions of polysaccharide, lipid, and protein, direct comparisons of the energy obtained through different conversion methods is possible. In addition, the opportunity to combine conversion methods can be assessed given the various inputs and outputs of each stage. Though biodiesel production is the focus of the present work, it is not the only strategy for converting algae biomass into liquid fuels. Indeed, anaerobic digestion, fermentation to ethanol, and thermochemical liquefaction are additional pathways that have also received significant research. Nevertheless, biodiesel production is the technology closest to commercial-scale viability with the potential to produce a relatively high-value energy product. If high lipid content and high overall biomass productivity can be assumed, the difficulty in producing biodiesel from algae lies in the harvesting, post-harvest processing, and oil extraction.

Solid-liquid separation, also known as dewatering, is necessary to concentrate algae for downstream processing. Typically, harvesting can account for 20-30% of the total cost of production and negatively impacts the energy balance of fuel production from algae given the high inputs of the process [6]. No universal harvesting process is suitable to all algae; rather, species-specific variation requires careful design for cost-effective harvesting.

Harvesting can be accomplished by sedimentation, flocculation/flotation, filtration, and centrifugation. Grima *et al.* (2003) provides estimates of the energy input required for centrifugation (1 to 8 kWh m^{-3}) and filtration (0.2-1.6 kWh m^{-3}) along with concentration factors feasible (between 10-100 fold). Normally, the percent of total solids (%TSS) in the concentrate following centrifugation is about 10% to 20% (or 100 g L^{-1} to 200 g L^{-1}) and major costs involve depreciation, maintenance of equipment, and electricity for operation [6]. Further drying can be accomplished by spray drying, drum drying, lyophilization, and solar drying. Thermal dehydration by sun drying is both difficult and unreliable, and spray drying, which uses atomizers to expose a fine spray of the slurry to hot air, or lypholization (freeze-drying), is energy intensive and prohibitively expensive [7].

To understand the energy used for harvesting in the context of biodiesel production, we propose a hypothetical situation in which algae at a density of 1 g d.w./L is being harvested by centrifugation. We assume this algal biomass contains 25% oil on a dry weight basis and the extracted oil has a similar density (0.916 g/ml) and calorific value (39.6 MJ/kg) to soybean oil [13]. If we only consider the oil harvested from 1 m^3 of suspended algae, the energy obtained is 2.75 kWh. As referenced above, harvesting could potentially require up to 8 kWh/m^3, suggesting this is not a viable harvesting strategy when used as a primary method.

Using data provided by Lundquist *et al.* (2008) based on an updated version of Benemann & Oswald's 1996 analysis, 5754 Mg of algae and over 410,000 gal of oil could be produced per year in 100 ha of open ponds treating wastewater. This economic analysis does not disclose how harvesting would occur, but includes capital and operating costs for algae settling units, gravity thickeners, and drying beds. Altogether the process is expected to consume 17 MWh/d, which results in electricity usage equal to 40% of the energy obtained in the algae when considering only oil production. The analysis did not include the energy necessary to extract the oil and convert it to biodiesel.

As evident in the above two examples, a significant amount of energy must be expended to harvest algae. As no reliable process has been developed for oil extraction from wet biomass, and there is great uncertainty in whether biomass can be cost-effectively dried to a point suitable for extraction in today's oilseed processing infrastructure, it is very difficult to estimate additional energy requirements for these key processes. However, it is noteworthy that combining wastewater treatment with biofuel production, as the model by Lundquist does, suggests that a credit must be applied for the energy normally required to treat wastewater using existing technologies. For example, wastewater treatment in the US consumes about 2,500 kWh/million gallons (MG) [5]. Though Lundquist's model requires 17 MWh/d, it was theoretically treating 20 MG/d, meaning a normal wastewater treatment facility would have expended 50 MWh/d just to clean the water. With algae production, less electricity was used and a valuable biomass was created. Of course, we have neglected electricity normally produced from the anaerobic digestion of sludge at wastewater treatment facilities and have not considered other important indicators of environmental impact, such as GHG emissions, land use, and the embodied energy in materials.

5. CONCLUSIONS

Based on our value chain analysis, the most value is added in the upstream segments of drilling, producing, and transporting crude oil in the petroleum industry, which parallels the grow out, harvesting, and transportation segments of the algae biodiesel chain. In the petroleum industry, this is likely due to the necessary specialized technology and equipment used, huge capital required for entry, and high risk involved in exploration. In the algae biodiesel industry, we predict the market pains to be similar, with the addition of an energy-intensive drying process to reduce transportation costs of excess water and make algal biomass amenable to conventional oil extraction processes.

Our preliminary life cycle assessment begins to outline how process improvements in harvesting and oil extraction could greatly reduce energy inputs for biodiesel production from algae. Future work must refine this analysis on a site and process specific basis, while continuing to assess opportunities for important credits based on reducing energy requirements for wastewater treatment compared to conventional technologies.

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