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Algae as a Biofuel Feed Source

A Study on Economics, Scaling and Investment

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Abstract

The United States is the world's largest importer of petroleum and is developing liquid fuel substitutes from biomass to displace fossil fuel consumption as a means of energy security of supply as well as secondary interests in reducing greenhouse gas emissions and supporting innovation. Algae based biofuel is a newer technology gaining momentum in the biofuel race due to very attractive growth properties and ease of distribution in current infrastructure. However, cost economics remain an issue. This study applies an experience curve as a basis for quantifying the investment needed for continued learning progress and scale up of algae biofuel production to reach cost parity with petroleum based fuels. The findings indicate investment will be substantial, perhaps exceeding $15 billion if progress is less than anticipated. This serves as the starting point for analysis of potential factions that would make these kinds of investments, their motivation and how investments might occur. Short term investments are best made in research to discover algae strains with high lipid yields combined with high productivity. Investment will most likely be a combination of public and private funding due to societal gains from research spillover effects and private gains from huge market potential and IP protection. Military support has the potential to be a game changer for algae technology. And, government policy support is important in the near term to encourage investment in continued research, development and commercialization.

Acknowledgements

A year ago I found myself much like Alice in Wonderland falling down a rabbit hole. Though a mix of serendipity, curiosity and proximity I stumbled into the world of algae and the possibility of it generating a liquid fuel. Many people have helped inspire, guide and challenge me in the thesis research, synthesizing and writing process. Thank you to all who supported me in tackling a somewhat unusual thesis topic.

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Abbreviations

ABO	Algal Biomass Organization
API	American Petroleum Institute
ARPA-E	Advanced Research Projects Agency-E, U.S. Department of Energy
ASP	Aquatic Species Program
bbl	Barrel of Oil (appox 42 gallons)
BP	British Petroleum
CCC	Carbon Capture Corporation
CO_2	Carbon Dioxide
DARPA	Defense Advanced Research Projects Agency
DOE	United States Department of Energy
E85	Ethanol85- a blend of 85% ethanol and 15% gasoline
EIA	United States Energy Information Administration
EISA	United States Energy Independence and Security Act of 2007
EPA	Environmental Protection Agency
FER	Fossil Energy Ratio
GHG	Greenhouse Gas Emissions
g/m^2	grams per $meter^2$
ha	Hectare (or 2.471 acres)
IP	Intellectual Property
LCA	Life Cycle Assessment
LR	Learning Ratio
NREL	National Renewable Energy Laboratory
OFLC	One Factor Learning Curve
PBR	Photobioreactor System
PR	Progress Ratio
R&D	Research and Development
RFS2	Renewable Fuel Standard under EISA
SD-CAB	San Diego Center for Algae Biotechnology
TAG	Triacylglyceride
TFLC	Two Factor Learning Curve
U.S.	United States

Converstion Rates

1 barrel of oil = 1 bbl
1 bbl = 42 gallons
1 gallon = 4 liters
1 liter = 0.25 gallons

1 hectare = 2.47 acres
1 acre = 0.4048583 hectares
1 square mile = 640 acres
1 acre = 0.0015625 square miles
1 square mile = 2.59 square kilometeres
1 square kilometer = 0.39 square miles

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1. Introduction and Research Question

With the United States (U.S.) increasing demand and consumption of liquid fuel, in addition to seeking energy independence for security purposes, the country continues to look for and support new technologies as alternative supplies of fuel.

Biofuel from algae is considered a 'far reaching technology' as it is in the research and development phase but working towards commercialization. From early trials and findings, it presents a promising opportunity for creating liquid fuels. Algae are one of the Earth's most prolific forms of life (they reproduce very quickly) and are a very simple organism to process into fuel. Algae need carbon dioxide ($CO_{2)}$ to grow, offering another benefit in the potential to help mitigate global warming. Algae can grow anywhere as long as there are sun, CO_2 and water, even non-drinkable water. Lastly, algal biofuel can be used in planes while ethanol cannot.

In the 'biofuel' race there seem to be three major players with corn ethanol being the largest mainly because it is the earliest commercialized biofuel technology and the most understood of the fuel alternatives. 'Cellulosic' is another area of interest and research, but it is not measuring up as originally envisioned. 'Algal' is the newest for commercialization and seeing some very promising results from the start.

1.1 Research Question

What will the investment necessary look like for algae biofuels to reach costs closer to incumbent fossil fuel technologies? In addition, who might make these investments happen and why might they make those investments?

1.2 Motivation

The motivation for this thesis research is to take an analytical look at a 'far reaching technology' to assess its future potential. The goal of this research is to provide useful information for public and private industry decision makers as they consider investment and support decisions.

The challenge when looking at a new technology, such as biofuel from algae, is a lack of concrete information in the public. However, applying economic tools and analyses help to derive a better understanding of potential. This study will help answer the questions of ‘will it happen’? If so, how? And what might the timeframe look like? This study will use the experience cost curve to estimate how production costs stand to come down over time as well as look at the investments necessary to reach a point where algae derived biofuels are close or at cost parity with fossil based fuels.

This research is exploratory with the objective of combining literature with economic analysis of an applied experience curve model to equip investors with grounded decision making tools and framework. In Chapter 2 I present an overview of economic theory as a foundation for this study. Chapter 3 provides an overview of algae, algae biofuel production, inputs and real potential for cost reductions. Chapter 4 is a review of previous studies on the estimated cost per gallon of algal biofuel, and Chapter 5 employs real world market data to the experience curve model as a means to analyze real investment necessary for scale up of the technology. Finally, Chapter 6 discusses the potential interest groups who might contribute to the overall investment of scale up and why they might invest. In addition, possible policy measures as a means to support investment are analyzed. Chapter 7 concludes by summing up the study and suggesting further research in this area.

2. Theoretical Framework

The notion of finite natural resources as well as the relatively recent interest of employing less greenhouse gas (GHG) intensive energy sources has brought the intersection on energy and innovation to center stage. General economic theory can, in many cases, provide guidance when analyzing growth within innovation in energy and natural resources. This chapter serves as an overview of economic theory to be applied in the analysis of the research question. The main economic tool employed in this study, the experience curve, is reviewed. Motivation for public and private investment in new technology development is also explored.

2.1 Technological Change

Technological change is the starting point for a study such as the development of algae as a biofuel feed source. Technological change over time plays an important role in the economic growth of a society. Many economists provide insight into the innovation and the technological change process.

Joseph Schumpeter (1947) wrote extensively in the area of innovation and entrepreneurism touting the pivotal role entrepreneurs play as a mechanism of economic change in capitalist society. Schumpeter builds on the traditional theory of ‘adaptive response’ postulating a ‘creative response’ which cannot be predicted by applying the ordinary rules of inference from pre-existing facts. Creative response has something to do with the quality of personnel available in a society, the relative quality of those personnel at the same time together and individual decisions, actions and pattern of behavior (Schumpeter, 1947).

Rosenberg (1976) builds on this concept by remarking it is impossible to analyze the effects of technological change apart from the particular context within which the change appears. He concludes the same technology will result in different kinds of consequences in societies that differ with regard to their institutions, values and resource endowments and histories.

Innovation and technological change are important economic drivers, but it is hard to predict ex-ante which technologies will be winners. However, underlying assets such as natural resources and knowledge capital have a positive effect on the innovation atmosphere of a society and potential. The U.S. is endowed with vast natural resources, human intellectual capital and promise for innovation. And, general technological change theory is reflected by the U.S.'s growth over the last century. Also, technological change theory supports the notion the U.S. is in a prime position to explore algae as a biofuel source and benefit from the domestic economic growth it might garner.

2.2 Endogenous Growth

Endogenous growth theory explains economic growth as involving a two-way interaction between technology and economic life. Technological progress is an important catalyst of progress in the economic system according to endogenous growth. It seeks an understanding of the interplay of this technological knowledge and various elements of the economy and society and how this interplay results in economic growth (Aghion & Howitt, 1998). There are alternate views and supporters of exogenous growth, a different school of thought, which outlines growth based on productivity, capital accumulation, population growth and technological progress but often fails to account for entrepreneurship or explain how technological change happens. Endogenous theory allows us to 'develop tractable and flexible models that embody the vision of economic life as an endless succession of innovation and change wrought by competition. With these tools we can bring to bear all that we have learned in economics about incentives, organization and institutions, not only on the problem of economic growth per se but also on the many other economic phenomena that interact with growth' (Aghion & Howitt, 1998).

The '$Y=AK$' endogenous growth model has re-emerged in the last few decades and shows production being dependent on knowledge, which is a function of physical capital, represented by 'K'. 'A' represents knowledge stock, a global public good, and introduces positive spillovers resulting in increasing returns to scale to the production function. Knowledge stock is usually observed similar to that of physical stock and assumed to be dependent on cumulated R&D expenditures. Arrow postulated the growth of A could be an unintended consequence of gained experience in producing new goods, also known as 'learning by doing' (Aghion & Howitt, 1998). Therefore this model incorporates endogenous technological change and states knowledge capital is essential to productivity growth rates. Climate economy models incorporate this knowledge-through-learning component indirectly through employing the use of experience curves (Kohler, Michael, Popp, & Edenhofer, 2006).

Endogenous growth theory supports the importance of technological change to economic growth and illustrates an important positive connection between production output and knowledge stock.

2.3 Experience Curve

It can be observed through history that the per-unit-cost of production for a product decreases over time as the product moves from its beginning stages to a more mature state. For most products and services, it is not simply the passage of time that leads to cost reductions. Cost reductions are observed more as a function of accumulation of experience (McDonald & Schrattenholzer, 2001). As Kohler et al. (2006) surmise, literature suggests experience curves document the correlation between cumulative experience with a technology and falling costs.

One theory explaining this is known as the ‘experience curve’ or the ‘learning curve’. This curve illustrates the development of costs per-unit of production as the cumulative quantity produced across the industry is double (Alberth, 2008). Another way of looking at this is, each doubling of cumulative production results in a per-unit cost decrease by a certain value known as the learning rate (Kahouli-Brahmi, 2008). The notion of technological learning, or learning effects reducing the cost per unit of production, has been widely covered in research and writing in reference to cost trends over time of new technologies (Nordhaus, 2009).

While difficult to predict cost developments with great accuracy a priori, modeling technological learning has become a popular way to estimate cost reductions per-unit-produced into the future. Overall, the modeling method results can provide important insights, especially in reference to new energy technologies (Kahouli-Brahmi, 2008). Observed learning investments across technologies as well as the potential break-even point with conventional technologies provides a better understanding of investments necessary and possible trade-offs as a basis for a forward moving strategy.

In this same way, technological learning has become a tool employed in policy analysis modeling new technology cost curve developments due to endogenous change (Kahouli-Brahmi, 2008; van Sark, 2008).

Past and continued research in the area of technological learning has identified different mechanisms justifying the observed decreases in the unit production costs. The two most applicable to an agricultural or manufacturing process, and hence, algal biofuel, are learning-by-doing and learning-by-researching. Learning-by-doing, introduced by Arrow in 1962, represents the notion that the repetition of manufacturing tasks involve an improvement of the production process due to increases in labor efficiencies, changes in production methods, etc. Learning-by-researching identifies research and development (R&D) expenditures as a driver in cost reductions by focusing on the innovation process and allowing the firm to leverage knowledge circulated in its environment (Kahouli-Brahmi, 2008).

Separating these two effects can be difficult in long term modeling but is possible in a two-factors learning curve (TFLC) (Kahouli-Brahmi, 2008). As McDonald and Schrattenholzer (2001) note, model inputs where learning and scale are joined into a single estimated learning rate, or a one-factor learning curve (OFLC), may be simpler and more useful than efforts to extract the two separate effects. As a result, experience curves communicate price reduction observations in a single parameter, the 'learning ratio'.

These relationships can be illustrated mathematically which allows us to derive a learning curve. Thus, the learning curve is an estimated illustration of the learning-by-researching and learning-by-doing effects. The performance indicators to construct the learning curve are capital costs, investment costs and production costs. In some cases, prices can act as a proxy for production costs (Kahouli-Brahmi, 2008). However, prices are driven by many factors other than cost. So, using prices as measures of learning and technological progress is an inferior measure to production costs (McDonald & Schrattenholzer, 2001). Cumulative installed capacity or the cumulative production serve as experience performance indicators. The usual expression of the one-factor learning curve, or the classical learning curve, is by using an exponential regression (Kahouli-Brahmi, 2008; Mejean & Hope, 2010)

$$C(Q) = a(X/X_0)^{-\alpha} \tag{1}$$

C = cost per unit of production, investment or capital

Q = cumulative production

a = cost of the first unit produced

X = cumulative production

X_0= initial cumulative production

α = elasticity of learning or the experience parameter, $\alpha \geq 0$

Parameter a is found by using one given point on the curve, usually the starting point:

$$a = \frac{C_0}{(Q)^{-\alpha}} \tag{2}$$

Equation (1) can determine the progress rate and, alternatively, the learning rate as:

$$\textit{Progress rate (PR)} = 2^{-\alpha} \tag{3}$$

$$\textit{Learning rate (LR)} = 1-2^{-\alpha} \qquad = 1- \mathrm{PR} \tag{4}$$

The progress rate, or the progress ratio, shows the cost-per-unit of production upon doubling production as a percentage of the previous level of production cost-per-unit. For example, a PR of 80% means a cost-per-unit of production reduced to 80% of the previous level after each doubling of cumulative production. Conversely, each doubling of units produced results in a decrease of production costs by 20%. This value represents the learning rate or the learning ratio. Also, the progress rate reflects to the slope of the learning curve (Kahouli-Brahmi, 2008).

The learning investment can be seen as the area below the cost curve but above the conventional technology cost as illustrated below (Figure 1).

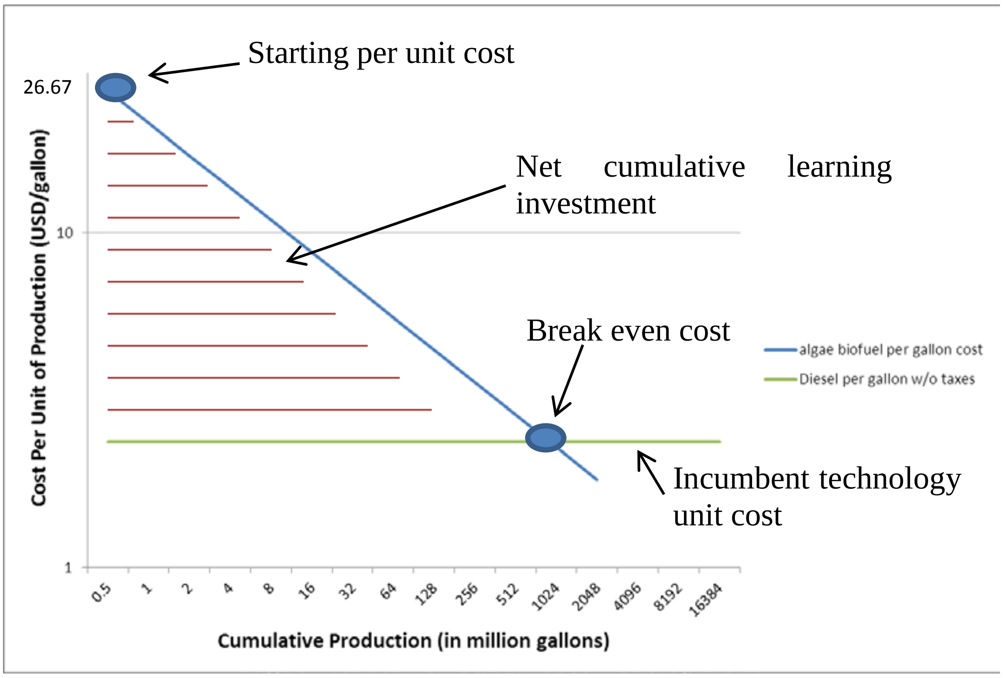


Figure 1: Log experience curve showing learning investments required

Source: authors own creation

2.4 Learning Rates

Kohler et al. (2006) aggregate literature and studies to find data suggesting some broad yet useful patterns in learning rates. As might seem intuitive, learning rates appear higher in earlier stages for many energy technologies. Also, literature has led to a general ‘rule of thumb’ learning rate of 20% for electricity generation technologies. Although non-electric supply technologies observe more variation. The collection of progress ratios by Dutton and Thomas (1984) (Fig. 2) shows this as well as supports the notion of the 20% learning ratio rule of thumb:

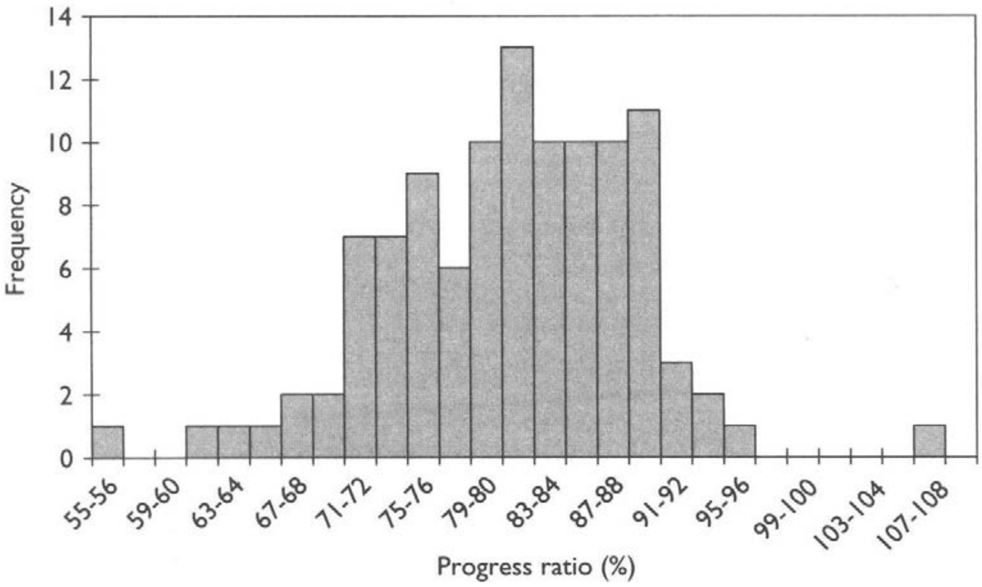


Figure 2: Distribution of Progress Ratios (PR) Observed in 22 Field Studies (Dutton & Thomas, 1984). The Learning Ratio is 1-PR

Kahouli-Brahmi (2008) collected learning rates across different energy technologies and found a range from 1% to 45.5% cost reductions for the learning-by-doing rates and around 1% to almost 44% for learning-by-researching rates. Although, the author notes, the lower learning rates tend to be in the more mature energy technologies such as coal and crude oil.

While these show large variations, learning rates can provide a useful starting point for cost reduction analysis. McDonald and Schrattenholzen (2001) studied learning rates across technologies and their application to new energy reduction technologies. By observing ‘estimated’ learning rates against actual reported learning rates, they suggest learning rates from studies not restricted to energy technologies can still serve as a useful starting point for energy modeling until more detailed studies on energy technologies are available.

2.5 Critics of the Experience Curve

It should be mentioned, there are critics of the experience curve as a forecasting tool. Opponents to the experience curve postulate that the fundamental element, the progress ratio, overestimates progress ultimately realized. Critics caution against the simplistic use of an industry experience curve or a firm’s own experience curve noting future progress rates from past historical patterns have proved unreliable (Dutton & Thomas, 1984).

Some critics question how robust conclusions drawn from learning curves and progress ratios may be considering the large possible variations in parameter inputs. As an example, the magnitude of learning rates differs from technology to technology. But, more importantly, the choice of data points and time period to derive the learning ratio can have a large impact on the learning rate applied to the future (Kohler et al., 2006). Kohler et al. (2006) also point out the challenge of incorporating uncertainty in climate-economy models.

Additionally, others recommend considerations for inputs that have the potential to enhance the accuracy of the experience curve forecasts. Some models put more weight on recent data so it has a stronger influence on forecasts, especially in light of limited historical data (Alberth, 2008).

In this research these criticisms are considered by tempering results through applying sensitivity analyses. The experience curve model is simplistic but is generated as prudently as possible. It serves as a starting point for analysis about the magnitude of future investment needed. The experience curve and learning investments aid in considering who might invest and why as well as identifying what policy mechanism could be effective in prompting investment.

2.6 Investment in Technological Change

Investment is necessary to realize learning rates, and it is important to understand motivations to invest in the development of new technologies, such as biofuel production from algae, for analysis of potential investors and policy mechanisms to encourage proper investment. And the motivation to make investments in the development of ideas, knowledge and processes for achieving technological change is multi-layered. There are various characteristics of new technology development investment- explicitly rates of return and property rights- and these ultimately define investment decisions.

One issue pertaining to investment in technologies not yet in the commercial space arises due to the fact that information and knowledge ‘goods’ typically become public goods. Once an idea or technology is discovered, it is easily moved to the public space. This can be via published research, key personnel moving around industry or inventing around patents which protect an idea but, at the same time, reveal it to the public domain. Information and knowledge goods are non-excludable and non-rivalrous in the public space. Timing on diffusion to the public space differs based on the technology. Once in the public space, the virtue of a competitive market ensures the efficient production and distribution of private goods. However, the efficient competitive price will not cover the development costs of the technology (Scotchmer, 2004). This uncovers the rationale behind the potential for underinvestment in R&D and is demonstrated by the following example.

Zvi Griliches and his work in hybrid corn studies in the mid-1900s measured investments in agricultural research and found the investments to yield benefits of about seven times the investments. Much of these benefit were in the form of 'spillovers' that were captured by others (Smith & Barfield, 1996). Knowledge spillover indicates the social returns to R&D very well can be higher than investment, as in the hybrid corn case (Kohler et al., 2006). And, on the whole, this is a benefit to society. However, this presents the problem that the entity that invests in the research, either the government or the private firm, often fails to capture all of the benefit.

This divergence between private and social returns to R&D sheds light on one reason for underinvestment in R&D. The public nature of knowledge fails to incentivize private investors in continued R&D. Therefore, weak protection of intellectual property will result in less than socially optimal investment (Smith & Barfield, 1996).

Intellectual property (IP) law plays an important role as a means of providing protection of covering development costs of new technologies, such as algae biofuel. Firms willing to invest in a risky value proposition gain monopoly of the market for their discovery for a time period after the patent is filed. This market potential is an important driver of investment. Strong property rights and protection of intellectual property, as experienced in the U.S., provide security in investment for firms seeking near term payback periods as well as attractive returns on their investment. However, a downside of IP rights is the obstruction of information sharing which is beneficial to innovation and society on the whole.

Public investment in R&D is important for this reason, amongst others. Public investment in R&D is rationalized by public utility, public benefits from spillover effects and the potential to make large impacts for the societal good. In this way, the gains government seeks from its investments in innovation and R&D are not necessarily direct financial returns to grant or research funding. Unlike private investors, government research funding values the gains of the spillover and learning effects generated from knowledge spillovers, data sharing and science findings. An attractive return on government spending is the ‘social return’ or the interest rate received by society as a whole (Smith & Barfield, 1996). Shared progress can also have the benefit of reducing the potential overall learning investment necessary because overlapping efforts in research are minimized.

Public investment in R&D also serves the important purpose of investing in basic research which private investors will not make due to ambiguity in profitability. Basic technology discovery can be tricky to compensate and market value is typically found in products developed further in the life cycle (Scotchmer, 2004).

The general motivations described above for both private and public investment in the development of new technologies are reflected by current U.S. government and industry spending to support R&D ventures. About one quarter of R&D in the U.S. is funded by the federal government which includes grants to universities, firms, and federally funded research and development centers. Universities receive just less than half of the federal government R&D funding. The majority of the remaining three quarters of R&D in the U.S. is funded by industry. Industry also receives just over half of the federal government’s spending on R&D.

It is important to dig deeper into these numbers because most industrial R&D is applied while most R&D in universities is basic research. While university R&D makes up about 14% of total R&D performance, they undertake about half of total basic research in the U.S. (Scotchmer, 2004). And, basic R&D is critical to generating technologies for future applied research.

3. Overview of the Algae Resource

This section serves to provide an overview of algae, details the attractive attributes of algae as a biofuel feed source as well as outlines the process of growing, harvesting and extracting the lipid, or oil, for biofuel production. This is not exhaustive; rather, its purpose is to provide a foundation with which to move towards a more informed economic analysis.

Generally, the ability to extract lipids from algae is not contested. Biofuel generated from algae is classified as a second generation biofuel which is also known as an advanced biofuel. These lipids from algae can be used to produce renewable biofuels for direct substitution of fossil fuels. The resulting fuels can be used in existing infrastructure, both fueling stations and engines, and is outlined in more detail below.

3.1 Organism Overview

One might envision green slime when thinking about algae, and, this is a fair picture. However, looking below the surface, an impressive feature of this green slime is the conversion of CO_2 to energy by capturing solar energy via photosynthesis. Therefore, just as 'land-based' plants, algae require the basic elements of sunlight, water and CO_2 to produce biomass.

Algae range from small, single cell organisms to multi-cellular organisms which can be fairly complex (A. Singh, Nigam, & Murphy, 2011). Algae are classified by leaf size as macroalgae, large leaf, or microalgae, small leaf to microscopic. Microalgae strains are typically implied when talking about algae as a biofuel feed source because of the high lipid content in many of these strains.

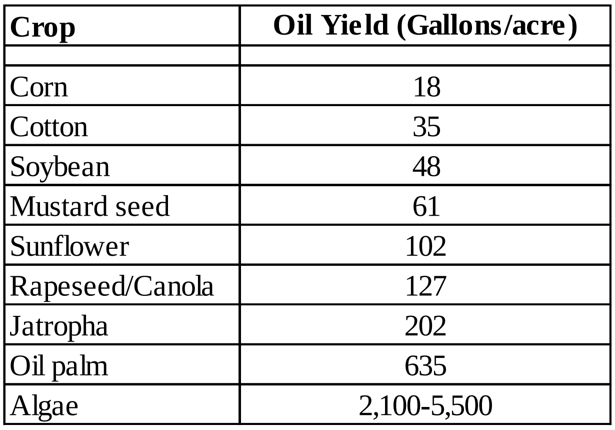
A single algae organism is formed by a mix of lipids, carbohydrates, proteins and hydrocarbons (Fig. 4). Each strain of algae differs by composition of these elements. There are approximately 1,000 species of algae showing potential for production of biofuels (Renaud, 2011). Each strain grows optimally under different conditions of inputs like temperature and nutrients. Thus, strain choice is an important element in the production process and the overall cost economics. This is also observed in traditional agriculture.

3.2 Productivity and Lipid Content

The two main concerns for increasing efficiency of algae biofuel production are high productivity, or biomass accumulation, coupled with high lipid content of that biomass. However, lipid generation and productivity are often inversely related (Christenson & Sims, 2011).

Lipid content refers to the oil extracted from algae biomass which is then refined into the final liquid fuel product. It is also sometimes referred to as triacylglyceride, or TAG oil. Lipid levels are observed between 20 to 75% of total biomass dry weight (J. Singh & Gu, 2010) but are usually estimated at between 25 to 40% of dry biomass (Sun et al., 2011) (Huntley & Redalje, 2007).

Algae's efficiency in reproduction is its biomass yield. As an example, it's not uncommon for strains of microalgae to double their biomass within 24 hours. Biomass doubling times have been observed as short as 3.5 hours (A. Singh et al., 2011). This higher productivity level contributes to a higher lipid yield per land area than other biomass sources. Studies show algae can produce 2 to 20 times more oil per acre than other crops (Fehrenbacher, 2012; Pienkos, 2012) (Fig. 3).



Crop	**Oil Yield (Gallons/acre)**
Corn	18
Cotton	35
Soybean	48
Mustard seed	61
Sunflower	102
Rapeseed/Canola	127
Jatropha	202
Oil palm	635
Algae	2,100-5,500

Figure 3: Potential oil yields (Pienkos, 2012)

3.3 Resulting Biofuel End Product

Algae biomass can be converted to various forms of biofuel. Unique strains of algae can be cultivated to produce different kinds of lipids, hydrocarbons and other complex oils (Fig. 4). Currently biodiesel and the use of flue gas are the main approaches, but bioethanol, biomethane, and biohydrogen are also important end products that can be derived from algae (N. K. Singh & Dhar, 2011).

Algae is affectionately getting to be known as ‘green crude’ as biodiesel has been proven to work as a direct fossil fuel substitute (Bigelow, 2012a; Casey, 2011; J. Singh & Gu, 2010). Additionally, as examples, Sapphire Energy and LiveFuels are working to commercialize a hydrocarbon derived from algae which they claim can be a direct drop-in to existing motor gasoline engines and infrastructure (Bigelow, 2012a). This would remove the need for additional infrastructure investments making algae very attractive as a biofuel feed over other biofuels.

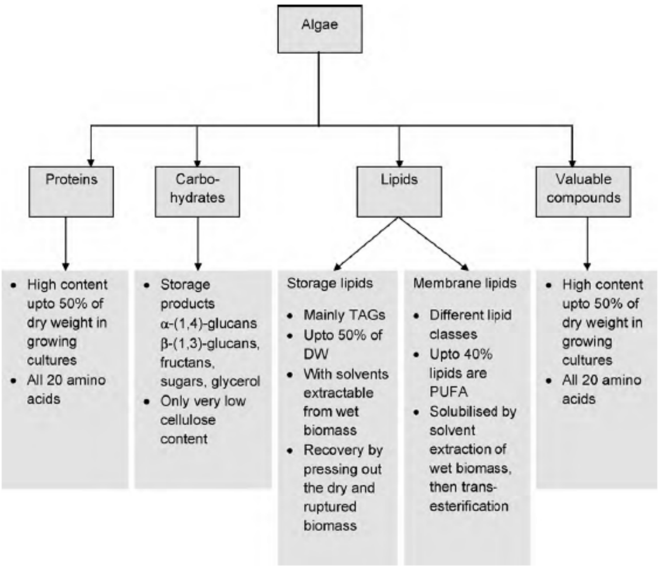


Figure 4. Overview of components of microalgae and potential end products (Singh & Gu, 2010)

3.4 Growth System Technologies

There are two main technologies presently employed to grow algae: open raceway systems and closed photobioreactor (PBR) systems. Both systems have benefits and drawback. Hybrids of the two systems that draw together the highlights of each are currently being designed and tested. Research also continues on alternative growth systems addressing not only issues of growth but also looking downstream into areas of biomass recovery. This is an important area of continued research for cost reductions in the algae biofuel production process.

3.4.1 Photobioreactor Systems

PBR systems are closed helical design tubes that allow for a more controlled growth environment ensuring the most efficient growth by keeping the proper temperature and feeding in the optimal level of any additional nutrients (Fig. 5). Also, PBRs can add additional CO_2 to the growth process which actually spurs algae growth. This closed system also ensures optimal growth by protecting algae from predators, foreign diseases and other strains of algae that might take over a pond (Bullis, 2012). However, PBRs continue to work out problems with toxic accumulation of oxygen, adverse pH and CO_2 gradients, overheating and high material and maintenance costs (Christenson & Sims, 2011).

One major drawback is higher capital costs than the raceway systems. Therefore, these PBR systems have been judged by many as unsuitable for large-scale biomass production because of the final theoretical selling price of the algae products. But, PBRs are viewed as having application for producing starter cultures for biofuel strains (Lundquist, Woertz, Quinn, & Benemann, 2010).

Figure 5: Photobioreactor system (“Web page: Harry Ried Center for Environmental Studies, Biofuels from Microalgae,” n.d.)

3.4.2 Open Raceway Systems

Open raceway systems are the most common large scale production systems and are shallow ponds in a raceway shape with a paddle wheel to provide continual circulation of the algae, water and nutrients (Fig. 6). Raceways require lower upfront capital expenditures than PBRs and also are relatively less expensive to operate but have the issue of lower productivity due to contamination and poor mixing. They also have a less efficient use of CO_2 compared to the PBR system because the system is open to the atmoshpere. CO_2

remains in equilibrium between the water in the pond and the atmosphere meaning there is no possibility to feed additional CO_2 into the system to stimulate growth as can be done in the PBR system (Christenson & Sims, 2011). The openness of the system has motivated research on disease resistant strains such as the strain used by Sapphire Energy bred to grow under harsh conditions such as high pH or salinity that other organisms can't tolerate (Bullis, 2012).

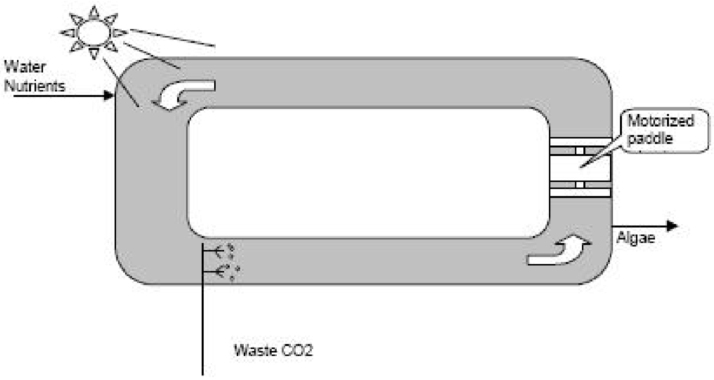


Figure 6: Open raceway system illustration ("Web page: Cultivation of algae in open ponds," n.d.)

3.5 Harvesting and Extraction

Both growth methods require harvesting algae by separating the algae from the water it grows in. Current methods include biological methods as well as chemical, mechanical and electrical based operations. This step remains a hurdle at the industrial scale processing partially due to the small size of algae. Also, due to the small size of algae, large volumes of water must be processed during harvesting. As a result, harvesting alone has been estimated to contribute 20 to 30% of the total cost of producing the biomass (Christenson & Sims, 2011) (N. K. Singh & Dhar, 2011).

Li, Horsman, Wu, Lan & Dubois-Calero (2008) also argue the harvest of algal biomasses could be relatively costly. Processing requires drying which could be expensive due to time and energy costs associated with the large water content of harvested algal biomass. But, the authors believe these problems can be overcome or mitigated as technology develops.

Oil extraction requires breaking the cell walls to extract the lipid. Currently solvent extraction shows to be the most economical method. Other methods are under development and this remains a target area for cost reductions (Lundquist et al., 2010).

3.6 Resource Inputs To Growth Systems

3.6.1 Water

Algae use water as the growth environment. This is a serious consideration for scale-up as it does take about 1,000 grams of water to grow 1 gram of dry weight algae (Bullis, 2012). However, many researchers don’t conclude this to be an issue. This is because one attractive property of algae is that many strains will grow in dirty non-drinkable water or saline water (A. Singh et al., 2011). As a result, algae growth need not compete with drinking water.

In fact, algae growth has been proven to act as a water purifier during the growth process. Thus, wastewater treatment has the potential to act as an added value co-product of algae growth. In many cases water runoff, especially from farming, has an excess of nitrogen and phosphorus which must be treated or can lead to downstream ecosystem damage. Chemical treatment can be costly and lead to secondary contamination. Algae treatment shows the potential to be a less costly and ecologically safer way to treat water as well as benefit from resource recovery and recycling. There is also the potential to save on fertilizer costs for the algae. However, challenges remain regarding the implementation of a large scale integrated system as well as incorporating harvesting (Christenson & Sims, 2011).

3.6.2 Land Use

Algae growth systems can be built anywhere meaning they can be built on marginal land or in industrialized areas (Renaud, 2011). This means growth systems can be built on inexpensive and non-crop producing land. Therefore, algae production need not compete with food growth and production. Algae technology thus evades the food vs. fuel debate. Algae may also have the potential to reverse the need for more agricultural lands as the co-production of animal feed is explored. The biomass remaining after lipid extraction may find a market replacing many land-intensive crops used for animal feed.

3.6.3 Review of Resource Availability in the United States

Wigmosta, Coleman, Skaggs, Huesemann & Lane (2011**)** find that using current technology, microalgae has the potential to generate 200 x 109 L yr^{-1} of oil which is equivalent to about 48% of the current U.S. petroleum imports for transportation. Overall the natural resources needed, namely water and land, to reach this amount of production are available with proper planning. The authors also find locations in the Gulf Coast region of the U.S. are the most favorable. Wigmosta et al.'s research goes on to explain not only does algae have many attractive physical aspects, but it also looks to be feasible based on the resources available. Therefore, the availability of natural resources does not seem to be a major barrier contributing to algal biofuels adoption in the U.S.

Sheehan et al. (2008) also conclude the resource limitations should not be an argument against microalgae biodiesel systems. They find many potential land, water and CO_2 sources available. In fact, algae have the potential to provide substantially more biodiesel than existing oilseed crops while, at the same time, using less land and water inputs (Christenson & Sims, 2011).

However, Lundquist, Woertz, Quinn & Benemann (2010) believe the availability of the aforementioned required resources for microalgae production found at the same site will likely limit the US potential for algae production. They believe the maximum production potential to be a few billion gallons annually, minor in comparison to the total consumption of total liquid fuel consumption by the transportation sector in the U.S., around 200 billion gallons per year given the current technology (Lundquist et al., 2010).

3.7 Life Cycle Assessment

Reports note an adequate life cycle assessment (LCA) of biofuel production from algae as a feedstock is still not available (A. Singh et al., 2011). Studies to date lack data from a commercial plant, amongst other limitations and, therefore, it's difficult to report on the energy balance of the algae production lifecycle. Steps in the production process requiring energy inputs are growth, harvest, separation of lipid from biomass, transportation to refining, refining, and transportation for distribution. The harvesting step, removing the algae from the water, requires the largest amount of energy in the production process (Sander & Murthy, 2010).

Sander and Murthy (2010) study two processes for producing algae biodiesel, a ‘filter press’ and ‘centrifuge’ process. Both processes produce a net positive energy balance, more energy produced than used for production. However, they find CO_2 emissions to be overall negative in the centrifuge process. A handful of other studies do not speak positively for algal biofuels over the oil obtained from other terrestrial crops. All note the need for improved process efficiencies as a main source for improved LCA results.

Singh and Gu (2010) find net energy ratios, as calculated using the formula below, for flatbed PBRs and raceway ponds to be positive.

$$\text{Net Energy Ratio} = \frac{\sum Energy\ Produced(lipid\ or\ biomass)}{\sum Energy\ Requirements}$$

Xu, Brilman, Withag, Brem and Kersten (2011) study the ‘fossil energy ratio’ (FER), the ratio of the energy content of the final product to the amount of fossil energy needed to make the fuel, of various energy sources. The authors find biofuel from microalgae, not taking into account any added value from the generation of ‘co-products,’ in a range of 1.37-1.50 illustrating algae’s energy output is higher than the fossil fuel input used to grow and process the microalgae. As a reference, corn ethanol’s FER is reported at 1.34 (Fig. 7).

Biofuel	**FER**
Corn Ethanol	1.34
Algae biofuel (no co-production)	1.37-1.50
Algae biofuel (coupling waste heat)	2.38

Figure 7: Fossil energy ratio of ethanol and algae biofuel

Additionally, the study shows that coupling waste heat into the process increases microalgae end fuel product FER to 2.38 which they comment is higher than the FER of other 1st generation bio-diesel (Xu, Brilman, Withag, Brem, & Kersten, 2011). The study concludes a significant energy balance can be achieved regardless of algae growth and processing systems.

However, LCA’s should continue to be explored as more information becomes available.

3.8 Real Potential For Cost Reductions

There are many targets for cost reductions mentioned in the sections above. Applying theory, these cost reduction are generally classified into categories of ‘learning-by-researching’ or ‘learning-by-doing’. The main areas for potential costs reductions for algae biofuel are summarized below. The following sections also provide the support for why the experience cost curve can be applied in our economic analysis.

3.8.1 Learning-by-researching

Many point out the primary need to identify algae strains generating a high lipid content that will also grow quickly to produce biodiesel, bio-crude and drop-in fuels. Studies on small scale production show if algae producers are able to use strains that garner 60% lipid content, many current studies use 25-40% as a conservative estimate, they can reduce the size and footprint of necessary production systems by as much as half. This would result in lower overall capital cost expenditures as well as reduce operating costs (J. Singh & Gu, 2010).

However, lipid generation and productivity are often inversely related. As a result, researchers are seeking to identify optimal growth conditions by using nutrient deprivation or other stresses to induce a natural lipid trigger while, at the same time, maintaining high productivity. Researchers are working to understand these processes better as well as work with genetic manipulation for simultaneous rapid growth and high lipid content (Christenson & Sims, 2011).

Increasing lipid yield also has the potential to reduce the environmental effect per unit of biofuel produced (*Renewable Fuel Standard: Potential economic and Environmental Effects of U.S. Biofuel Policy*, 2011).

There’s optimism in the increasing lipid productivity via metabolic engineering and systems biology. A significant aspect of algae and second generation microalgal systems is their amenability to highly innovative biotechnology approaches. R&D of this nature provides potential for rapid improvement (N. K. Singh & Dhar, 2011). Research in algae biofuel is truly a marriage of agriculture and biotechnology.

3.8.2 Learning-by-doing

Progress in the growth, harvesting and oil extraction processes of the algae biofuel production process is essential to continue to bring the production cost-per-unit down. Singh and Gu (2010) point out capital and operational costs, costs of drying and extraction and development work to increase productivity by discovering more efficient harvesting systems as key issues to address moving forward. Separate from processes improvements, researchers are employing genetic and metabolic engineering of microalgae strains as a mechanism for harvesting improvements in addition to lipid productivity (Christenson & Sims, 2011).

As an example, Sapphire Energy is already employing process improvements in their test facility. They have found ways to reduce costs by building cheaper ponds out of dirt and waterproof liners as opposed to concrete ponds. Future plans are to do away with liners and make ponds that resemble rice paddies. They also mention plans to do away with energy-intensive paddle wheels used to circulate algae in favor of a system that uses only the wind sweeping across the New Mexico desert for circulation (Bullis, 2012).

Additionally, some strong supporting evidence in the notion that time and cumulative production will bring current cost-per-unit of production down, a recent study from the University of Illinois finds that learning-by-doing, fostered by an increase in ethanol production, aided in prompting technological progress in the ethanol industry. The study finds factors such as economies of scale, learning-by-doing, induced technological innovation as a result of rising input prices and trade-induced competition were leading factors in reducing the processing costs of corn ethanol in the U.S. by 45 percent while also increasing production volumes seventeen-fold from 1983 to 2005 (“Policies, learning-by-doing played important role in reducing ethanol costs,” 2012).

3.8.3 Summed Up

The combined effects of learning-by-researching and learning-by-doing in reducing production costs of algae biofuel are summed up in a real world example of Sapphire Energy. The company has stated they hope to lower the cost of producing algae fuels by ‘changing every part of the production process.’ They envision this as increasing the quality and amount of oil produced from their algae strains, reducing the cost of building ponds in addition to developing low-cost ways to harvest the oil. They are currently building out their test facility to a commercial demonstration facility (Bullis, 2012).

4. Cost Economics of Algae

While many consider the biological features of algae attractive to pursuing biofuel production, cost economics remains a significant issue. A handful of studies have been carried out in an effort to estimate potential per gallon costs of algae biofuel as a means to assess if algae will eventually reach cost parity with fossil fuels.

There are a range of costing reports based on a mix of input assumptions and a small amount of actual data available adding complexity to accuracy and bringing an additional level of necessary discernment. Fishman et al. (2010) argue the economic analysis continues to be challenging due to R&D and variable cost inputs of water, land, energy prices, carbon credits and the question of ability to amortize over economies of scale. However, there are indications from many studies that a combination of improved biological productivity and fully integrated production systems can bring the cost down to a point where algal biofuels can be competitive with petroleum at around $100 per barrel.

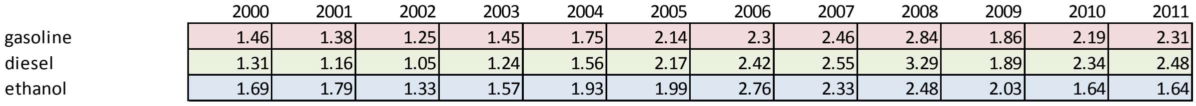
4.1 Petroleum Prices in the United States

As a starting point for looking at the projected per gallon costs of algae, it’s important to have perspective of the current marketplace and the current cost in dominant liquid fuel technologies of motor gasoline and diesel in the United States. These costs provide reference and aid in understanding of the estimated per gallon cost of production of algae biofuel. These costs also show the possible cost of production gap between fossil fuels and algae based fuels and will be employed to assess the possible net investment necessary in algae research and production.

4.1.1 Current Prices without Federal and State Taxes

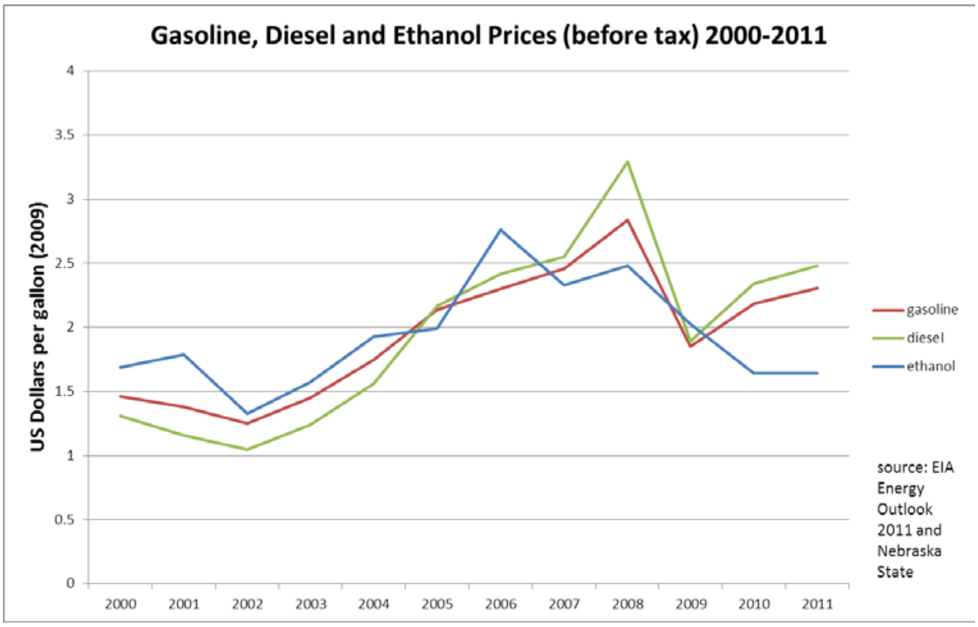
Figure 8 shows prices for each liquid fuel source after federal and state taxes are removed. Data on pricing was collected from the U.S. Energy Information Administration (EIA) for years from 2000 to 2011 reported in 2009 dollars (Fig. 8). Prices were reported in prices paid at the pump. Average federal and state taxes, as reported by the American Petroleum Institute (API), were subtracted. This provides the resulting prices without taxes and reflects the cost of incumbent technologies unencumbered by taxes. Nominal wholesale ethanol prices were collected from the state of Nebraska and corrected for 2009 dollars.

As a note, the combined federal and state excise tax on petroleum products has remained relatively unchanged since 2000 with about a $0.10 average overall increase in the middle of the decade (American Petroleum Institute, 2012). The federal excise tax on gasoline and diesel has reminded unchanged at 18.4 and 24.4 cents respectively since 1997 (American Petroleum Institute, 2012, U.S. Energy Information Administration, 2012). So, the minor increase in tax has come at the state level. Overall, the tax portion of the total price paid at the pump has decreased over the decade as wholesale prices have increased.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
gasoline	1.46	1.38	1.25	1.45	1.75	2.14	2.3	2.46	2.84	1.86	2.19	2.31
diesel	1.31	1.16	1.05	1.24	1.56	2.17	2.42	2.55	3.29	1.89	2.34	2.48
ethanol	1.69	1.79	1.33	1.57	1.93	1.99	2.76	2.33	2.48	2.03	1.64	1.64

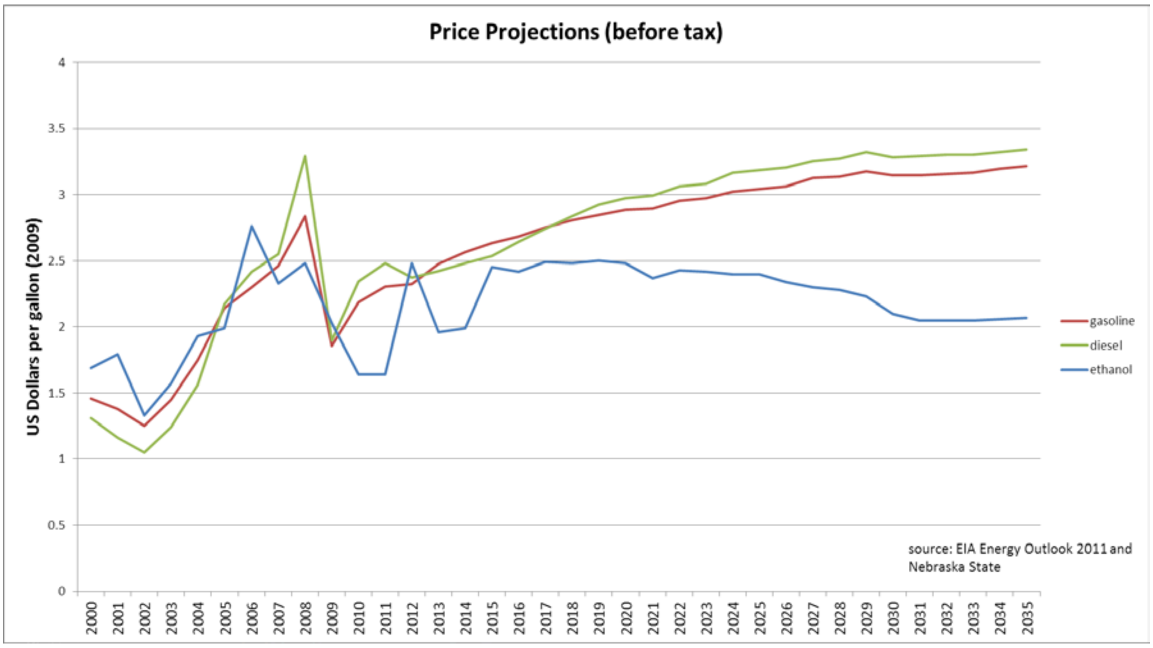
Figure 8: Summary of U.S. prices (without tax) of Gasoline, Diesel and Ethanol



Graph 1: Average gasoline, diesel and ethanol prices without taxes 2000-2011

4.1.2 Price Projections to 2035

The end of the decade saw marked price increases in liquid transportation fuel prices. Many suspect fossil fuel based fuel prices will continue to climb, albeit at a low rate. As a reference for possible growth, the base case from the Energy Information Administration Annual Energy Outlook 2011 show both gasoline and diesel increasing at about 1.8% annually (Graph 2). The base case assumes no change from current day policy and generally business as usual. In this scenario, gas and diesel reach \$3.22 and \$3.34 gallon^{-1} respectively by 2035 (without tax and in 2009 dollars).



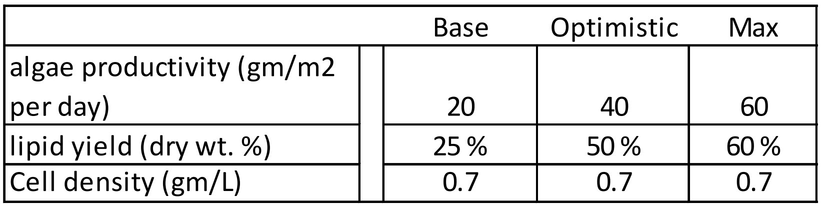
Graph 2: Gasoline, diesel and ethanol price projections to 2035

4.2 Projections of Algae Biofuel Per-Gallon-Cost

Studies to date offer a wide range of possible cost per gallon based on scale effects and input costs. The Aquatic Species Program (ASP), a program funded by the U.S. government in the 1990s and carried out by National Renewable Energy Laboratory (NREL), projected the cost of microalgae oil production able to reach a range from \$39 to \$127 bbl^{-1} (barrel of oil) based on different scenarios of inputs (Sheehan, Dunahay, Benemann, & Roessler, 1998). Huntley and Redalje (2004) conducted costing research on a small scale and concluded algae oil production costs to be around \$84 bbl^{-1} assuming no improvements in current technology. Assuming 40 gallons in a barrel, these per gallon costs range from \$0.98 to \$3.18. Gallagher (2011) looks at capital costs and productivity per hectare (ha) provided by four studies and arrives at a cost of about \$4/gallon.

Sun et al. (2011) provide the most comprehensive analysis. They outline a consistent framework for costing inputs across a dozen public studies in an effort to make the studies more reasonably comparable and re-run the studies. This allows for a comparative cost analysis of algal oil production with the goal of identifying a more reasonable, and smaller, range of cost per gallon of production. Indeed, a smaller range providing better insight on the feasibility and viability of large-scale algae biofuel production. Initially studies report a range from \$0.92 to \$42.60 gallon^{-1} before harmonization. The post-harmonization range of oil production costs is from \$10.87 to \$13.32 gallon^{-1} based on conservative ‘base case’ assumptions about algae productivity and lipid content.

The ‘base case’ analysis, based on currently achievable and conservative lipid and productivity assumptions, serves as a starting point for the study. The study also reports two sensitivity analyses based on more optimistic lipid content and production yields. The assumptions used for each scenario are outlined in Figure 9.



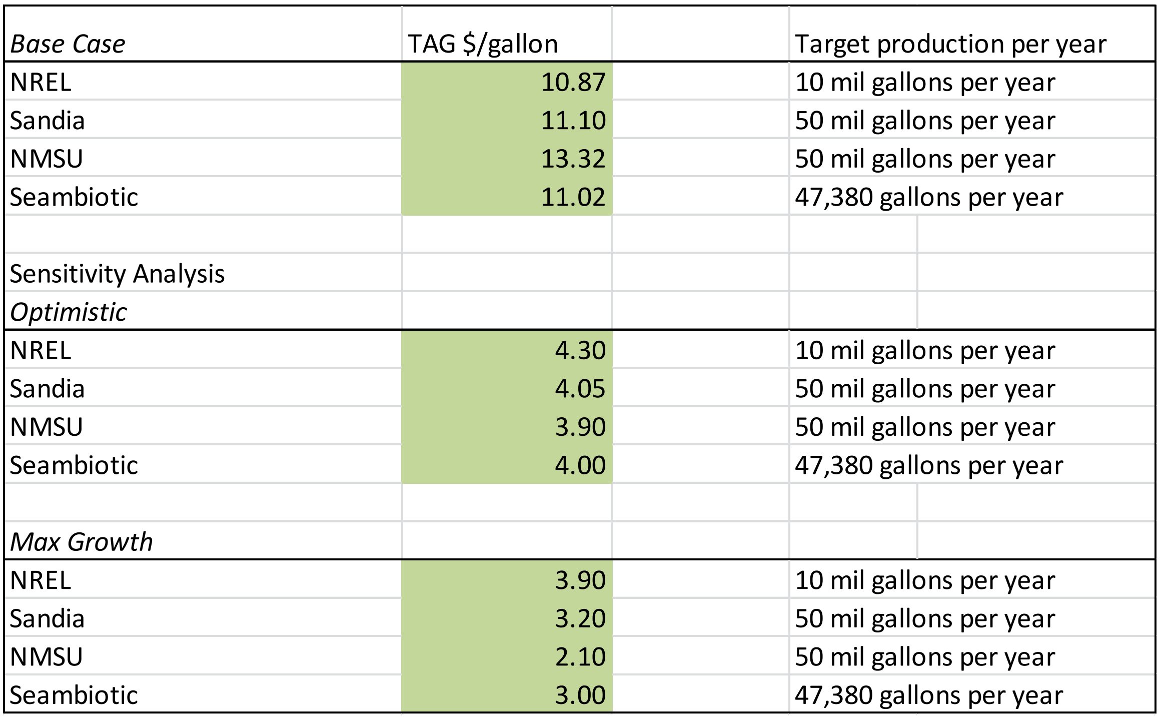
	Base	Optimistic	Max
algae productivity (gm/m2 per day)	20	40	60
lipid yield (dry wt. %)	25 %	50 %	60 %
Cell density (gm/L)	0.7	0.7	0.7

Figure 9: Parameters used for each scenario in Sun et al’s cost harmonization

The ‘base case’ parameters of algae productivity and lipid yield are very realistically achieved with today’s technology. 25% lipid yield is on the conservative side when lipid yields are observed at 20-75% of total biomass dry weight (J. Singh & Gu, 2010). Algae productivity is also reported between 14-40 grams/meter^2/day (gm/m^2 per day) with many strains showing over 20 grams/meter^2/day of biomass productivity (Park, Craggs, & Shilton, 2011)

The base case scenario would yield approximately 2,100 gallons (8,400 liters) of oil acre^{-1} year^{-1} (Lundquist et al., 2010). But, many studies and companies report higher yields per acre currently indicating productivity and lipid content are exceeding base case scenario assumptions. Thus, the optimistic and max case per gallon cost results should be considered as a real possibility as research continues.

Using the aforementioned parameters and assessing reliability of inputs across the studies collected, Sun et al. (2011) highlight four of the twelve studies in their cost harmonization: National Renewable Energy Laboratory (NREL), Sandia National Laboratories, New Mexico State University and Seambiotic (an industry source). The harmonized costs are reported on a TAG per gallon cost (Fig. 10). Many studies note refining is a minor component of the total overall cost. Therefore TAG cost per gallon is representative of the overall cost-per-gallon (Huntley & Redalje, 2007; Sun et al., 2011). The authors point out scaling up to large volume can vary by geo-location and by technology.



Base Case	TAG $/gallon		Target production per year
NREL	10.87		10 mil gallons per year
Sandia	11.10		50 mil gallons per year
NMSU	13.32		50 mil gallons per year
Seambiotic	11.02		47,380 gallons per year
Sensitivity Analysis			
Optimistic			
NREL	4.30		10 mil gallons per year
Sandia	4.05		50 mil gallons per year
NMSU	3.90		50 mil gallons per year
Seambiotic	4.00		47,380 gallons per year
Max Growth			
NREL	3.90		10 mil gallons per year
Sandia	3.20		50 mil gallons per year
NMSU	2.10		50 mil gallons per year
Seambiotic	3.00		47,380 gallons per year

Figure 10: Baseline and sensitivity results for cost per gallon of TAG production

The ‘base case’ parameters find that, at a scaled quantity, algae biofuel should be able to be produced at a cost of \$10-\$13 gallon^{-1}. This would be in the range of \$400-\$520 bbl^{-1} as compared to June 2, 2012 price of petroleum around \$85 bbl^{-1} which is down from just over \$100 bbl^{-1} in April 2012 (“Energy & Oil Prices,” 2012).

Under the ‘base case’ conservative assumptions, 10 million gallons of production per year (Fig. 10) would take just under 4,800 acres and 50 million gallons of production per year would take just under 24,000 acres. An international soccer (European football) field is about 2 acres. Manhattan in New York City is about 23 square miles (59 square kilometers) or 14,720 acres (Wikipedia contributors, 2012). Under conservative assumptions, less than two times the area of Manhattan could produce 50 million gallons of algae biofuel annually. Liquid fuel consumption in the United States was about 300 billion gallons in 2008 (Pate, Klise, & Wu, 2011).

The ‘optimistic’ case parameters are plausible today with current technology or in the near future with progress made in the lab and in the growth, harvesting and extraction process.

The likeliness of the ‘optimistic’ case is reflected by the fact that yields reported usually exceed 2,100 gallons $acre^{-1}$ $year^{-1}$ (Fig. 3). Research studies and companies working to commercialize algae biofuel report in the area of 4,500 to 7,000 gallons $acre^{-1}$ $year^{-1}$ (Pate et al., 2011; J. Singh & Gu, 2010). In the ‘optimistic’ case, around 2,000 acres would be required for 10 million gallons of annual production and as little as 7,200 acres for 50 million gallons annually. At these productivity and lipid rates, a land area the size of Manhattan with proper growing conditions could yield 100 million, or 1 billion, gallons of algae biofuel annually.

However, the cost economics at the ‘optimistic’ level still pose an issue. The four highlighted studies agree on around a \$4 $gallon^{-1}$ cost which equates to about \$160 bbl^{-1}. While this exceeds current barrel of petroleum prices, it isn’t far from 2008’s high at \$147 bbl^{-1} (\$149 adjusted to 2009 dollars when the study was conducted) (Khan, 2009). \$4 $gallon^{-1}$ continues to exceed projected fossil fuel prices in the near future (Graph 2) bringing to light the importance of continued progress in learning-by-researching and learning-by-doing cost reductions.

The ‘max’ growth scenario is possible, especially as companies and research groups work on genetic engineering of algae growth properties. Additionally, companies are working on harvesting and extraction technologies and techniques which could contribute to cost reductions as harvesting alone is currently around 20-30% of biomass production cost. Should the parameters of the ‘max’ growth scenario be achieved, algae biofuel will be a game changing biofuel feed source due to cost competitiveness with fossil fuel prices and the attractive qualities garnered by its domestic production and more environmentally friendly properties. It will take continued investment in research and process learning as well as a supportive marketplace encouraging investment to reach these levels.

The Algal Biomass Organization (ABO), one of the leading trade associations for the algae industry, conducted a survey in February of 2012. The survey had 384 respondents, a good portion of whom are from companies that produce or research algae products for commercialization or university research laboratories. Just under 12% of respondents said it is extremely likely algae based fuels will be cost-competitive with fossil fuels in 2020 and 50% felt this was very likely or moderately likely (Algal Biomass Organization, 2012). However, these views should be taken with a dose of skepticism since cost reductions are in their best interests.

5. Experience Curve Model

A critical element of analysis of a new technology is to attempt to quantify what magnitude of investment could be needed to increase production such that costs reduce to a point of cost parity with incumbent technologies. In this case, studies show cost parity of algae oil and petrol oil is possible but advances in algae production need to be made. Current economics might not make sense, but studies show promise to reductions in cost per unit production as the technology matures. What might it take to get there?

McVeigh, Burtraw, Darmstadter and Palmer (1999) evaluate the performance of renewable energy technologies. They find renewable energy technologies have meet or exceeded expectations with respect to their cost reductions over time. They find costs have, in general, fallen as projected and have sometimes even exceeded projected deadlines. This provides support for our application of the experience cost curve in this study.

We can employ an ‘experience curve’ as a tool for measuring potential investment needed. It’s been established that cost reductions can be achieved in the per-unit-cost of algae biofuel production by finding efficiencies in lipid production (learning-by-researching) as well as in efficiencies in the harvesting and lipid extraction production process (learning-by-doing). As a result, the experience curve and ‘learning ratio’ mechanism are sound tools to produce rational estimates about the potential investments necessary and the amount of production that may need to be supported to reach a level closer to, or at, cost parity with fossil fuel sources. An important element of the experience cost curve is it provides insight on the magnitude of the potential investment necessary.

5.1 The Model: Data Inputs

5.1.1 Assumptions

This model will use real world market information from recent U.S. Naval purchases of algae biofuel as a basis for analysis. The amount paid per gallon of fuel is the only public information found and is, therefore, used as a proxy for the cost per gallon of production. This is acknowledged to be second-best to comprehensive information on costs. A handful of companies currently have test facilities running and are producing small amounts of crude and refined products for testing. However, their per gallon costs are not publically available.

Another assumption is the energy content per volume is about equal to that of fossil fuels. In this case, the end product purchased by the Navy is a biodiesel for use in ships. And, biodiesel is about 88 to 95% that of diesel but the fuel economy of both are generally comparable due to the improved lubrication of biodiesel (Gallagher, 2011). As a note, ethanol’s energy content is about 66% that of gasoline.

The separation of ‘learning-by-researching’ and ‘learning-by-doing’ is made in the previous sections to illustrate the real potential for efficiencies and cost reductions in both areas. This section combines the two when looking at the progress and learning ratio because this model is employing a one factor learning curve.

5.1.2 Base Case Cost and Cumulative Quantity Produced

At the end of 2011, the Navy purchased 450,000 gallons of algae biodiesel for $26.67 per gallon from Solazyme, a leading producer of algae biofuel (Mick, 2011). While the experience curve inputs are total quantity and industry cost per unit produces, the Solazyme case is used due to the fact there have been no other major public sales of algae biofuel. Most leading producers are still in the test facility phase and producing small quantities. As a result, the Solazyme sale is mostly representative of industry to date. The starting cost and quantity for the model are:

C_0= \$26.67
Q_0= 450,000

5.1.3 Learning Rate

In October 2010, the U.S. Navy purchased 20,055 gallons of algae biofuel at a reported cost of \$424 gallon^{-1} (Mick, 2011). This purchase was also from the company Solazyme. These numbers are not used as the input numbers for the ‘base case’ scenario for the simple reason that this study using a one period model. As theory shows, larger gains in biological and production efficiencies are made in the early stages. In addition, as this model does not allow for multiple periods, the dramatic decrease over this year would distort a one-period experience curve.

However, we can use these numbers for a basic extrapolation of an early learning rate for algae biofuel. We will use 500,000 gallons for total production assuming some biofuel has been produced in addition to the 20,055 starting gallons and the 450,000 current gallons.

We can back out an early learning ratio using:

C_0= \$424
Q_0= 20,055
C_1= \$26.67
Q_1= 500,000

$$26.67 = 424 * (500{,}000/20{,}055)^{-\alpha}$$
$$\alpha \approx 0.86$$

$$PR = 2^{-0.86} = 0.55$$
$$LR = 1-0.55 = 0.45$$

This learning rate represents the cost per unit of production decreasing by 45% each time the cumulative production quantity is doubled. As a comparable, corn production costs per ton saw a learning ratio of 45% from the period of 1975 to 2005 (Hettinga et al., 2009). But, in reference to other technologies, this is a large learning ratio. As we build the model, the early learning ratio derived provides some grounding and insights for learning ratios applied in the model.

The rule of thumb learning ratio from the theoretical framework is 20%. To error on the conservative side, our base-case will employ 15%. The sensitivity analysis will look at learning rates of 11% and 20%.

While this study is based on limited and early stage input information, results can be refined over time in this quickly moving development space. This model can remain current and up-to-date as it is created in excel and is easily updated when more data points become available.

5.1.4 Gasoline, Diesel and Ethanol per-gallon costs

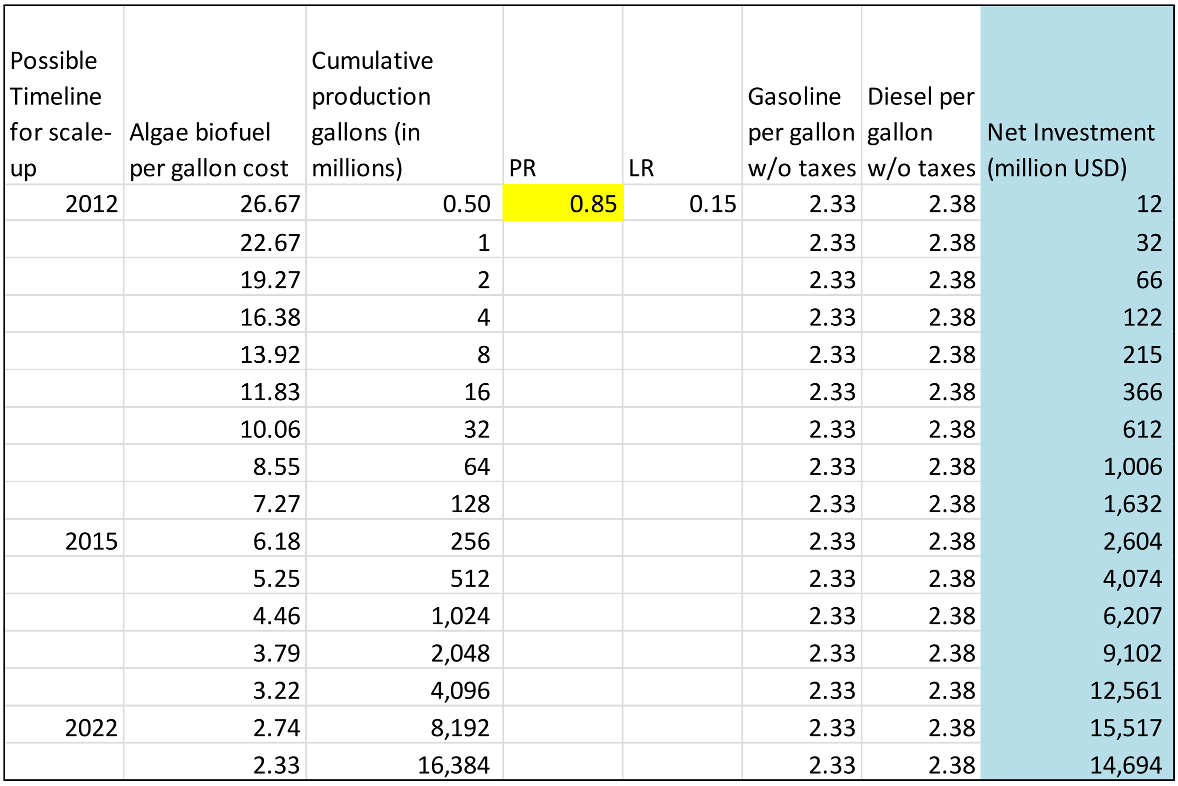
Values are added for 2 motor fuel liquids cost-per-gallon of production: motor gasoline and diesel. Market values from the Energy Information Administration (EIA) minus federal and state taxes, as shown in Chapter 4, are used to represent the cost per unit of incumbent technology. These values are held constant because we have not added a time element in the model since we do not know the timing of scale-up at present. While we estimate the value of fossil fuel prices to climb over time, we cannot say, with certainty, what the timeframe will be in our experience curve model.

The value of diesel is used in determining the net learning investment in algae biofuel in this analysis because the purchase made is biodiesel. Thus, petrol diesel is being displaced. The ‘learning investment’ required for the technology to reach the forecasted break-even point is the area between the experience cost curve and the cost of the incumbent technology (Alberth, 2008). Without algae biodiesel the amount of petrol diesel would still be paid. Therefore, this cost can be subtracted from the cost of algae biodiesel to show the net investment above and beyond the cost to purchase the same quantity of petrol diesel.

Gasoline is also included because this is another near term area algae companies are looking to compete. ‘Green crude’ can be refined to hydrocarbons as a substitute for petrol based gasoline. For this analysis, ethanol is not included.

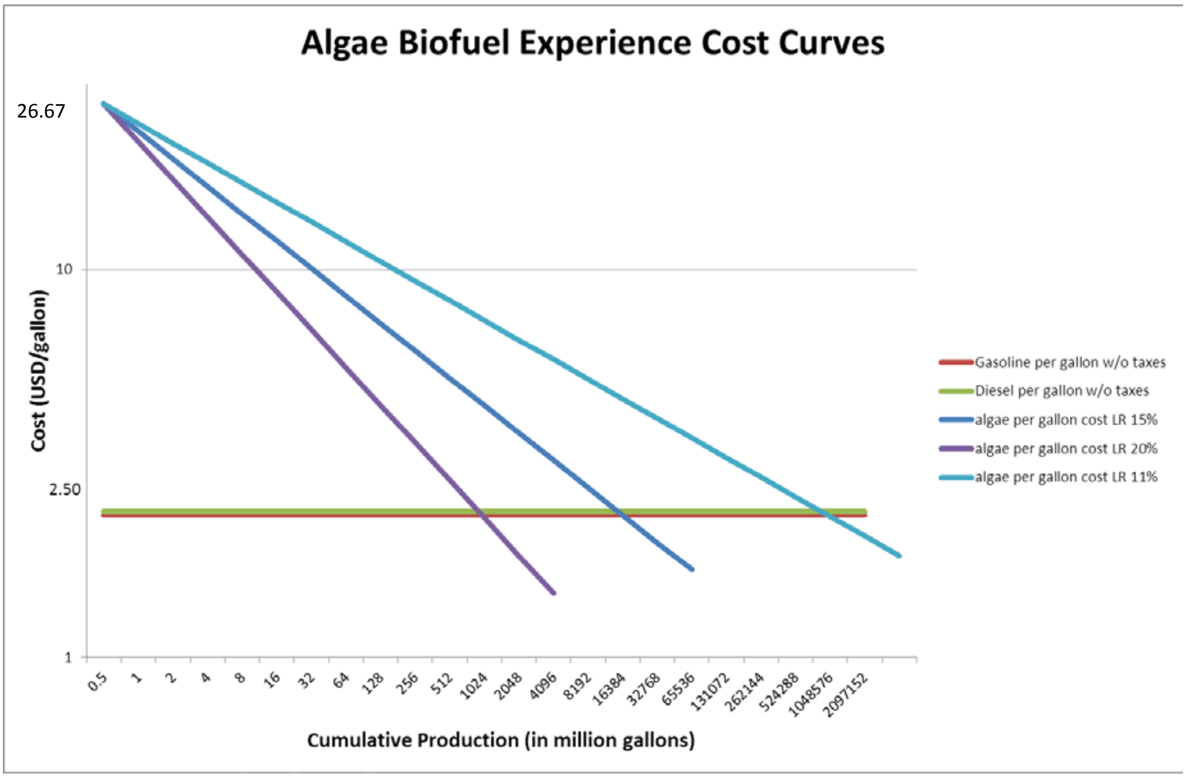
5.2 Results

5.2.1 Base Case Scenario: Learning Rate 15%



Possible Timeline for scale-up	Algae biofuel per gallon cost	Cumulative production gallons (in millions)	PR	LR	Gasoline per gallon w/o taxes	Diesel per gallon w/o taxes	Net Investment (million USD)
2012	26.67	0.50	0.85	0.15	2.33	2.38	12
	22.67	1			2.33	2.38	32
	19.27	2			2.33	2.38	66
	16.38	4			2.33	2.38	122
	13.92	8			2.33	2.38	215
	11.83	16			2.33	2.38	366
	10.06	32			2.33	2.38	612
	8.55	64			2.33	2.38	1,006
	7.27	128			2.33	2.38	1,632
2015	6.18	256			2.33	2.38	2,604
	5.25	512			2.33	2.38	4,074
	4.46	1,024			2.33	2.38	6,207
	3.79	2,048			2.33	2.38	9,102
	3.22	4,096			2.33	2.38	12,561
2022	2.74	8,192			2.33	2.38	15,517
	2.33	16,384			2.33	2.38	14,694

Figure 11: Experience model results at LR 15%



Graph 3: Log representation of experience curves

Looking at Figure 11 and Graph 3, the experience curve is represented by the log scaled LR 15% line. The experience curve model shows an overall ‘learning investment’ for the base case of about $16 billion and a total cumulative production of around 12 billion gallons.

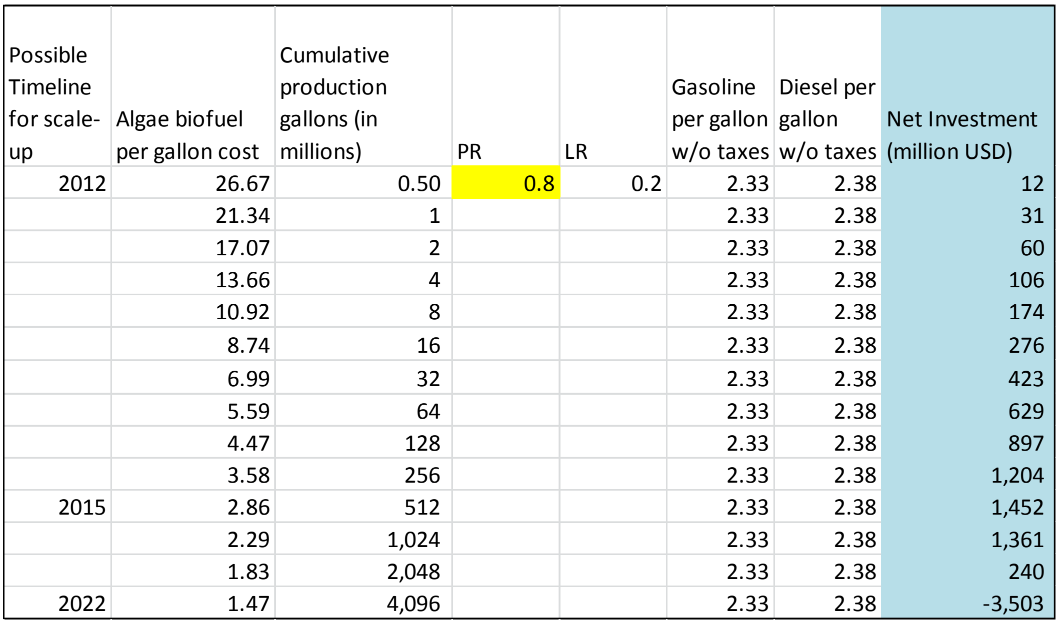
The left column of Figure 11 has been included as a general guideline as to when these production quantities might be possible. One study polled private algae biofuel production companies on their estimated production quantity by 2015. Summing their responses shows they believe they will be able to produce over 300 million gallons by 2015 (*Renewable Fuel Standard: Potential economic and Environmental Effects of U.S. Biofuel Policy*, 2011). Greentech Media predicts algae biofuel could be produced at a rate of 6 billion gallons per year by 2022 (“Algae industry: industry projections,” n.d.). A recent presentation by NREL also supported the idea 5 billion gallons of algae biofuel could be produced per year as of 2022 (Pienkos, 2012). In addition, the 2007 U.S. Energy Independence and Security Act (EISA) calls out a renewable portfolio standard with production of 36 billion gallons of biofuels by 2022 of which at least 21 billion gallons must be advanced biofuels (not- corn based ethanol). Many believe algae will help deliver a portion.

5.3 Sensitivity Analysis

The sensitivity analyses were conducted by changing the learning ratio parameter input illustrating the effect and importance of continuing to achieve productivity and production efficiency goals in the algal production process.

These analyses also serve to show the importance of data input points and how the model will become more accurate over the life of algae biofuel as costing data and better progress rate and learning rate data are accumulated.

5.3.1 Optimistic Scenario: Learning Rate 20%



Possible Timeline for scale-up	Algae biofuel per gallon cost	Cumulative production gallons (in millions)	PR	LR	Gasoline per gallon w/o taxes	Diesel per gallon w/o taxes	Net Investment (million USD)
2012	26.67	0.50	0.8	0.2	2.33	2.38	12
	21.34	1			2.33	2.38	31
	17.07	2			2.33	2.38	60
	13.66	4			2.33	2.38	106
	10.92	8			2.33	2.38	174
	8.74	16			2.33	2.38	276
	6.99	32			2.33	2.38	423
	5.59	64			2.33	2.38	629
	4.47	128			2.33	2.38	897
	3.58	256			2.33	2.38	1,204
2015	2.86	512			2.33	2.38	1,452
	2.29	1,024			2.33	2.38	1,361
	1.83	2,048			2.33	2.38	240
2022	1.47	4,096			2.33	2.38	-3,503

Figure 12: Experience model results at LR 20%

The results from the optimistic scenario of a 20% learning rate show algae biodiesel reaching cost parity with petrol diesel at around 1 billion cumulative gallons of production and about $1.5 billion net investment. Graph 3 shows the log representation of the experience curve denoted by LR 20%.

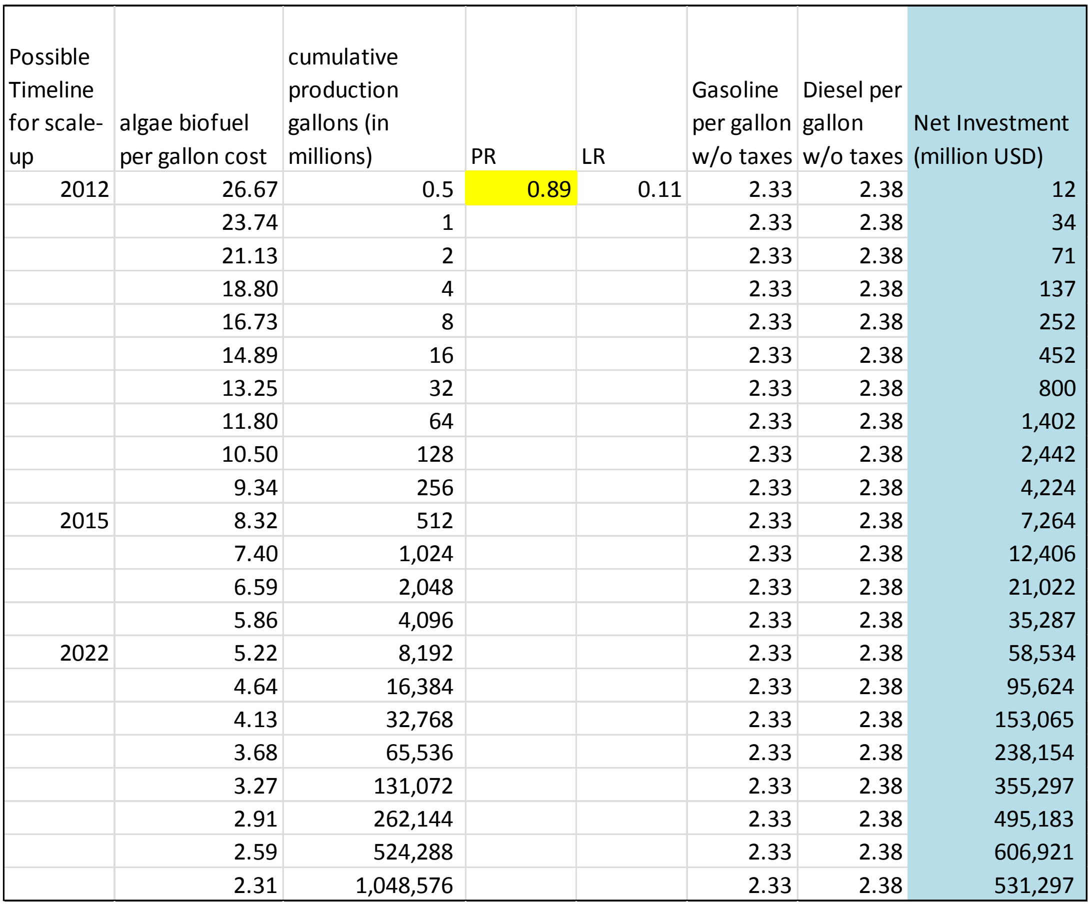
One reason a 20% LR is ‘optimistic’ for this study is because the major cost reductions implied by assigning a high LR will most probably be achieved by successes in genetic engineering to produce the ‘best’ strain of algae possessing a combined high lipid yield and high productivity. Continued research and funding for this research is needed to realize this aggressive biological progress. Inevitably, not all R&D spending will produce results.

Algae biofuel is working towards commercialization and has gained compelling interest in the recent past. However, it still has progress to make before it reaches the marketplace. This could stifle R&D investment which is needed for genetic engineering progress. Other renewable energy projects closer to the marketplace might be more enticing for investors looking for shorter payback periods and a better probability of success.

Additionally, research breakthroughs in algae could be firm specific and not made in the public space. In this case, Intellectual Property (IP) law rewards the investments of the firm but stifles the progress of the overall industry. Nonetheless, IP rights are necessary to incentivize industry investment in a technology with some hurdles to overcome to get to commercialization.

Taking all of these factors into account provides the rationale behind a 20% learning ratio as the ‘optimistic’ scenario.

5.3.2 Pesimistic Scenario: Learning Rate 11%



Possible Timeline for scale-up	algae biofuel per gallon cost	cumulative production gallons (in millions)	PR	LR	Gasoline per gallon w/o taxes	Diesel per gallon w/o taxes	Net Investment (million USD)
2012	26.67	0.5	0.89	0.11	2.33	2.38	12
	23.74	1			2.33	2.38	34
	21.13	2			2.33	2.38	71
	18.80	4			2.33	2.38	137
	16.73	8			2.33	2.38	252
	14.89	16			2.33	2.38	452
	13.25	32			2.33	2.38	800
	11.80	64			2.33	2.38	1,402
	10.50	128			2.33	2.38	2,442
	9.34	256			2.33	2.38	4,224
2015	8.32	512			2.33	2.38	7,264
	7.40	1,024			2.33	2.38	12,406
	6.59	2,048			2.33	2.38	21,022
	5.86	4,096			2.33	2.38	35,287
2022	5.22	8,192			2.33	2.38	58,534
	4.64	16,384			2.33	2.38	95,624
	4.13	32,768			2.33	2.38	153,065
	3.68	65,536			2.33	2.38	238,154
	3.27	131,072			2.33	2.38	355,297
	2.91	262,144			2.33	2.38	495,183
	2.59	524,288			2.33	2.38	606,921
	2.31	1,048,576			2.33	2.38	531,297

Figure 13: Experience curve results at LR 11%

This sensitivity analysis demonstrates the importance of algae continuing to reach production performance goals. Under the given assumptions, a learning ratio of 11% would require over $600 billion in net investment and over 500 billion total gallons produced. This shows that, should learning-by-researching and learning-by-doing achieve lower rates of productivity gains, algae could result in large overall sums to reach cost levels of fossil fuel based liquid fuels. In this case, investment in algae would likely slow in favor of other, more promising, alternative fuel and transportation technologies.

This analysis also demonstrates high non-linear sensitivity to learning rates when compared with the 20% learning ratio scenario.

Ultimately, as more data becomes publically available, more accurate ranges of investment needed and cumulative quantity produced can be generated.

5.4 Limitations of Model Design

An important element of the experience curve is the accuracy of data inputs and accuracy is achieved through access to historical data. Thus, one serious limitation of employing the experience curve, especially in this study, is limited access to historical data. In this case, and in the case of new technologies, we lack any real history over which to collect data. Algae biofuel is in early stages of production with few commercial facilities existing. Much of the current information about costs and potential is based on research done at a small scale. In addition, detailed information from private companies is not usually available. As observed by sensitivities to changes in learning ratio input, changes in value can have a significant impact on the resulting forecasted net investment required. Similarly, changes to the starting quantity or starting price can affect the results of the experience curve model.

A limitation for consideration is the fact that the experience curve and learning ratio are a measure of the overall industry, yet, the input data for the study is from one company. Learning curves and the learning ratio are estimates of what will customarily be a variable process for all producers. Variability will result due to things such as geographical location. And, these inconsistencies inevitably presented in the data pose a larger challenge in predicting and adjusting the learning ratio. Solayme’s sales to the Navy are the only known major sales of algae biofuel to date. So, they can, for this study, be representative of the industry. However, it is acknowledged their learning rate will likely be different from other companies in the industry (McDonald & Schrattenholzer, 2001). New input data can easily by input and new, more current, results can be reported as more companies ramp up to a scaled level and start making commercial sales.

In addition, the input parameter of the learning ratio limits the accuracy of any experience curve study. This is because the learning ratio is a best guess of the anticipated progress based on predictions. But, to date no one has discovered a way to completely and stably predict the phenomena of ‘progress’. The notion of improvement with experience is supported, but, in few instances, has a progress or learning ratio been forecast with precision (Dutton & Thomas, 1984).

Another limitation of this model is its simplicity. It gives a sense of the overall investment necessary. But, it does not give direction on where the investments should be made. As mentioned before, for simplicity of modeling the learning curve, we do not differentiate between learning-by-researching and learning-by-doing. But, in the case of algae biofuel, research shows large cost improvements to be made by finding or genetically modifying strains to produce a higher lipid content. In this respect, higher investment in R&D over process improvements could be important at this juncture. However, the learning curve gives decision makers no additional direction in this area.

Lastly, a limitation of the experience curve is the inability to add a time element. This limits the prospect to forecast rising prices of incumbent technologies used as the benchmark. For this study, rising costs in diesel over time, as predicted by the EIA, would have a positive reductive effect on the net overall investment in scaling up algae biofuel production. However, due to the inability to add a time element, based on the fact one cannot predict the timing of production scale up, diesel pricing remains fixed.

6. Discussion

A diverse mix of scientists, politicians and industry professionals are optimistic about the commercialization of algae biofuel, and the United States is in a promising position to move the technology forward. Schumpeter and Rosenberg illustrated the importance of natural, personnel and intellectual resources in technological development and change. The United States shows great potential and leadership in all three categories.

The state of algae biofuel generation today and projections using the experience cost curve show that biofuel from algae as a feed source will only happen in the near future, the next 10 years, if it is supported by investment from the public and private sectors. It will take substantial investment, perhaps in the ballpark of $15 billion, to reach economic feasibility, and progress rates should be monitored.

The first part of this chapter outlines underlying incentives driving private and public investment in algae biofuel research and development and process improvements. The next section illuminates various sectors or interest groups that might support the technology and why. The last part of this chapter outlines public policy measures that can be implemented to encourage the support of investment in the scale up of algae biofuel production.

6.1 Private Versus Public Incentives for Investment in Algae Biofuel

Investment in algae biofuel is investment predominantly in the R&D stage. Universities are working on algae strain development and are mostly funded through government supported grants. Private companies are working on many parts of the value chain from strain manipulation to production processes and are currently supported by a mix of government grants and private venture capital investments. It is important to understand the incentive drivers for public and private investors in a technology, such as algae biofuel, which is currently not profitable. As outlined in the theory chapter, public and private investment are defined by different intrinsic drivers. These differences effect who might invest in algae biofuel scale up and why.

In the case of algae biofuel, private investors are driven by the potential for large returns when algae biofuel reaches commercialization and scale. IP law is strong in the U.S. which generally protects investors by allowing them to reap the rewards of their upfront investment. The U.S. consumes a large amount of liquid fuel each year. As a result, there is huge market potential should algae biofuel become economically competitive and reach commercialization scale. In addition, there is international market potential for algae biofuel technology. IP law also provides the opportunity for technology developers to generate income by licensing or selling technology rights.

Public government investment in algae development as a biofuel potential is from the position of security of energy supply and potential for economic growth from more domestic fuel production. Both of these goals value the high social interest rate that realizing algae biofuel would provide society as a whole. Also, government investment in R&D works as a driver for private investment in R&D. Lastly, government R&D funding is important in the case of algae biofuel because the industry and timeline to scale up can benefit from spillovers generated by research conducted and published to the public.

In many cases, public and private investments support the same projects and firms working towards algae biofuel commercialization.

6.2 Potential Factions and Their Motivation to Support Scale Up

6.2.1 The Federal and State Government

History shows the government’s vital role in supporting new technology developments in their early stages. Due to high investment costs, stronghold of incumbent technologies, uncertain marketplace, and questions surround intellectual property right (IP) just to name a few issues, new technologies can face an uphill battle.

In the U.S. there is an increasing interest in energy independence and some interest in GHG emission reduction at both the federal and state level. However, with a slowly recovering economy, Climate Change and GHG emissions reductions are a more difficult value proposition.

The federal and state governments are also showing interest in reducing reliance on imported oil. One goal agreed upon in both conservative and liberal leaning states, thus a general consensus across the country, is to become less reliant on unstable governments for their primary energy source.

Another reason for interest in investing in algae biofuel development could be to support the domestic economy. In 2010, the U.S.'s trade deficit of goods and services was around $500 billion. Of that, net imports of petroleum accounted for about $265 billion, or around half the national trade deficit (The Information Technology & Innovation Foundation, 2011).

An attractive quality of algae based biodiesel and hydrocarbons to both the federal and state government is limited need for additional investments in infrastructure. Biodiesel produced from algae is said to act as a 'drop in fuel' functioning with existing fueling and driving infrastructure including refineries, reservoirs, pipes, vehicle tanks and engines. As an example, the U.S. Navy tested 20,000 gallons of algae biofuel as part of a 50-50 blend with standard marine petroleum fuel on a decommissioned destroyer to see if the fuel could be used as a drop-in replacement with no special equipment or procedures. A Logistics Center fuel officer explained (Casey, 2011):

> *"We use the same types of trucks, hoses and other pierside equipment to transfer the fuel, and no modifications are required either from a fueling perspective or on the shipboard side. It's going to be pretty amazing to see where these fuels take us in the future."*

The limited need for additional infrastructure is part of the value proposition in terms of limiting investment needed. It also provides the potential for mitigating public fear in supporting and adopting the technology. There is reduced opportunity for public debate such as the recent Keystone Pipeline project, a large construction project which was proposed to bring synthetic oil from Canada. Also, there is a comfort to consumers in the similarity of fueling process making them more apt to accept and adopt to change.

Multiple branches of the federal government currently support R&D programs in algae biofuel, especially the Department of Energy. Funding from the federal government typically comes in the form of grants, contracting and procurement or loan guarantees. Funding is awarded to both public and private firms and funding serves to support both basic research in the area of algae growth properties and strain development as well as private firms working on bioengineering, scaling up test facilities and who are working towards commercialization.

The U.S. Department of Energy (DOE) is a large supporter of energy research and has a dedicated group, Advanced Research Projects Agency-Energy (ARPA-E), to focus on creative 'out-of –the-box' energy, such as advanced biofuels. ARPA-E awards grant amounts ranging from roughly $400,000 to $9 million each. The group worked with a budget of just under $300 million in 2011 to support projects. While grants are an arms-length form of research support providing minimal supervision, ARPA-E reports they have annual performance metrics for program assessment. As they note, ‘the program’s performance measures and associated quarterly milestones will be reviewed and approves by the ARPA-E Director’ (Department of Energy- Advanced Research Projects Agency-Energy, n.d.). Energy projects in biofuels also find grant and loan-guarantee funding from the Department of Agriculture.

The DOE also offers a loan guarantee program initiated under the Energy Policy Act of 2005. The Loan Program Office provides direct loans and guarantees these loans, they agree to repay the borrower’s debt obligation in the event of a default, to eligible clean energy projects. This program is for technologies well on their way to being developed for commercial scale adoption so algae biofuel companies in more advanced stages are eligible. The loan program is meant for groups seeking $25 million and above. And the loan terms require full repayment over a period not to exceed the lesser of 30 years or 90% of the projected useful life of the physical asset to be financed. Application fees insure seriousness of application. The application also requires multiple environmental impact assessment reports. The program is currently supporting a total in loans across technologies of $34.7 billion around the U.S. (“U.S. Department of Energy Loan Programs Office,” n.d.).

California is a leading state showing support of algae biofuel development. The San Diego Center for Algae Biotechnology (SD-CAB) is a consortium of researchers and businesses supporting algae biofuel’s commercialization based in San Diego, CA. They have received funding from the state government with the purpose of training and educating both blue and white-collar workers to be prepared for the algae biofuel production process. This is a unique way to build strength in the overall industry without picking direct winners which can happen when awarding funding to companies directly. Funding such as the SD-CAB program shares the liability of industry development with private companies. It also plays the important role of signaling investors that the state is motivated to support the development of the industry. California also amended State Assembly Bill 642 on June 4, 2012 which now reads (Calderon, 2012):

‘This bill would enact the Salton Sea Stabilization and Agricultural Cultivation Act, which would authorize the Secretary of the Natural Resources Agency to establish an Algae Production Program in the Imperial Valley to meet high-priority economic and environmental goals, expedite regulatory application and review processes, and provide grants to facilitate research and the commercial development of algae for fuels, foods, medicines, and clean water within the state.’

6.2.2 The United States Military

The armed services could support development of algae biofuel by being an early customer ensuring a marketplace and acting as a proving ground building consumer equity in the product. The Navy has already shown leadership by moving forward with their ‘Great Green Fleet’ and Navy Secretary Ray Mabus has made declarations of using 50 percent non-petroleum based fuel by 2020.

The military is the largest single consumer of fossil fuel based transportation fuel in the United States so they hold particular interest in the future of transportation technology. They are especially interested in the predictability of pricing which a domestic biofuel such as algae could offer. When oil prices go up even $1 per barrel, it equates to a $31 million increase in fuel costs to the U.S. Navy reports Navy Secretary Mabus (Casey, 2011). Mabus contends this is grounds to explore alternatives, even if they don’t make sense right now. As he stated at a Senate hearing in March 2012,”when anyone says we can’t afford to invest in developing alternative sources of energy, my reply is, ‘We can’t afford not to.’ We can’t afford to wait until price shocks or supply shocks leave us no alternative” (Casey, 2011).

Algae has found a big supporter in Mabus. His farsighted leadership poised the Navy to purchase $12 million in algae biofuel at the end of 2011, a small line item out of the Department of Defense’s annual budget of around $550 billion (Casey, 2011). He has been unapologetic about supporting new technologies that cost more in the near term. “If we made all of our decisions on the cost of a new technology, we wouldn’t have nuclear submarines today. We wouldn’t have nuclear carriers today. We wouldn’t have computers today because they’re a lot more expensive than typewriters,” he said in an interview (Stewart, 2012). In his view, the Great Green Fleet doesn’t have an environmental agenda.

It’s about maintaining America’s military and economic leadership across the globe in the 21st century.

This draws parallels with Winston Churchill’s action to move the British Royal Navy from coal to petroleum after his insights into the costs of efficiencies of petroleum on the brink of World War I. Churchill, who was the chief of the British Navy at the time, prodded the government to support a new oil discovery in Persia. As a result, the British government became the largest stakeholder in the Anglo-Persian Oil Company (Tharoor, 2010). This action was instrumental in supporting the beginning of the company now known as British Petroleum, BP. Many parallels could be drawn to Mabus and the U.S. Navy, a current day global military power, should they continue support of algae biofuel discovery.

The U.S. Air Force has also expressed great interest in the development of alternative fuels resulting from the branch spending over $8 billion each year on jet fuel. Most of the fuel purchased is fossil fuel based and from foreign countries. They report active development and testing of new biofuels as part of their mission. Discovery of a fuel that could be produced domestically would save the Air Force billions of dollars annually (Franklin, 2012). Although, the Air Force does not call on algae specifically. Rather, they are ‘feedstock agnostic’.

6.2.3 Aviation

Aviation might be a particularly interesting niche for algae biofuel for two main reasons. First, it is one of the few biofuels feed sources which can be refined to a kerosene jet fuel drop in. Ethanol cannot be used in jet engines currently while oil based fuels, such as algae, can. The below freezing temperatures of high flying altitudes would cause the water in ethanol to freeze. United Airlines successfully flew a jet, without passengers, from Houston, Texas to Chicago, Illinois powered by an algae jet fuel mix in November 2011 (“United enters the biofuel age,” 2011).

Second, aviation technology is not characterized by rapid technological change. Generally it takes at least one generation of new aircraft before new technologies are integrated. The design and certification period takes approximately 10 years and a design life for a plane is around 30 years. Therefore, it can take up to 40 years to implement a new technology in aviation (Kivits, Charles, & Ryan, 2009).

Research and industry are showing kerosene as a promising niche for algae. Lundquist et al. (2010) believe renewable algae oil could be a major contributor to biofuel resources, particularly in specific markets, such as aviation fuel. (Lundquist et al., 2010) And, FedEx, a global freight shipping company, mentioned their desire to use algae as their alternative jet fuel of choice. They deploy almost 700 planes daily and see the fluctuations in petroleum prices as a real business risk (Ydstie, 2012). Kerosene hit $4.08 per gallon in July of 2008, a large jump from $2.19 in July of 2007 (U.S. Energy Information Administration, 2012). A locked in price of domestically produced algae based kerosene would be a welcomed reduction to pricing uncertainty.

6.2.4 Wastewater Treatment

Sheehan et al. (1998) find that focusing on long term energy displacement goals will slow down development of algae technology. This report believes a more balanced approach including near term opportunities should be included which will help launch the technology into the technological arena, for example, wastewater treatment. The economics of algae technology are much more favorable when it is used as a waste treatment process and as a source of fuel. Coupling ‘high rate algal ponds’ with wastewater treatment is reported to cover the costs of algal production and harvesting thereby reducing capital and operating costs (Park et al., 2011)

In addition to a positive impact on the cost economics of algae production, coupling with wastewater treatment has positive environmental benefits decreasing the environmental footprint. Wastewater treatment utilizes chemicals to clean the water which could be replaced by algae as one means to reduce environmental impact. Additionally, using wastewater for growth will reduce impact in terms of water footprint (Park et al., 2011).

6.2.5 The Oil Industry

Mascerelli (2010) reports in Environmental Science & Technology that oil industry giants such as ExxonMobil Corp, BP and Chevron Corp have made recent major investments in companies seeking to develop renewable fuels from algae, pushing the notion of biofuel from algae to center stage. Fishman et al. (2010) also point out the oil industry has begun to show interest in algal biofuel but emphasize the industry’s support for R&D efforts has been minor to date. Both authors maintain it is difficult to say if oil companies will pursue the development of the industry.

This gives the impression oil holds some interest in the development of algae and might continue to pursue the development of algae for a couple of main reasons. Perhaps they see their long term business model as unsustainable and are looking towards the future of liquid fuel transport by investing in different biofuel technologies. This is reflected by BP's continued investment in boosting capacity at a mill in Brazil which will be able to generate 8,000 barrels per day of ethanol or a 90-million barrel green reserve over a 30 year lifetime (Daily, 2012).

On their other hand, there is evidence of impure motives to support biofuel production. There is a real potential for 'green washing', or the good will gained by advertising the fact that they are investing in renewable energy projects. Exxon has a 4 page marketing PDF highlighting their partnership with Synthetic Genomics and their support of more than $600 million if research and development milestones are successfully met ("ExxonMobil algae biofuels research and development program," n.d.). Additionally, an industry association, the American Petroleum Institute, filed a lawsuit earlier this year challenging the Renewable Fuel Standard (RFS2) requirements for cellulosic-based ethanol under the Energy Independence Security Act of 2007 calling the requirements 'unachievable' (Daily, 2012). These episodes shed light on the unreliability of, and bring an additional level of skepticism to, the oil industry's investment interests.

Exxon's investment in Synthetic Genomics sheds light on the contracting method oil companies might employ for investment. Exxon has provided funding but has set milestones Synthetic Genomics must meet to achieve funding support. This limits Exxon's risk of investment should Synthetic Genomics fail to see progress in their R&D. Also, Exxon does not currently have anyone sitting on the board of directors for Synthetic Genomics. This hints at a very hands-off approach to technology development to meet the agreed upon performance metrics. Nonetheless, Exxon is using their marketing to highlight the burgeoning new technology. Additional marketing heightens consumer awareness which is a positive for the algae industry. Nevertheless, this also makes it seem likely Exxon is using their algae investments to portray themselves as environmentally friendly.

Regardless of motivation, oil companies generate large revenues and one or two might choose algae development as one source and investment. Even one company deciding to support could make a substantial difference in industry funding. Lastly, being involved in development also offeres them some level of control. None of these factors can be underestimated.

6.3 Public Policy Measures

Public policy is an important element influencing the investment in new energy technology R&D and projects. Innovation in new technologies can often be subject to market failures and this can negatively affect investment, R&D decisions as well as information sharing. Market uncertainty reduces investment, and scaling production to reach per unit cost reductions implied by the experience curve becomes increasingly challenging. Therefore, technological policy should aim to correct market failures, which, in turn, prompts investment and development of new technologies that hold the possibility of long run positive societal effects.

An important element to achieving these aims is mitigating investment risk for investors by generating certainty in a future marketplace. Policy provides expectation and acts as a signal for investors. Energy projects are often characterized by the need for large initial capital investments. Algae biofuel is no exception. IP law serves to protect investors by ensuring returns to recover upfront investments. Policy can also help drive investment as observed in ethanol production where policy induced production beyond the free-market level and acted to increase the competitiveness of the industry over time (“Policies, learning-by-doing played important role in reducing ethanol costs,” 2012).

However, policy must also be cautious to provide the right incentives without inducing over-investment with exceedingly attractive R&D enticements (Scotchmer, 2004).

Biofuels policy can be complex. Biofuels are at the intersection of energy, agriculture and environmental policies (*Renewable Fuel Standard: Potential economic and Environmental Effects of U.S. Biofuel Policy*, 2011). Often a range of departments including the U.S. Department of Agriculture, Department of Energy, Department of Defense and the Environmental Protection Agency all hold interests in biofuel policy. Also, there are different biofuel feed sources in development. It’s a challenge to achieve a balance of supporting all technologies without picking winners as well as implementing policy that achieves the desired effect instead of encouraging unintended alternate effects.

In the National Algal Biofuels Technology Roadmap, Fishman, Majumdar, Morella, Pate & Yang (2010) argue the absence of current policy support as an underlining uncertainty in project development in the algal biofuels sector. Proper policy will reduce uncertainty and risk which will encourage scientists, entrepreneurs and investors to enter the arena in large numbers and remain for the time needed to bring the industry to realization. Also, market incentives, usually resulting from policy, provide confidence to investors because they have the potential to see a return on their investment in a shorter timeframe. This is important when looking at projects, such as algae, with a long potential project life and long payback time for investors.

In May 2012 executives with a Danish investment firm who invested in a new enzyme plant in Nebraska praised the U.S. government's continued support for biofuels. Novozymes, who built the plant, say it is crucial that the U.S. maintain a strong standard for the use of renewable fuel to promote growth in the industry ("Biofuel executives praise US support for industry," 2012).

Responses from the ABO survey, comprised mainly of people at the executive or management level from companies researching and working to at commercialize algae or universities and research groups, showed just under 50% felt federal support was extremely or very important for the development of their company or division. While policy is agreed to be important in the near term, of the respondents to the ABO survey, about 42% of respondents felt no one in their company or division had ever contacted federal legislators in their district or Washington, DC about policies that effect the industry (Algal Biomass Organization, 2012). This could be attributed to the relative newness of algae research and commercialization. Industry cohesiveness is still taking shape. Also, the industry started in the science arena, not always the most politically active community outside of seeking research grants. However, the industry is quickly evolving and gaining a mix of business and legal practitioners who could take on a larger role representing the industry to local and federal government.

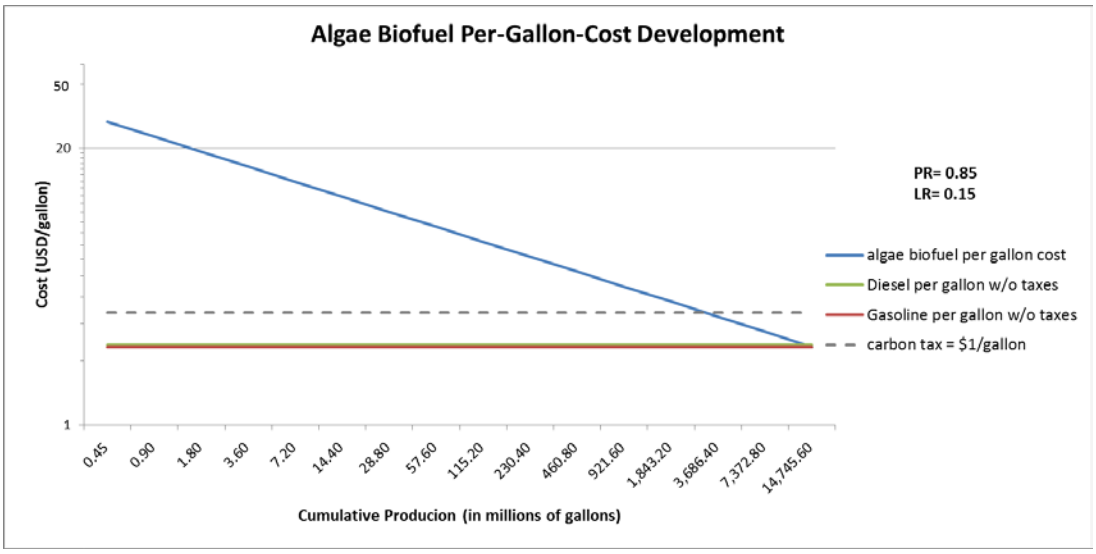
The following discussion and analysis looks at leading policy mechanisms government can consider employing to promote continued investment in algae biofuel and promote movement to the commercial space.

6.3.1 A Carbon Tax

A tax per unit of carbon emission is attractive for many reasons as a means to price carbon. A Pigouvian tax, or a standard charge imposed directly on the level of emissions, is often seen as equitable because the 'polluter pays' per unit of emission. In this case, gallons consumed correlate with carbon emissions, so, the purchase point works as a fair implementation point. As a result, there are minimal institutional costs, or costs associated with the implementation, of a uniform tax at the pump.

The carbon tax raises the per-unit-cost for fossil fuel based sources to include the cost of negative externalities of carbon emissions into the price of gasoline or diesel purchased at the pump. The new pump price prompts a change in consumer behavior and alters market demand in many ways including demand for fuel efficiency and demand cleaner fuels. More importantly for this study, the result of implementing a carbon tax would be to make alternative fuels, like algal based biofuels, more attractive in the nearer future. This supports investment, especially private investment, in the new technology as well as generates revenue for the government that can be invested in new technology R&D. And, this highlights an additional attractive quality of a carbon tax- it does not, per se, pick winners of new technologies. It merely works to level the playing field of fossil fuel based and clean energy based transportation technologies.

We can apply a carbon tax to the gasoline and diesel costs in our model to see an estimated effect. While the U.S. did not ratify the Kyoto Protocol, should they aim to reach the GHG emission reductions proposed, 93% that of 1990 levels, the carbon tax needed would range from $94 to $400 per ton of carbon. That works out to a tax of $0.33 per gallon to $1.40 per gallon (McKibben & Wilcoxen, 2002). The graph below shows the impact a carbon tax of $1 per gallon on top of production costs would make in the study 'base case' scenario with a learning rate of 15% (Graph 4).



Graph 4: Illustration of the effect of an emissions tax on the ‘base case’ LR of 15%. Authors own rendering

While an emission, or carbon, tax has many attractive theoretical qualities, the reality of implementation possesses many drawbacks. The first major hurdle is the public opposition of levying new taxes. Adding a tax is a widely unpopular move, specifically in the United States. This alone makes a carbon tax in the United States unlikely in the near future. Additionally, while the institution cost might be low, it is difficult to ascertain what the optimal tax level should be to reach desired emission reductions. Often politicians err on the conservative side, and this limits the effect of a carbon tax.

6.3.2 Continued Investment in Research and Development

Continued investment in R&D is critical to supporting algae technology as well as the catalogue of new transportation technologies. Research efforts in both learning-by-researching and learning-by-doing can facilitate overall per-unit cost reductions. A reoccurring theme in algae biofuel production is the finding that higher lipid content as well as faster growth rates are important in reaching economies of scale and reducing costs. Investment in R&D throughout the value chain is important, but public and private investment should consider focused R&D efforts in the laboratory and with genetic engineering and advancing strain growth properties at present.

As discussed, protection of intellectual property is an important support mechanism provided by the government to encourage continued research, especially for promoting industry investment. While IP law isn’t perfect due to a reduction in open and shared information, it does serve an important purpose of providing strong property rights in the U.S. In this way, IP law is important to support industry investment in genetic manipulation by providing the ability to patent new modified strains. And, as demonstrated, overall industry investment in R&D is substantial in the U.S. Thus, continued IP protection and enforcement is an important service of the federal government.

Research funding has been an important form of new technology development support from the U.S. government since World War II and government grants, contracting and loans such as those described in previous sections can continue to be employed. As described, investment usually comes from mission-oriented government agencies, which decide what fields and projects to support (Smith & Barfield, 1996).

And, spending by governments on R&D has also been shown to spur private firm investment in related invention or commercialization activities (Afuah, 2003). The intuition here is that, if the government deems a technology promising enough for investment, this provides a sense of security for private investors as well as a contracting partner in an R&D venture spreading the liability of development. The Obama administration very publically supported $14 million more to algae R&D funding in February 2012 (“President Obama announces $14 million funding opportunity to develop transportation fuels from algae,” 2012). Algae biofuel is still a ways from commercialization and continued support from the government will be instrumental in continued progress and scale up.

But, R&D has large uncertainties and might take a long lead-time. Additionally, it requires government monetary outlays which is not always popular. And, an unfortunate consequence of short sighted and near term political agendas could be the lack of supportive policy. Investing in a solution that costs now and could see commercialization in a decade might not be in the best interest of politicians since political agendas tend not reach far beyond the short duration their term in office.

Public expectations on algal biofuels have increased dramatically in recent years, and, as a fortunate consequence, algae continues to find public and private funding in its early stages. Synthetic Genomics has received private funding from Exxon to research and develop next-generation biofuels as well as from Draper Fisher Jurvetson, Meteor Group, Biotechonomy and BP (“Top 50 VC-funded greentech startups,” 2010). Draper Fisher Jurvetson, a venture capital company, invested $30 million in Series A, or seed capital, funding in 2005 when Synthetic Genomics was founded. It is also reported that Draper Fisher Jurvetson’s managing director Steve Jurvetson sits on the company board (Tikka, 2009). Draper Fisher Jurvetson is more active in the development of the company to protect their investment.

Draper Fisher Jurvetson also invested $70 million in the startup GreenFuel Technologies Corporation before the company closed its doors in 2009 (Primack, 2012). Risks are real when investing in a technology not yet at commercialization. This example highlights the importance of government support to encourage industry support. Government support of R&D provides a partner in risky research endeavors spreading risk and policy generation secures a favorable investment environment.

Sapphire Energy’s investors include private funding from agriculture company Monsanto and Bill Gates’ investment firm Cascade Investments. Sapphire has also received a $50 million grant from the U.S. Department of Energy and a $54.4 million loan guarantee from the U.S. Department of Agriculture. In early April 2012 Sapphire announced raising an additional $144 million in Series C funding bringing their total raised to over $300 million in both public and private funds. Series C funding is funding raised after Series A, seed funding, and B, start-up capital. The notation of A, B, C and so forth allows investors to know where they stand with respect to previous investors. And, Series C funding is typically capital used to substantially ramp up existing operations (Newton, 2001). The Series C funding is dedicated to the build-out of their test facility.

Nevertheless, the dramatic increase in expectations, public interest and subsequent funding infusion can also have damaging side effects of causing resources to be diverted due to eventual failures. Publicity and high expectations have resulted in a number of projects, investments and research groups. Not all of them will be sound initiatives according to experts (Oltra, 2011). This is observed in the current news of Carbon Capture Corporation (CCC), selling their test facility to Synthetic Genomics, a more established algae biofuel research and commercialization company. CCC owned and operated a 40 acre algae growth test facility that started with the purpose of making algae derived biofuels. It eventually went to producing animal feed products when the revenue flow was not there for algae biofuel. The company is privately held and identified government grants and other revenue sources, such as technology licensing and consulting services to power plant operators and oil companies (Bigelow, 2012b).

6.3.3 Renewable Fuel Standard

A Renewable Fuel Standard supports the development of alternative fuels by setting mandates on the use of renewable fuels in the fuel mix. To date policy has typically been an ethanol blending mandate to generate marketplace security. These mandates can be specific to ensure support of newer technologies, such as algae, over more developed technologies, such as ethanol. This helps avoids a ‘lock-in’ scenario by the more mature technologies. However, this also means the government is somewhat dictating and not allowing efficiencies of the marketplace to award lower cost sources.

The federal government is already showing proactivity via the Energy Independence and Security Act (EISA) of 2007 and the subsection calling out a Renewable Fuel Standard (RFS2). RFS2 states production of biofuels shall be at 36 billion gallons by 2022 of which 21 billion gallons must come from advanced biofuels (Pienkos & Darzins, 2009). This phrasing limits the choosing of winners by providing a provision for the general category of advanced biofuels, or not-ethanol based biofuel. This entices some cost competition amongst second generation fuels. And, should any advanced or cellulosic biofuel become less expensive than corn based ethanol, the mandate of 36 billion gallons by 2022 could be filled entirely with advanced or cellulosic biofuels. Thus, the RFS2 provides a market for biofuels produced even when they are at a cost higher than fossil fuels thereby reducing investment uncertainty.

Ambiguity in the enforcement and implementation of RFS2 mandate levels can erode investor confidence. The Environmental Protection Agency (EPA) retains the right to waive or defer enforcement of RFS2 under a range of circumstances.

Also, it is shown achieving RFS2 would increase the federal budget. This is based on the need for outlays mostly as a result of increased spending on payments, grants, loans and loan guarantees to support the development of cellulosic biofuels, including algae, as well as foregone revenue as a result of biofuel tax credits (*Renewable Fuel Standard: Potential economic and Environmental Effects of U.S. Biofuel Policy*, 2011). Again, government monetary outlays are not always a popular notion amongst fiscal conservatives. Investors should keep an eye on any potential for modifications to the RFS2 should there be major shifts in the federal government.

At the state level, Minnesota has been distinguished as providing especially effective policy for corn ethanol adoption by combining measures that support both production and consumption of ethanol. Since 1997 the state has required that all gasoline sold in the state must have a 10 percent ethanol content. This has been paramount to supporting sales, and, thereby, production. In addition, Minnesota boasts a state fuel tax exemption on E85, an ethanol production payment of $0.20/gallon ($0.05/litre) and the most extensive E85 infrastructure in the country with over 300 retail outlets, or just over 25% of the national total of E85 retail outlets. In 2005 Minnesota consumed over 276 million gallons of ethanol which was just under 8% of the national total (Solomon, Barnes, & Halvorsen, 2007).

Some states are considering or implementing low carbon fuel standards, which could have an impact on the development and use of biofuels. These states include California, Oregon, Northeast and Mid-Atlantic states (*Renewable Fuel Standard: Potential economic and Environmental Effects of U.S. Biofuel Policy*, 2011). Perhaps they will consider blending mandates of advanced biofuels, much as Minnesota did for ethanol, as a mechanism to reach set aggressive emission reduction standards.

In theory, blending mandates seem like a way to ensure demand therefore providing assurance for investors. However, the government must consider supporting the production to reach mandates set. For example, Chevron spoke of supply problems even when a mandate was set. In addition, a Ford representative noted there simply are not enough producers yet to meet the mandates set by the government. The representative noted this as a problem standing between biofuel integration and their current fuel system. The company plans to start designing cars that support alternative fuels when the fuels become more available and customers demand the re-designed verhicles (Franklin, 2012).

Survey respondents to the ABO survey identify a renewable fuel standard as their most favored government policy behind continued investment in research and development. They favor a renewable fuel standard above reliable federal customers (Department of Defense), production tax credits, loan guarantees, fuel subsidies and a price on carbon (Algal Biomass Organization, 2012). However, many commented to the fact that policy should only be used in the short term for support and production should be able to stand on its own for the long term.

6.3.4 Government Support via Military Spending

The Military can be an important supporter of new technologies, especially when they are not yet cost effective. Some people miss the connection of the military as support from the government. However, they tend to have large budgets from tax revenue and make large investments in the latest and most cutting edge technologies for defense. Technology advances and learning spillovers from this research have brought us some important commercial technological developments. As U.S. Navy Secretary Mabuis stated, without the military's early support, technologies like nuclear or the computer might have had a longer road to commercialization (Casey, 2011). This exemplifies a benefit of the government using the military as a vehicle to support R&D.

Defense comes in many shapes and forms, not just guns. Investing in new technologies to ensure security of supply can also be viewed as a defense mechanism. Also, a benefit of public investment in the form of military spending is the chance to give new technologies a trial ground with a consumer who will make purchases at a cost above the incumbent technology. This highlights a current contracting mechanism used to date in the case of algae biofuel. The military, in this case the Navy, contracts with a company, Solazyme, guaranteeing to purchase a certain quantity of fuel based on certain fuel specifications, i.e. a biodiesel. In this way, contracting is an arms-length form of research support. The Navy provides a customer willing to purchase a set amount at a set price but has no commitments to the R&D investments made by the firm. Also, the Navy is not required to pay if the product is not delivered. Along these lines, the Navy can continue to provide a development partner to algae biofuel companies by contracting to purchasing products.

As seen in the experience cost curve model, the U.S. Navy has already been instrumental in purchasing some of the first algae biofuel. However, these purchases have become controversial press fodder and the U.S. Congress is currently working on blocking future purchases at prices so high above fossil fuel prices. This exposes one issue of reliance on the Military as a customer- they are subject to political pressures in Wasthington, DC.

Defense contracting is another vehicle for military spending on algae biofuel R&D. The general process of contracting with a government agency is much the same as applying for a grant. Companies submit proposals based on bid request released by a government agency, such as the Department of Defense. The request for bid defines the asset to be delivered.

The best proposal wins the contract and is awarded funding to carry out the proposed work. While this sounds like a hands off approach, the military often requires progress reporting and has an entire unit, the Defense Contract Management Agency, to ensure the contracted goods and services are delivered on time, at projected cost and meet all performance requirements (“U.S. Department of Defense,” n.d.).

SAIC and General Atomics, both defense contracting firms, have received defense contracts to develop algae biofuel technology. General Atomics received funding from the Defense Advanced Research Projects Agency (DARPA) to lead a team of university and industrial partners examining all aspects of algae to jet fuel production process (Garthwaite, 2009). Also under DARPA, SAIC won a defense contract of \$15 million to develop a \$3 gallon^{-1} algae derived fuel for military jets (Garthwaite, 2009).

6.3.5 Subsidies

Subsidies are another policy instrument to spur adoption and can take many forms stimulating both supply and demand. Subsidies can be initiated at the federal or state level. This is observed in the introduction of corn based ethanol into transportation fuels in the U.S. Three federal government initiatives were said to be integral in supporting the early uptake of corn ethanol. However, due to the overlapping of numerous support mechanisms since 1979, it’s difficult to quantify the impact of any single policy instrument (Solomon et al., 2007)

First, was the partial exemption from the federal gasoline excise tax for gasohol, a fuel containing at least a 10 percent component of bio-mass derived ethanol. This was signed in under the Energy Tax Act of 1978 and went into effect in 1979. In 1980, a fuel blenders tax credit and a pure alcohol fuel credit were added. But, the excise tax exemption was by far the most important of the early ethanol support mechanisms due to the magnitude of its benefits and its ease of implementation. And, this support mechanism saw little change except for benefit levels increasing and decreasing from 1978-2004. 1990 saw the passage of the Small Ethanol Producer Tax Credit providing small plants additional income tax credits. 2004 and the introduction of the Volumetric Ethanol Excise Tax Credit (VEETC) changed the basic mechanics of the subsidy to a volume based measure. Federal support for ethanol in recent years has equaled a taxpayer subsidy of \$3.8 billion per year (Solomon et al., 2007).

At the state level, ethanol can also provide a historical illustration. Support started in the late 1970s, mirroring the timing of the federal government, and over a dozen state governments swiftly approved partial or total gasohol exemptions from state and road use taxes. As of 2005 nine states were offering some level of excise tax exemption and producer credits were offered in eleven additional states. Several other states offered grants, loan programs or tax exemptions (Solomon et al., 2007).

Just under 50% of respondents to the ABO survey felt that similar tax treatment as other biofuels would make it extremely or very likely that current production of algae derived fuels would expand. However, a handful of respondents call out the importance of biofuels needing to stand on their own ultimately. Many point out the importance of not relying on subsidies in the long run (Algal Biomass Organization, 2012).

6.3.6 Public Private Partnerships (PPP)

Fishman et al. (2010) emphasize the importance of a private-public partnership (PPP) in the success of an algal biofuel industry. They claim the industry benefits overall from PPPs due to a quickened pace of innovation. This, in turn, increases the capital efficiency of commercial firms as well as reduces the risk to private investors. But, the authors acknowledge this is a unique proposition due to the infancy of the industry and concerns over intellectual property (IP) and future earnings. As a result, many companies have not adopted an openness of working together or sharing data and science findings. The authors believe this can have a negative effect on the overall development of the industry. To date, the industry is comprised mostly of small technology-rich firms who are focused on various aspects of the algal biofuels value chain and are not yet at the commercialization stage.

More mature companies, in reference to the industry, are many of the companies mentioned in this study such as Solazyme, Sapphire Energy and Synthetic Genomics. It is no surprise they have received support and funding from both public and private partners.

6.4 Competition with other biofuel sources

The notion of algae derived biofuel does not exist in a vacuum. There are many biofuel feed sources in development such as jatropha and lignocellulosic energy crops, all of whom hold interests in both public and private support. To maintain support, it is important the algae biofuel industry be aware of the potential dynamics between biofuel feed stock sources.

Algal biofuels do not compete on a level playing field, especially due to the loud voices of lobbyists for established biofuel interests (corn and cellulosic) (Fishman, Majumdar, Morello, Pate, & Yang, 2010). Algae is a newer technology so smaller in number of interested parties and just forming trade organizations to represent their interests in Washington, DC. As a result, there is a strong need for leadership from the U.S. Department of Energy in coordinating with other federal agencies to support research, infrastructure development and information management at the national level as well as promote policy to support emergence of the industry.

There is limited published about the ethanol industries direct impact on algae as of yet. But, Hahn (2008) asserts ‘interest group support’ for ethanol is a leading factor in increased production of corn-based ethanol. It can be concluded this group has influence at the policy level. However, the ultimate interest group may be the farmers and growers, who probably do not ultimately have a preference as to which crop they grow if they have the prospect of making more money. As an additional proposition, if the remaining biomass after lipid extraction was utilized as an animal feed, there could be synergies with the cattle and dairy industry lobby. This support might translate into subsidies for farmers to convert their forage crops to algae.

Currently, ethanol and advanced generation biofuels look to be funny bedfellows. They work together on federal renewable portfolio standards and specifically on the revisions of the EISA RPS2. But, corn ethanol could stand to lose from the potential successes of second generation biofuels. So, ultimately the power the corn industry wields could create a battle amongst the biofuel feedstock sources generating trouble for algae. Additionally, corn and ethanol are very important industries in swing voting states adding to the industries potential pull in Washington, DC. Corn ethanol could choose to focus its battles on more direct competition such as other feedstock that produce primarily ethanol like cellulosic. Perhaps algae would garner less opposition, especially if focusing on aviation where ethanol cannot be used currently.

Hopefully more momentum from any one biofuel feed source will be an overall positive for biofuels. There’s plenty of fossil fuel based transportation fuel to be displaced for all biofuel feedstocks to flourish over time as they make continued progress in scaling up and cost economics.

6.5 A Note on Public Perception

Pike research reports about consumer awareness and shows, in general, biofuels have a ways to go in consumer education and acceptance. They also report that over the last couple of years of reporting that biofuels suffered the most precipitous decline in favorability, dropping 17 points from 56% in 2009 to 39% in 2011 (Vyas & Wheelock, 2012).

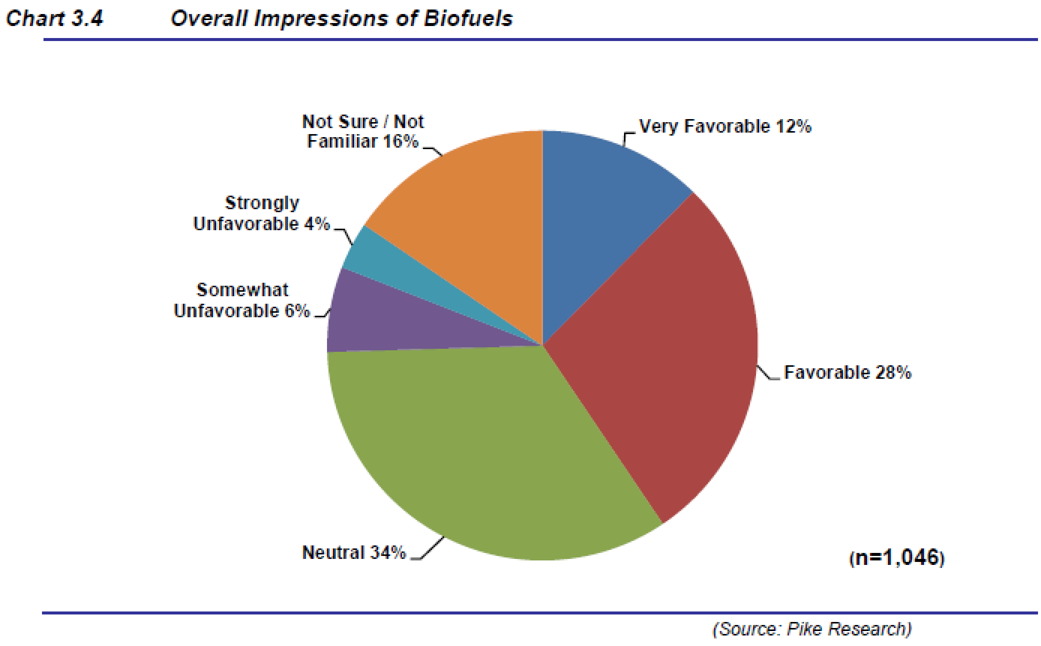


Figure 14: Overall Impression of Biofuels (Vyas & Wheelock, 2012)

While acceptance had opportunities to make progress, research shows consumers are willing to pay a premium for ethanol, the only biofuel available in the marketplace today. It was found that when ethanol increased 10 cents gallon^{-1} above the price of gasoline, there was only a 12 to 16% decrease in demand. This finding surprised researchers who were expecting to see a sharp reduction in the sales of E85, 85% ethanol used in FlexFuel vehicles, the minute the price rose above the price of gasoline on the energy-adjusted basis. Therefore, one can conclude buyers are willing to pay a premium for ethanol fuel (Jessen, 2012). This follows intuition. If people purchase a FlexFuel vehicle, they are most likely more interested in the environment and are willing to pay a premium for fuels deemed more environmentally friendly. Perhaps this holds true for some consumers who are environmentally friendly and don’t have access to E85 due to limited fueling station infrastructure. This finding bodes well for advanced biofuels, especially algae that can be refined into a gas or diesel drop-in, as they work on bringing costs down.

The ABO survey also echoed the importance of the general public having information about the benefits and potential of algae. Over 70% of respondents believe education of the public on the benefits of biofuel from algae is quite to very important (Algal Biomass Organization, 2012).

7. Conclusion

Overall, algae based biofuel production and scale up looks very promising. It is difficult to conclude exactly how the investment necessary for scale up and cost reductions will occur, but there are a range of interest groups who have different motivations to support algae biofuel production moving towards commercialization.

Government policy plays an important role in generating incentives to support investment. Key turning points could come by commitment from the U.S. armed forces or from a sector like aviation looking to hedge against major fluctuations in pricing. Public policy like the RFS2 renewable fuel standard promote investment by securing a future marketplace for the product. 2022 and the RFS2 serves as a good benchmark of algae biofuels progress. The next 10 years will bring more clarity and provide a better indication of the commercialization and adoption potential of algae biofuel.

However, policy measures such as the RFS2 are ultimately subject to political pressures and leanings of elected officials in Washington, DC and at the state level. Unfortunately, policy can suffer from inconsistency in policy priority and this is something that must be monitored carefully when assessing funding from the government as well as the investment environment generated by policy.

Still, optimism remains from researchers, industry and government. And, biofuel production from algae as a feed source seems to be finding investors. Currently both public and private investment is supporting algae biofuel’s road to commercialization. Government funding via research grants supports university laboratories where discovery benefits society by open accessibility to findings and spillover effects within the industry. Government is also funding algae R&D through program specific grants, loans and contracts awarded to firms working to commercialize algae. Venture capital and industry investment is also playing an increasing role in firms closer to commercialization.

A major form of current government support comes from the U.S. Navy who has been an early customer and test bed for algae biodiesel. Continued contracted purchases from the Navy could be a game changer in algae biofuel development by providing some security of scaling up.

Continued investment needed is likely to be sizable, but, support in investment is expected to continue and be consistent over the next few decades, in large part due to the RFS2 advanced biofuel production standard as well as states taking a possible leadership position. Investment in the short term should focus on progress gains in learning-by-researching as a leading finding for increasing algae biofuel’s cost effectiveness is finding or genetically engineering strains that grow quickly and produce high oil yields.

2012 will continue to be a big year for algae biofuel production. Multiple algae biofuel producers have secured funding for larger demonstration facilities or build-outs on existing facilities. Joule, Sapphire Energy and Kent BioEnergy, to name a few, are under construction and hopeful to be up and running by the end of 2012.

An area of further research from this study is to explore the impact of high value product co-production in the short run as a means of capturing a revenue stream until biofuels starts to infuse the marketplace. This is one of the exciting, albeit tricky, elements of algae- it has a lot of possibilities. Some point to the important segment of animal feed which could make good and profitable use of the leftover protein rich biomass after lipid extraction.

Another area for further research with this model could be to incorporate credits to cost of production due to CO_2 capture in the production process and see what impact this might make on the overall learning investments necessary.

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