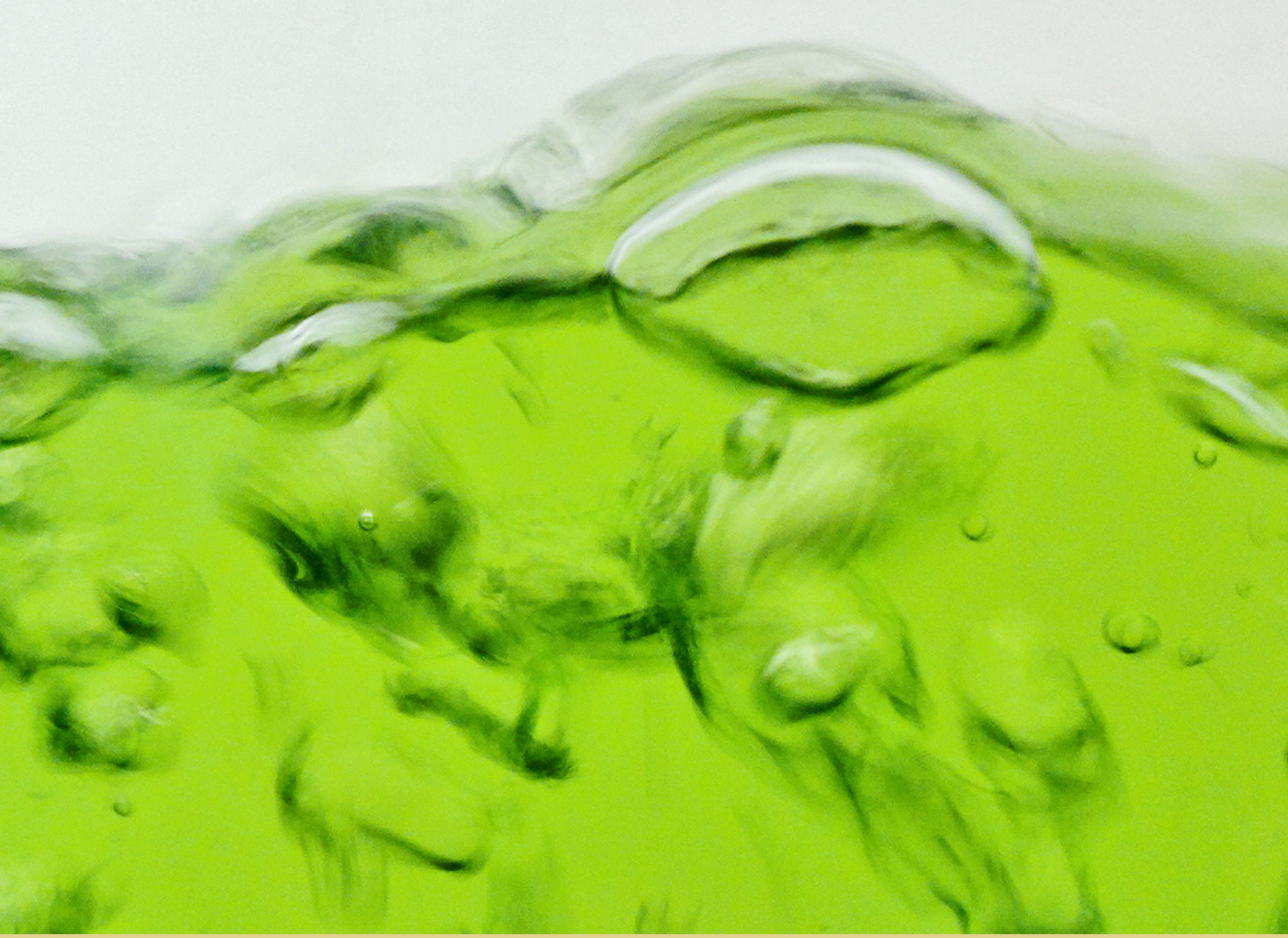

Lauro André Ribeiro

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Doctoral Thesis in Sustainable Energy Systems, supervised by Professor Patricia Carla
Gama Pinto Pereira Silva Vasconcelos Correia and Professor Stephen Connors,
submitted to the Department of Mechanical Engineering, Faculty of Sciences and
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September, 2014

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UNIVERSIDADE DE COIMBRA

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ABSTRACT

Due to the dwindling of the global oil reserves, that are becoming harder and more expensive to explore, and the current efforts to reduce greenhouse emissions from fossil fuels consumption, new and renewable energy sources, in particular, must be developed and implemented. Therefore, the proposed study aims to analyze the use of microalgae as an advanced biofuel feedstock with an emphasis in its sustainability, and assess the economical, technological and political factors that can be critical to the success of this technology. The methods used to analyze the prospects of using microalgae as a feedstock for biofuels and to develop future diffusion pathways of emerging biofuels were a combination of a qualitative Delphi Survey with experts and modeling future scenarios using Stochastic Automata Networks. In this way, it was possible to draw several conclusions related to the potential development for microalgae commercialization in the biofuel market and to demonstrate the effectiveness of some public policies in the dissemination of advanced biofuels in the future.

Keywords: Biofuel, Microalgae, Policies, Economy, Emerging Technologies, Advanced Biofuels, Scenarios, Assessment, Sustainability, Market Diffusion, Model, Delphi, Stochastic Automata Network.

RESUMO

Devido à diminuição das reservas mundiais de petróleo, que estão tornando-se mais complexas e caras para exploração, e os esforços atuais para reduzir as emissões de gases relacionados ao consumo de combustíveis fósseis, novas fontes de energia renováveis precisam ser desenvolvidas e implementadas. Portanto, este estudo tem como objetivo analisar o uso de microalgas como matéria-prima para biocombustíveis avançados, com ênfase em sua sustentabilidade, e avaliar os fatores econômicos, tecnológicos e políticos que podem ser cruciais para o sucesso desta tecnologia. Os métodos utilizados para analisar as perspectivas do uso de microalgas como matéria-prima para biocombustíveis e desenvolver futuros caminhos para a difusão destes biocombustíveis emergentes foram uma combinação de uma pesquisa qualitativa com especialistas com o método Delphi e modelagem de cenários futuros, utilizando Redes de Autômatos Estocásticos. Desta forma, foi possível tirar várias conclusões relacionadas com o potencial de cultivo e comercialização de microalgas no mercado de biocombustíveis e demonstrar a eficácia de algumas políticas públicas na disseminação de biocombustíveis avançados no futuro.

Palavras-chave: Biocombustível, Microalgas, Políticas, Economia, Tecnologias Emergentes, Biocombustíveis Avançados, Cenários, Avaliação, Sustentabilidade, Difusão no Mercado, Modelo, Deplhi, Redes de Autômatos Estocásticos.

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ABBREVIATIONS

ABO	Algal Biomass Organization
ALS	Amyotrophic Lateral Sclerosis (Lou Gehrig's Disease)
AM	Algal meal
ARRA	American Recovery and Renewal Act
BMAA	β-N-Methylamino-L-alanine
Btu	British Thermal Unit
C	Carbon
CH_4	Methane
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CO_2 eq	Carbon dioxide equivalent
CO_2	Carbon dioxide
DOE	United States Department of Energy
EISA	Energy Independence and Security Act of 2007
EROI	Energy Return on Investment
g	Grams
GHG	Greenhouse gas
GWP	Global Warming Potential
H_2	Hydrogen
Ha	Hectare
HTL	Hydrothermal Liquefaction
IEA	International Energy Agency
K	Potassium
kg	kilos
km	kilometers
L/ha	Liters per Hectare
LCA	Life cycle assessment
M ha	Million Hectares
m^2	Square meters

MABEL	Meta-Model of Algae Bio-Energy Life Cycles
MBtu	one thousand BTUs
Mg	Magnesium
MIT	Massachusetts Institute of Technology
MJ	Mega Joule
N	Nitrogen
NER	Net Energy Ratio
NO_x	Nitrogen oxides
NREL	National Renewable Energy Laboratory
NUMA	Non-uniform Memory Access
O&M	Operations and Management
O3FA	omega-3 fatty acids
P	Phosphorous
PBR	Photobioreactor
R&D	Research and Development
RFS	Renewable Fuel Standard program
RFS2	Revised Renewable Fuel Standard
S	Sulfur
SAN	Stochastic Automata Network
SET	Strategic Energy Technology Plan
SO_x	Sulfur oxides
T	Metric Tonne
TIMES	The Integrated MARKAL-EFOM System
TAG	triacylglycerol
UG	Users of Natural Gas
UP	Users of Petrol
WFP	Water Footprint
wt	Weight

1. INTRODUCTION

1.1. Background and Motivation

Sustainability is currently a fundamental principle in environmental resources management (U.N., 1987; Daly, 2007). Currently it is increasingly clearer to society that the continued use of fossil fuels for energetic purposes is unsustainable. The dwindling of current global oil reserves, increased difficulties and costs in its explorations, and the need to reduce the emissions of greenhouse gases associated with their use are placing constraints in the usage of fossil fuels. In this context, biofuels are particularly important since they can be used in today automobiles with little or no modifications of engines and as an option for means of transportation that lack other fuel options (especially trucks, ships and aircrafts).

Alternative energy sources derived from terrestrial crops such as sugarcane, soybeans, maize, rapeseed, among others, inflict a lot of pressure on the global food markets, contribute to water scarcity and precipitate the destruction of forests. Therefore, other innovative technologies and sources of energy must be developed to replace fossil fuels. The overall sustainability of biofuels will depend on the development of viable, sustainable, advanced technologies that do not appear to be yet commercially viable.

In this perspective, algal biofuels are generating substantial awareness in many countries. Several studies have been conducted on the technical feasibility of growing algae for biofuel production in the laboratory (Tao and Aden, 2009; Chisti, 2007; Brennan and Owende, 2010; Carvalho et al, 2006; Hirano et al. 1997; Ono and Cuello, 2006; Pulz, 2001; Pulz and Gross, 2004; Sheehan et al., 1998; Spolaore et al., 2006; Terry and Raymond, 1985; Ugwu et al, 2008), which have proved the absence of many of the major drawbacks associated with current biofuels. However, not much information can be found concerning the production of biofuels from microalgae in a commercial scale because this is still an immature technology. Though several companies that grow algae on a large scale and produce biofuels from them emerged in recent years, the price of this biofuel still appears to be too high to be competitive when compared to currently used fuels, even renewable ones.

The current economic situation appears to be that large-scale production of algae biodiesel is not yet viable as a solution to displace petroleum-based fuels (Ribeiro and Silva, 2013). The technology to efficiently produce biofuels from microalgae seems to remain not yet competitive with more advanced and emerging renewable technologies such as wind, solar, geothermal, and other forms of biofuels. However, with policy support and incentives, the algal biofuel industry could continue to develop and assuming that this technology follows renewable energy cost trends, costs would decrease to eventually reach economic viability. (Pienkos and Darzins, 2009). This development is already happening with other renewable energy sources, such as wind and solar power to generate electricity due to advances in technology and policy support, a pathway that can be pursued by microalgae as feedstock for biofuels.

By assessing the viability of algae projects from a market perspective, it is clearly apparent that total installed costs, operational and maintenance costs will be a major hurdle to future commercialization. According to Mcgraw (2009), current technologies should be improved, or even new ones invented, to reduce costs and increase yields. This can be accomplished through focused, comprehensive, and well-funded Research and Development (R&D) programs, at the international, national and even regional levels, with the participation of all relevant stakeholders, in particular companies.

Public policies could also perform a great boost in this area lowering the costs of renewable energy sources to support the development of renewable technologies, either through direct means such as government-sponsored R&D, or by enacting policies that support the production of renewable technologies (Popp et al., 2011). In the United States, for example, they may contribute to achieve the biofuel production targets set by the Energy Independence and Security Act of 2007. Likewise, in the European Union, they may assist to the achievement of goals established in the recent Renewables Directive, that concerning transportation sector fuels, states that each member state should reach a minimum 10% share of renewable energy by 2020 (E.U., 2009). In order to address the technical-economic barriers to the further development of this type of bio-energy, it is thus necessary to contribute with a study that incorporates biomass feedstock availability assessment, sustainability and feasibility of production, diffusion pathways, possible policies and use it in support of the scaling up of this promising technology if it is the general interest to do so.

1.2. Definition of the problem and research questions

The question addressed in this thesis is not whether biofuels from algae are technically possible, but rather focuses on the issue of whether they can be produced with an economical viability and at a scale sufficient to help contribute to the world's fuel demand. Moreover, the overall sustainability (environmental, economical and social) of the algae biofuels produced is of great importance. Therefore, the first step of this work is to investigate the current status and prospects of using microalgae for biofuels production. Afterwards, the first research question arises: 1) **What are the main drivers that influence the overall sustainability of microalgae biofuels, considering economic, social and environmental impacts?**

After analyzing these key aspects for the future development of such technology, there is a need to analyze the present policy situation of cultivating microalgae for biofuel production, to evaluate possible opportunities and weaknesses and to forecast ways to enhance the diffusion of algae biofuels in the market. This leads to addition objectives to be attended: 2) **Which policies currently affect microalgae biofuels industry?** and 3) **What policies could enhance the diffusion of microalgae in the transportation market share in the future?**

1.3. Methodology

In order to make the intersection of three major areas of knowledge: the economic policies that handle the regulation of the biofuel energy industry (with analysis of the incentives, regulatory constraints and taxes), with processes of technological diffusion and performance evaluation (Figure 1), these three major groups of knowledge were separated in three different categories. One category handles with economic policies, the second focuses on processes of technological diffusion of emerging technologies; and the final category assesses the economical evaluation analysis of this technology.

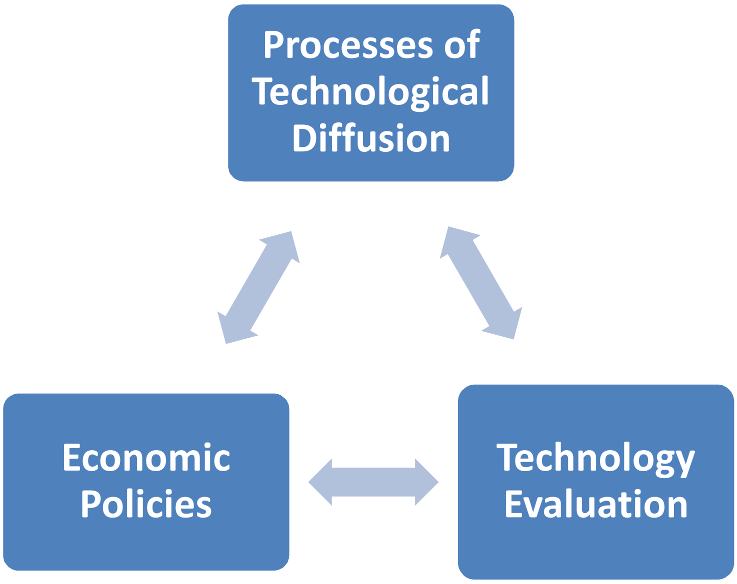


Figure 1: Three studied categories in the algal biofuels market

For the economic policies category, an examination was created to point out the main differences between policies around the world concerning algae biofuels and other biofuels that could substitute fossil fuels, and how they have developed during the last years. As this is an emerging energy market and, so far, there is no reliable and consistent data on the performance of the microalgae industry, a policy review of biofuels was carried out to point out some of the most efficient policies and technologies so far.

As for the technological evaluation analysis of microalgae biofuels, a qualitative Deplhi Survey research was applied within an universe of worldwide algae biofuel experts. The key objective of our Delphi study was to determine the prospects of using microalgae for biofuels production within a time scale extending to 2030 and to identify the experts' consensus pros and cons of this emerging technology. This method is especially suitable in judgment and long-range forecasting (20-30 years) situations, when expert opinions are often the only source of information available, as is the case of this emergent industry, due to a lack of appropriate historical, economic or technical data (Gupta and Clark, 1996).

Strictly linked with the previous categories, the subsequent category of this study targeted to provide information regarding to the technology diffusion of recently found energetic pathways, in particular to assess how they are developing and which are or were the main barriers found along their diffusion. Besides a first stage of data collection, the methods used to develop future diffusion pathways of emerging biofuels were a combination of the Delphi Survey with experts and modeling future scenarios using Stochastic Automata Networks (SANs).

For the scenario modeling, it was required widen levelized costs estimates that represent the fundamental assumptions, so that biofuel cost estimates can be usefully compared across technologies, taking into account the market value of the power generated and the associated externalities. In this way, it was possible to draw several conclusions related to the most effective public policies implemented so far and to present possible scenarios that could demonstrate the dissemination of this emerging technology in the future.

1.4. Significance of the study

The focus of using renewable energy in the transport sector leads to reduced dependence on oil, and consequently a reduction of the external trade deficit balance. Also, the usage of biofuels based on algae or other crops oils could lead to reductions in the CO_2 emissions, thereby contributing to tackle climate change by reducing greenhouse gases emissions (IEA, 2012). Moreover, diversification of supply sources has the ambition to increase security of supply by the endogenous production of fuels, essential to the transport sector.

This is where the algal biofuels can really make a contribution to the future world sustainability, since most studies confirmed the technical and biological feasibility to produce biofuels in large quantities from microalgae. However, the research so far in this area is more scientific than technical, often related to areas such as biology or chemistry, pointing the need to investigate in other spheres (namely, economical, social, environmental, technical and practical implementation of new or improved technologies, and policies), so that policy makers, industries or entrepreneurs can make the decision whether, or not, to invest in this technology.

The study herein offered targets to fill-in, at least partially, the above-mentioned gap by considering different categories of scenarios that exemplify some key drivers that may have been restraining this technology successful path. Thus, this work could support, not only private companies so that they could decide on the adequate method of cultivation/production to explore, but would also benefit governments when deciding what policies to adopt to enhance the diffusion of such technology.

1.5. Thesis overview

This thesis is organized in 6 Chapters. In this first Chapter, the introduction, background, and definition of the problem, methodology and significance of the study were presented. Afterwards, a literature review of microalgae as a feedstock for biofuels is developed in Chapter 2. Biofuels diffusion and policies are discussed in Chapter 3. The performed Delphi survey method and results are described in Chapter 4, while the diffusion scenarios methods, results and discussion are presented in Chapter 5. Finally, conclusions are drawn in Chapter 6.

2. LITERATURE REVIEW: MICROALGAE AS A BIOFUEL FEEDSTOCK

This section gives an overview of algae, details the attributes of producing algae biomass and describes the process of cultivating, harvesting and producing biomass. This chapter also aims to provide a literature review of the relevant economic, environmental and social assessments.

2.1. Algae cultivation techniques

Microalgae are photosynthetic organisms that can grow in a wide variety of environments and conditions, including fresh, salty and brackish water (Benemann, 2012). Their mechanism of photosynthesis is similar to higher plants, with the difference that the conversion of solar energy is generally more efficient because of their simplified cellular structure and more efficient access to water, CO_2, and other nutrients.

> “Its uniqueness that separates them from other microorganisms is due to presence of chlorophyll and having photosynthetic ability in a single algal cell, therefore allowing easy operation for biomass generation and effective genetic and metabolic research in a much shorter time period than conventional plants”.(Singh and Sharma, 2012; p.2348).

In addition, the cultivation requirements are quite small, as most species only need water, CO_2, and some essential nutrients such as nitrates and phosphates and potassium, without needing the use of pesticides or fertilizers (Groom et al., 2008; Singh and Sharma, 2012). Microalgae can produce lipids, proteins and carbohydrates in large amounts over short periods of time. For these reasons, microalgae are capable of producing 30 times as much oil per unit of land area when compared to terrestrial oilseed (Sheehan et al., 1998). And this oil can be processed into both biofuels and valuable co-products (Singh and Sharma, 2012).

The microalgae cultivation can be either heterotrophic or autotrophic. The heterotrophic method is a biochemical conversion that relies on input feedstock derived from an upstream photosynthetic source. This approach uses closed bioreactor systems in a biochemical conversion process without light inputs. This dark fermentation process is based on the consumption of simple organic carbon compounds, like sugars or acetate. The cultivation of algae using cellulosic sugars produced from wood and agricultural wastes or purpose grown energy crops is an area of active research and development (Buford et al. 2012).

On the other hand, the autotrophic cultivation requires only inorganic compounds such as CO_2, salts and a source of light energy for their growth. This photosynthetic conversion involves two main methods: open ponds and closed photobioreactors (PBRs). The biomass produced in these autotrophic processes include lipids that can be converted to fuels. (Brennan and Owende 2010; Buford et al. 2012). In Figure 2, a simple microalgae facility schema is presented.

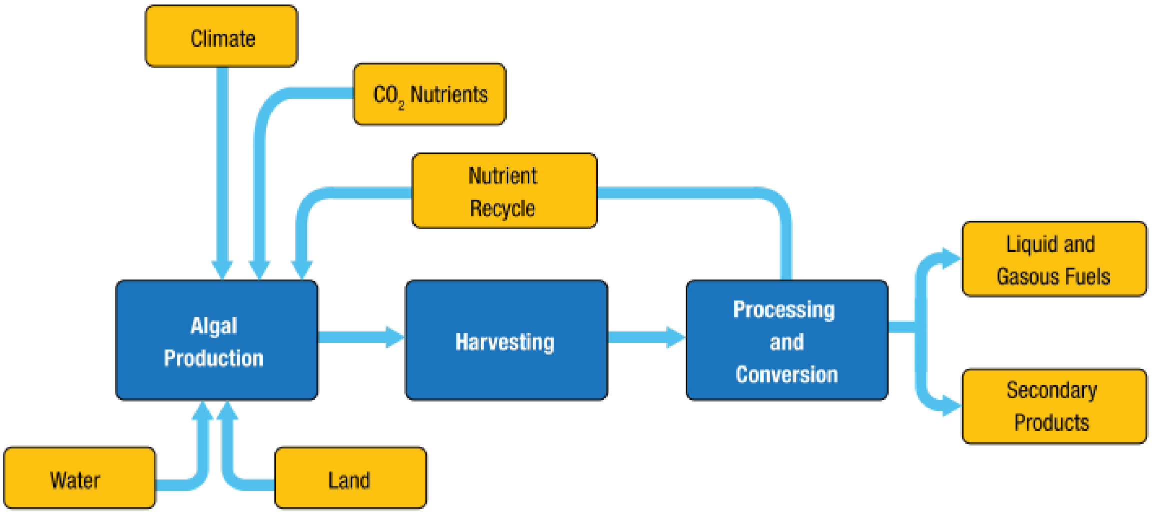


Figure 2: Algae biofuel requirements and simple production process (U.S. DOE, 2010).

According to Benemann (2012), algae have been essentially produced in open ponds with the main strains currently being cultivated are *Spirulina*, *Chlorella*, *Dunaliella* and *Haematococcus*. Most designs include mixing systems that use paddle wheels and carbonation techniques to supply and transfer CO_2 (in-ground carbonation pit, bubble covers, in-pound sumps).

Microalgae are also grown in tanks and small-scale photobioreactors (PBRs), in hundreds of different systems around the world, producing from small amounts to huge sums of biomass annually. In this closed autotrophic approach, algae grow with sunlight or artificial lighting (Benemann, 2012; Buford et al., 2012). Different types of photobioreactors have been designed and developed for cultivating algae, that can be horizontal, vertical, tubular, flat, etc. (Benemann, 2012; Singh and Sharma, 2012). Each of these photobioreactors has their own advantages and disadvantages. Several studies are being developed which may overcome their limitations in the years to come (Singh and Sharma, 2012).

2.1.1. Comparing open ponds and photobioreactors systems

Commercial algae production facilities employ both open and closed cultivation systems. Each of these present advantages and disadvantages, but both require high capital input (Pienkos and Darzins, 2009). Open ponds are cheaper than closed systems because it demands relatively high capital and operations and management (O&M) costs associated with installation and operation of PBRs (Benemann, 2012; Buford et al., 2012).

Lower costs and the possibility to scale up to several hectares turn open ponds the main choice for algae commercial production (Benemann, 2012). However, open pond cultures suffer from many limitations that can disrupt algal productivity during unexpected environmental events. Another challenge for this system includes having access to an adequate supply of water for growth due to continuing loss of water through evaporation. Therefore, open ponds must be in a geographic setting that has a fairly near source of water and a relatively flat terrain to avoid costly earthworks (Buford et al., 2012). Moreover, the open systems are susceptible to wind-born biological agents that can affect the cultivation, such as grazers, infectious fungi, lytic bacteria, viruses, other algae, etc., and also lower temperatures in colder climates (Benemann, 2012).

These open pond limitations stimulate PBRs development, however, only a few commercial plants use closed PBRs, mainly due to high costs as abovementioned. Nowadays, according to Benemann (2012) microalgae cannot be grown in PBRs for biofuels and are not even successful for high value products. However, PBRs can be used for seed culture production, though only for ~0.1% of the biomass. Closed photobioreactors are significantly more expensive to construct, but have not been engineered to the extent of other reactors in commercial practice, and so there may be opportunities for significant cost reductions.

Neither open ponds nor closed photobioreactors are mature technologies. Therefore, until large-scale systems are built and operated over a number of years, many uncertainties will remain. Cultivation issues for both open and closed systems, such as reactor construction materials, mixing, optimal cultivation scale, heating/cooling, evaporation, O_2 build-up, and CO_2 administration, have been considered and explored to some degree, but more definitive answers await detailed and expansive scale-up evaluations (Pienkos and Darzins, 2009).

Concerning the various algal species and strains, they vary from study to study, depending on location and culture techniques. For that reason it is not yet possible to predict what species or strain will be the best suited for commercial biofuel production, but it is most likely that it will differ from case to case, depending on the location, cultivation techniques chosen, processing technologies available, nutrients source, local climacteric conditions, among other potential factors.

2.1.2. Harvesting methods

The algal biomass production process requires one or more solid-liquid separation steps. Generally, first stage involves a separation of biomass from the bulk suspension (including flocculation, flotation or gravity sedimentation). The second stage (thickening) raises the concentration of the slurry through techniques such as centrifugation, filtration and ultrasonic aggregation; hence, it is generally a more energy intensive step than bulk harvesting (Brennan and Owende, 2010).

The flocculation is the first (preparatory) stage that is intended to aggregate the microalgae cells in order to increase the effective ‘‘particle’’ size. Unlike flocculation, flotation methods are based on the trapping of algae cells, using dispersed micro-air bubbles. Gravity and centrifugation sedimentation methods are based on characteristics of suspended solids and are determined by density and radius of algae cells and sedimentation velocity. It is the most common harvesting technique for algae biomass in wastewater treatment because of the large volumes treated and the low value of the biomass generated. The filtration process is better suited for harvesting relatively large (>70mm) microalgae such as *Coelastrum* and *Spirulina*. The membrane microfiltration and ultra-filtration (hydrostatic pressure) are viable alternatives to recovery of biomass from smaller algae cells (<30mm), like *Dunaliella* and *Chlorella* (Brennan and Owende, 2010). Some species are much easier to harvest, considering algae densities and size. The strain characteristics, cost and energy efficiency are the main factors to select harvesting technology (Brennan and Owende 2010).

2.1.3. Extraction of algae oil

The common techniques for oil extraction are mechanical pressing, the usage of solvents and supercritical fluid extraction. Each of these different methods presents its own advantages and disadvantages. The oil extraction method can be divided into expression and ultrasonic-assisted extraction and the efficiency normally ranges from 70 to 75% (Rengel, 2008). The main drawback of this method is that it generally requires drying the algae beforehand, which is an energy intensive step.

Using solvents such as n-hexane, benzene, ethanol, chloroform and diethyl ether can efficiently extract the fatty acids from algae cells. However, the use of chemicals in the process could present environmental, safety and health issues. In many cases, manufacturers of algae oil use a combination of mechanical pressing and chemical solvents in extracting oil to improve efficiency (around 95%).

Supercritical extraction requires high-pressure equipment that is both expensive and energy intensive. In this process, carbon dioxide is heated and compressed until it reaches a liquid-gas state. Then, it is applied to the harvested algae and acts like a solvent (Mendes et al., 1995; Ferreira et al., 2013).

Apart from these, there are some other more expensive and less known and utilized methods which are enzymatic extraction that uses enzymes to degrade the cell walls with water acting as the solvent; and osmotic shock, that is a sudden reduction in osmotic pressure that can cause cells in a solution to rupture.

Once the oil is extracted through these methods it is referred to as "green crude". However, it is not ready to be used as biofuel until it undergoes a process called transesterification. This step is a chemical reaction in which triglycerides of the oil react with methanol or ethanol to produce (m)ethyl esters and glycerol (Rengel, 2008). This reaction creates a mix of biodiesel and glycerol that is further processed to be separated and leaves ready to use biodiesel.

Direct conversions from a non-dry state are being studied and some possibilities that may play an important role in offsetting the costs and improve oil extraction efficiency are arising. Among these, it is important to highlight in situ transesterification and hydrothermal liquefaction (Chen et al., 2009; Patil et al., 2008). Nevertheless, due to limited level information in these processes for algae, more research in these subjects is still desirable.

Meanwhile, work is being made to reduce energy input and costs of extraction processes. Many industries claim they have come up with cost-effective methods in this area, however, until large scale facilities are deployed it is hard to tell which one will work in a large scale basis.

The whole algae, bio oil or the residues from oil extraction are excellent feedstock for making other fuels and products via different processes. Some of these products will be presented in the next section.

2.2. Products and processes

Microalgae have been studied for many years for production of goods and special human foods and animal feeds. Moreover, algae can generate a wide range of biofuels, including biohydrogen, methane, oils (triglycerides and hydrocarbons, convertible to biodiesel, jet fuels, etc.), and, to a lesser extent, bioethanol. Meanwhile, these products creation involves different processes such as biochemical and thermochemical conversions or chemical separation or a direct combustion (Huesemann et al., 2010). Like a refinery, it is still possible to obtain other non-energy products in the cultivation of microalgae, such as cosmetics, animal feed, nutraceuticals, among others.

Subhadra and Edwards (2011) analyzed algal biorefinery-based integrated industrial sector that produce primary biofuel (biodiesel) and co-products such as algal meal (AM), omega-3 fatty acids (O3FA) and glycerin. They demonstrated that biorefineries have a clear market for AM and O3FA up to a certain level, thereafter, diversification for other co-products is desirable. However, co-product market analysis and water footprint (WFP) of algal biorefineries need to be studied before large scale deployment and adoption. In addition, Benemann (2012) argued that saying that "animal feeds could be readily co-produced with algae biofuels are incorrect”; because there are significant differences in the processes focus, quantities production, volume and market values, comparing co-products with biofuels. However, algal biofuel can be integrated with aquaculture to treat the wastes.

2.2.1. Human and animal products

The commercial potential for microalgae represents a largely untapped resource, once there is a huge number of algae species. Some microalgae are mainly used to human nutrition, but are suitable for preparation of animal feed supplements. Like a biorefinery, it is possible to produce from biofuel and co-products (especially glycerin) to pigments and nutraceuticals.

The production of microalgae started in the early 1960s with the culture of *Chlorella* as a food additive and had expanded in others countries (Japan, USA, India, Israel, and Australia) until 1980s (Brennan and Owende, 2010). The oil (triglycerides) extract from microalgae *Chlorella*, produced by dark fermentation, has high nutrient value and protein content, and their omega-3 fatty acid – DHA has been used as an ingredient in infant formulas (Brennan and Owende, 2010; Benemann, 2012). *D. salina*, is exploited for its b-carotene content. Many strains of cyanobacteria (e.g. *Spirulina*) have been studied to “produce the neurotoxin β-N-Methylamino-L-alanine (BMAA) that is linked to Amyotrophic Lateral Sclerosis (Lou Gehrig's Disease) (ALS) and Alzheimer’s disease.” (Brennan and Owende, 2010 p. 572). The human consumption of microalgae biomass is restricted to very few species

(*Chlorella*, *Spirulina* and *Dunaliella* species dominate the market) due to the strict food safety regulations, commercial factors, market demand and specific preparation. According to Subhadra and Edwards (2011; p.3520),

> “a market survey of global algal producers indicated that more companies are planning to grow algae and extract the O3FA to market to consumers […] an immediate market of 0.2– 0.4 million ton can be foreseen for algal based O3FA. A small portion can be further refined for marketing as human nutraceuticals and a significant portion for fortifying the AM produced as a co-product by algal biofuel refineries.”

In the end of biodiesel production, it is possible to obtain a significant amount of glycerin that has a clear existing market from many industries such as paint and pharmaceuticals. Some studies “have also shown that glycerin in turn can be effectively utilized to grow more algal biomass, another viable method of using glycerin in algal biofuel industry” (Subhadra and Edwards, 2011; p.3520).

Although the microalgae biomass is being produced essentially to human nutritional products, perhaps it is most attractive as animal feeds (Benemann, 2012). Algae are the natural food source of aquaculture species such as molluscs, shrimps and fish. In addition, it assists the stabilization, improvement and enhancement of the immune systems of these cultures (Brennan and Owende, 2010). They possess high protein rate (typical 50%) and energy content (~20 MJ/kg) and high concentrations of astaxanthin (used in salmon feed) and valuable carotenoids (e.g. lutein - used in chicken feed). Microalgae has also a long-chain of omega-3 fatty acids to replace fish meal/oil (Benemann, 2012).

2.2.2. Energetic products

As stated before, like in a refinery, it is still possible to obtain other products in the cultivation of microalgae, such as methane, biohydrogen and ethanol. Some examples of these possibilities are presented as follows.

2.2.2.1. Methane

Since early studies on microalgae biofuels the production of methane biogas production by anaerobic digestion of biomass was a main focus (Benemann, 2012). This microbial conversion (of organic matter into biogas) produces a mixture of methane, CO_2, water vapor, small amounts hydrogen sulfide and sometimes hydrogen (Gunaseelan, 1997 apud Huesemann et. al., 2010). This process has been successfully and economically viable despite the recalcitrance of some algal species to biodegradation and inhibition of the conversion process by ammonia released from the biomass (Benemann, 2012; Huesemann et. al., 2010). According to Huesemann et al. (2010; p.169):

> "Methane generation by anaerobic digestion can be considered to be the default energy conversion process for microalgal biomass, including algal biomass produced during wastewater treatment and for the conversion of residuals remaining after oil extraction or fermentation to produce more valuable liquid fuels. "

2.2.2.2. Hydrogen

There are three main processes to produce hydrogen from microalgae: dark fermentation; photo-fermentation and biophotolysis. The first involves anaerobic conversion of reduced substrates from algae, such as starch, glycogen, or glycerol into hydrogen, solvents, and mixed acids. Secondly, these organic acids "can be converted into hydrogen using nitrogen-fixing photosynthetic bacteria in a process called photofermentation." The latter, biophotolysis processes use microalgae to catalyze the conversion of solar energy and water into hydrogen fuel, with oxygen as a byproduct (Huesemann et. al., 2010). Although these mechanisms were successfully proven in laboratory scale, they have not yet been developed as a practical commercial process to produce hydrogen from algae (Huesemann et al., 2010; Ferreira et al., 2013).

2.2.2.3. Ethanol

On the other hand, ethanol can be generated from two alternative processes: storage carbohydrates (fermented with yeast) or endogenous algal enzymes (Benemann, 2012; Huesemann et. al., 2010). The main process is "yeast fermentation of carbohydrate storage products, such as starch in green algae, glycogen in cyanobacteria, or even glycerol accumulated at high salinities by *Dunaliella*" (Sayadi et al., 2011). A self-fermentation by endogenous algal enzymes induced in the absence of oxygen has been reported for *Chlamydomonas*. Against the very low ethanol yield from fermentation, several private companies are now reported to be developing ethanol fermentations.

2.2.2.4. Electricity and Gasification

The microalgae biomass can be dried and combusted to generate electricity, but the drying process is fairly expensive even if solar drying is employed. The combustion and thermal process can destroy the nitrogen fertilizer content of the biomass and generate elevated emissions of NO_x. In addition, the combustion process competes with coal and wood biomass that are cheaper than microalgae biomass (Huesemann et al., 2010). Although expensive, this can be a key factor for algae to achieve energetic balance and improve its sustainability as presented in the "environmental assessment" section. Effusive research is being carried in new and more effective drying techniques in order to reduce costs and impacts.

2.2.2.5. Oil

The significant quantities of neutral lipids, primarily as triacylglycerols, can be extracted from the biomass (green algae and diatoms) and converted into biodiesel or green diesel as substitutes for petroleum-derived transportation fuels. “Lipid biosynthesis is typically triggered under conditions when cellular growth is limited, such as by a nutrient deficiency, but metabolic energy supply via photosynthesis is not” (Roessler, 1990 apud Huesemann, et. al., 2010; p.170).

The biodiesel produced from algal oil has physical and chemical properties similar to diesel from petroleum, to 1st generation biodiesel produced from crops, and compares favorably with the International Biodiesel Standard for Vehicles (EN14214) and other national and international norms (Brennan and Owende, 2010).

Algal biocrude could also be produced and mixed with fossil oil in existing oil refineries. When compared to petroleum-derived fuels, algal biocrude can offer several advantages due to its elemental composition, low sulfur content, and relative lack of heavy metals (Liu et al., 2013).

2.2.3. Other products

There are several other products that can be produced from microalgae cultivation. From them, special attention should be given to Glycerol (1,2,3-propanetriol or glycerin) that is a byproduct obtained during the production of biodiesel (Demirbas and Demirbas, 2010). Crude glycerol is the principal byproduct of biodiesel production, which accounts for about 10 wt% of vegetable oil. For every 9 kg of biodiesel produced, about 1 kg of a crude glycerol byproduct is formed (Dasari et al., 2005).

Jet fuels can also be made from microalgae, making it very interesting for the air transportation lack of biofuel options so far. In the same manner, algae biofuel can be made for marine engines and have already been tested in both industries with positive results (Stratton, Wong and Hileman, 2010). Other possibilities of production are biopolymers, P-series fuels, Dimethyl ethers, biofertilizers, among others.

2.2.4. Processes schematics

The main petroleum-based fuels are gasoline and diesel. When biomass is used in the production of biofuels, using different processes, different products can be obtained, such as sugar ethanol, cellulosic ethanol, grain ethanol, biodiesel, pyrolysis liquids, green diesel, green gasoline, butanol, methanol, syngas liquids, biohydrogen, algae diesel, algae jet fuel, and hydrocarbons (Demirbas and Demirbas, 2010). Petroleum-based and bio-based transportation fuels are presented in Figure 3.

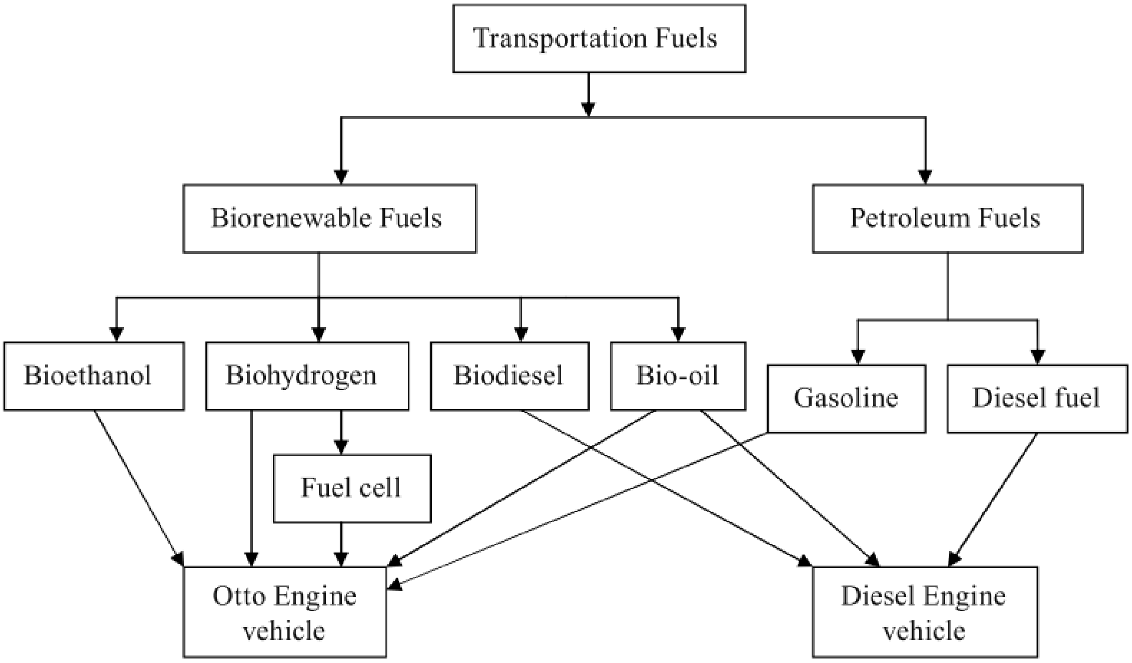


Figure 3: Petroleum and bio-based transportation fuels (Demirbas and Demirbas, 2010).

Focusing only in the renewable biomass part of the diagram, the range of feedstocks processes, and potential products is large. Each combination of feedstock, process, and product is characterized by its own unique combination of technical and economic opportunities, emerging technologies, and barriers (Demirbas and Demirbas, 2010). An overview of conversion routes of plant biomass feedstocks to biofuels is shown in Figure 4.

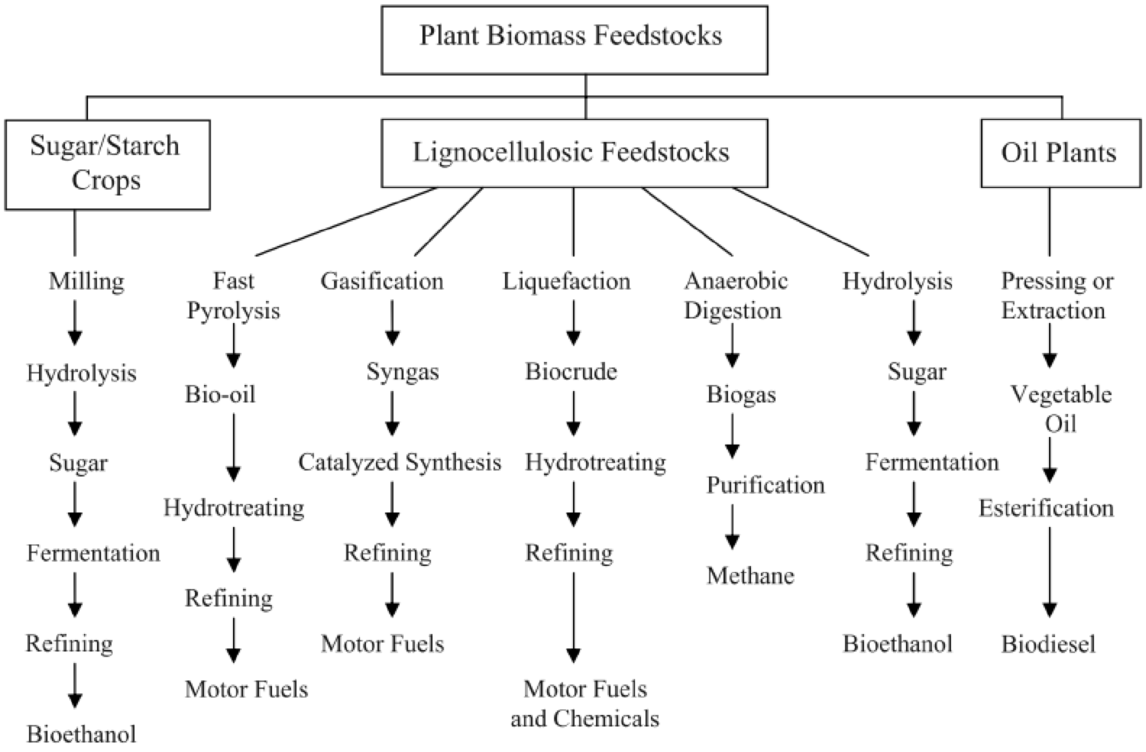


Figure 4: Overview of conversion processes of plant biomass feedstocks into biofuels (Demirbas and Demirbas, 2010).

As said previously, when using algae as a feedstock for biofuels, it is possible to employ the biorefinery so that the overall process becomes more cost-effective. Biorefinery is a conceptual model for future biofuel production where both fuels and high-value co-product materials are produced. Biorefineries can simultaneously produce biofuels as well as bio-based chemicals, co-products, heat, and power. Future biorefineries would be able to mimic the energy efficiency of modern oil refining through extensive heat integration and co-product development. Resources, energy and heat that are produced from some processes within the biorefinery could be used to meet the needs of other processes in the system (Demirbas and Demirbas, 2010). A basic concept of biorefinery is shown in Figure 5.

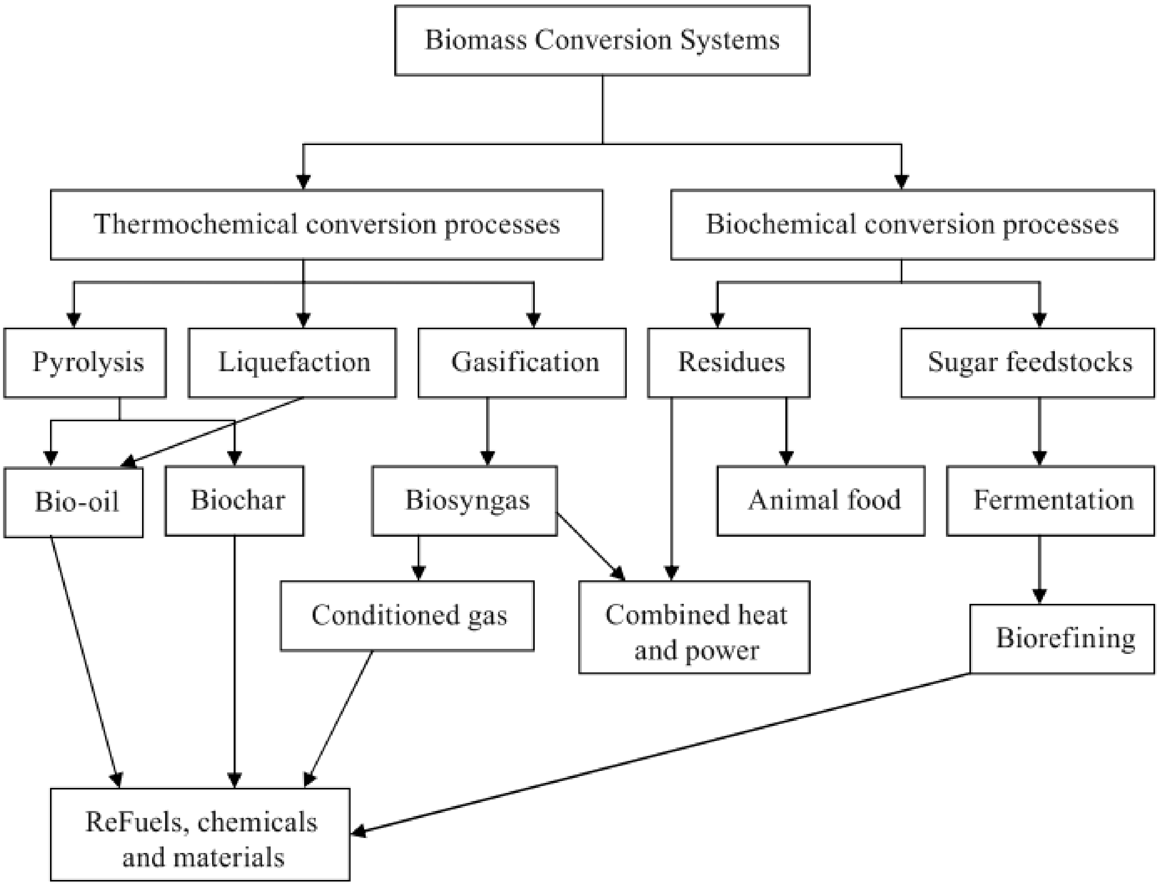


Figure 5: Biorefinery concept (Demirbas and Demirbas, 2010)..

Regarding processes to obtain energy products from microalgae, there are various processes described in the literature. As the cultivation of microalgae is not a mature process to produce biofuels, little is known about which processes are going to dominate the possible algae biorefineries in the future. Depending on the process chosen, different requirements are needed and products are made. Some of these processes are shown in Figure 6 and possible co-products depending on the options made in Figure 7.

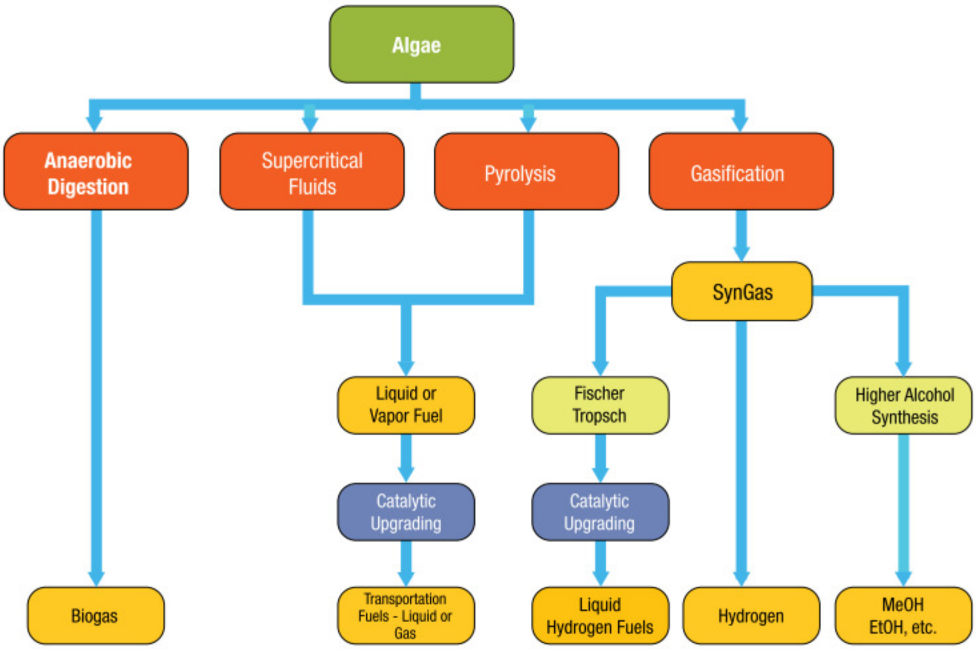


Figure 6: Algae biofuel possible processes (U.S. DOE, 2010).

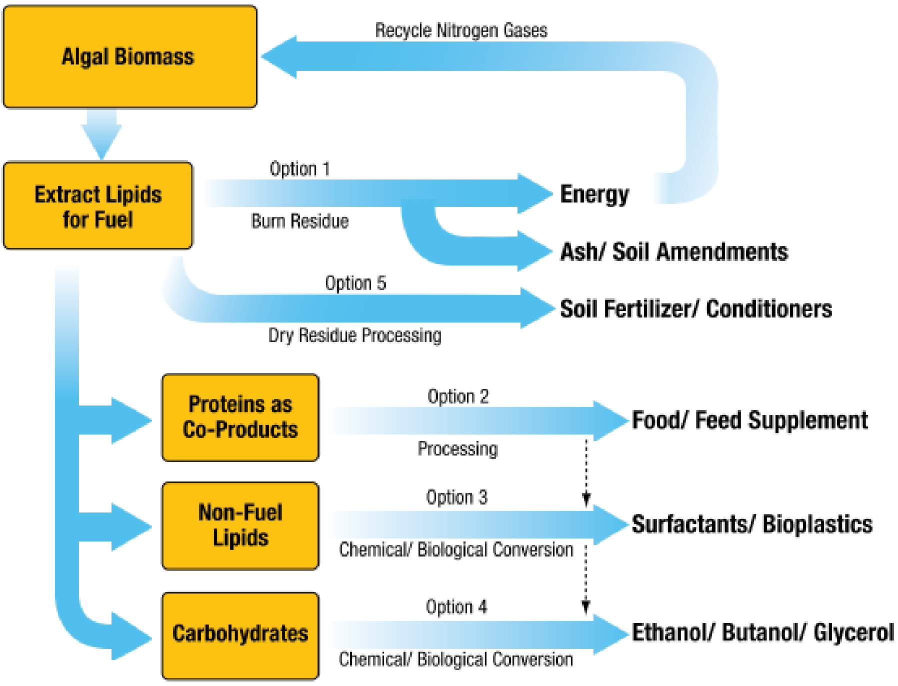


Figure 7: Algae biofuel possible process options and co-products (U.S. DOE, 2010).

A lot of research is been carried in many of these processes so that the overall efficiency in terms of productivity, economical feasibility and environmental impact are enhanced. Unfortunately, so far it is difficult to predict which processes and co-products are going to be the chosen ones in order to maximize the algae biofuel potential.

2.2.5. Productivity and lipid content

When the oil yield of different biofuel crops are compared, it becomes clearer that microalgae biofuels are far more efficient, as demonstrated in Table 1.

Table 1: Comparison of estimated production and land-use requirement from various biofuel crops

Crop	Oil Yield (L/ha)	Land area needed (M ha) [a]
Corn	172	1540
Soybean	446	594
Canola	1190	223
Jatropha	1892	140
Coconut	2689	99
Palm oil	5950	45
Microalgae [b]	**136.900**	**2**
Microalgae [c]	**58.700**	**4.5**

[a] For meeting 50% of all transport fuel needs of the United States.
[b] 70% oil (by weight) in biomass.
[c] 30% oil (by weight) in biomass.
Data source: Chisti, 2007.

From this table is possible to note one of the reasons why algae as a biofuel feedstock has drawn so much attention. However, the microalgal oil yield can vary immensely depending on the cultivation process and algae strain employed. Some of this oil yields as well the algae strain used and the cultivation process can be seen later on Table 3 (section 2.3.2.2.7).

Genetic modification may also be promising in improving biomass and oil productivity (Beer et al., 2009; Radakovits et al., 2010). However, genetically modified highly resilient algae species could have very important and negative impacts on native algal species and to marine and freshwater ecosystems in general (Passell et al., 2013). The overall sustainability of algae biofuels is presented in the succeeding section.

2.3. Sustainability of algae biofuels

In order to address the sustainability of microalgae biofuels, first it is important to conceptualize sustainable development and Sustainability. The concept of sustainable development was described by the Bruntland Commission Report (United Nations, 1987; p.15) as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.

Depending on the author, there are a different number of dimensions to be considered regarding sustainable development. In this study, the dimensions considered are society, environment and economy, which are intertwined. Therefore, sustainability is a paradigm for thinking about the future in which environmental, societal and economic considerations are balanced in the pursuit of an improved quality of life (UNESCO, 2014). The classic "Triple Bottom Line" displayed in Figure 8 represents these dimensions.

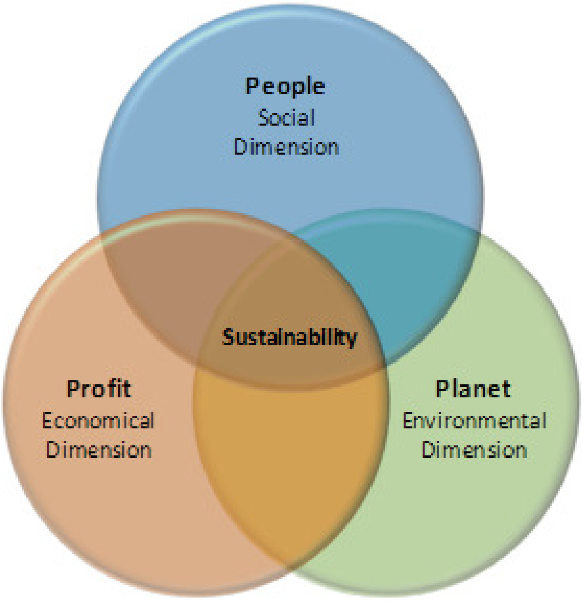


Figure 8: Sustainability Triple Bottom Line

In the next sections the three dimensions abovementioned are discussed having microalgae biofuels in line.

2.3.1. Environmental assessment

This section gathers a comprehensive literature review of the main findings from algae-based biofuels production environmental impacts. Life cycle assessments (LCAs) of published scientific papers and reports were used in the development of the subsequent sections.

2.3.1.1. Land

The production of 1st generation biofuels being based on agricultural products, where land is the main input, represents a shift in land use away from food production and poses a global dilemma: the need to feed humanity *versus* the greater monetary returns to farmers from agro-energy (Azar, 2003). This shift of land use increases food prices and decrease stocks of food products, with respective decline of exports (Rathmann et al., 2010). The increased pressure on arable land could also lead to severe food shortages, in a world where already 842 million people suffer from hunger and malnutrition (FAO, 2013).

As opposed to first generation land-based biofuels produced from agricultural feedstocks, cultivation of algae for biofuel does not necessarily use fertile agricultural land (Iersel and Flammini, 2010; Pittman et al., 2011). Thus, if non-arable land is used in the production of emerging biofuels, all the dire effects just mentioned will not occur. This is said to be one of the main advantages of algae biofuels cultivation and production.

However, emerging biofuel technologies could become unsustainable if they compete with food crops for available land. In this scenario, their sustainability would depend on whether producers comply with criteria such as minimum lifecycle Greenhouse Gas (GHG) reductions, including land use change and social standards (Eisentraut, 2010).

Another important requirement for cultivation is flat land, due to higher costs associated with soil excavation and water pumping (Davis et al., 2012). Just to cite an example of feasible land normally considered in algal biofuel studies, Davis et al. (2012; p.15) from an Argonne and RNEL study characterize the usable land as

> "From the suitable slope areas, only non-agricultural, undeveloped, or low-density developed, non-sensitive, generally non-competitive land was considered for microalgal culture facilities. Specifically, this excludes open water, urban areas, airports, cultivated cropland and orchards, federal and state protected areas such as national and state parks, wilderness areas, wildlife refuges, wetlands, and other areas that are deemed environmentally sensitive."

With the possibility to use non-arable land, microalgae biofuel production has the potential to provide benefits such as making use of abandoned land, promote rural development and improve economic conditions in emerging and developing regions (Singh et al., 2011). This could benefit vast regions in the globe that are not proper for agricultural purposes and, in the present day, are not economically attractive.

As presented in Section 2.2.5 (Table 1), another important quality of algal-based fuels is oil yield. This is a crucial factor to be considered for the diffusion of algae as a feedstock for biofuels, because make it possible to produce large amounts of fuel in considerable less land than 1st generation biofuels. Land use estimates show that algae cultivation on roughly 13% of the United States' land area could meet the nation's total annual energy consumption (Clarens et al., 2010).

Due to all exposed before, when compared to other sources of biofuels algae performs favorably concerning land issues (Figure 9).

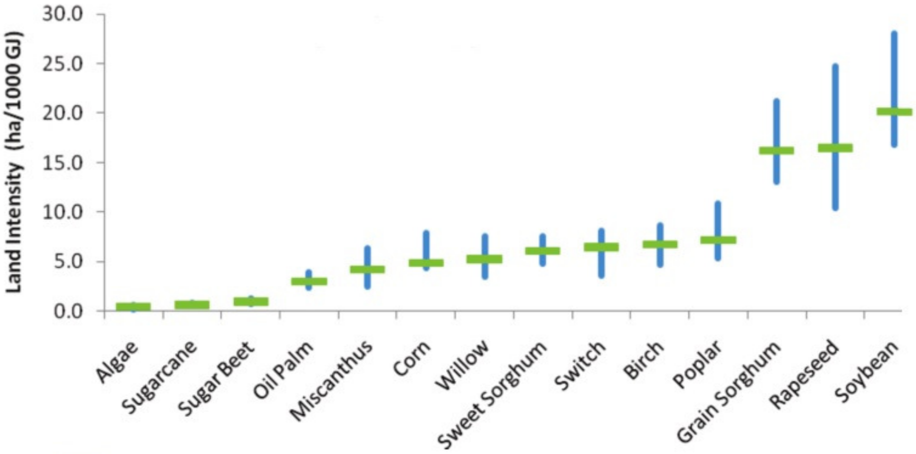


Figure 9: Hectares of land needed to produce 1000 GJ of raw energy (Miller, 2010).

Regarding where are the best places to establish an algae biofuel facility, it is important to take into account the easiness of source of water. Topic that will be discussed in the next section.

2.3.1.2. Water

Water utilization is a key factor on the cultivation of microalgae where a regular source of water supply is fundamental for this process of producing biofuels. As fresh water is a natural resource with a highest consumption rate and increasingly scarce, it can be addressed as a significant environmental concern in the development of algal biofuels, as water is the essential medium of algae growth and many of the world's aquifers are dealing with an unsustainable level of water extraction (Mcgraw, 2009).

It is estimated that algae biofuel production will necessitate a significant amount of annual water utilization. Pienkos (2007) has estimated that in order to displace the entire U.S. diesel demand, which is more than 60 billion gallons per year, the water requirement would be within the range of 16 – 120 trillion gallons of water per year, depending on the efficiency of cultivation and production. Just for comparative purposes, around 5000 trillion gallons of fresh water is used to irrigate the U.S. corn crops, main feedstock of current U.S. biofuel industry (Barton and Clark, 2014).

Although the water issue could become a problem for the cultivation of algae biofuels, one of the advantages of microalgae is that they can be effectively grown in conditions which require minimal freshwater input, thus making the process potentially sustainable with regard to pre-serving freshwater resources (Pittman et al., 2011). The main reason for that is that many algae strains can be cultivated in saline or brackish water. For example, microalgae could be cultivated near to the sea to utilize saline or brackish water and minimize the use of freshwater. For this purpose, there has therefore been significant interest in the growth of microalgae for biofuels under saline conditions (e.g. Rodolfi et al., 2009; Takagi et al., 2006).

However, the need for high amounts of salt water could also generate some concerns, as Mcgraw (2009; p.24) states:

> "Salt water aquifers would, in this case, be the entities under threat resulting in the possible competition and dispute over a previously nearly untouched resource. Coastal operations present problems in coastal management as highly productive ecosystems are typical of coastal regions. Coastlines are naturally dynamic entities and movement will be artificially maintained through the construction of permanent structures under algal biofuels development. These issues can be managed to reduce changes to natural systems, but proper precaution is required."

Even considering the above-mentioned issues, just the possibility of using saline water instead of freshwater, like most of other agricultural-based biofuels, is an advance in the biofuels industry. Nonetheless, the implementation of wide large-scale algae farming for biofuel would raise new questions and concerns regarding saline water resources that need to be addressed in the development this technology.

Ideally, most of algae farms would be located somewhere near (less than 50 km) a saline source of water that would be used in cultivation. Since it is generally not desirable to have to transport the water over long distances as costs will increase sharply in addition to environmental and social impacts that may arise from implementing long distance pipelines (Mcgraw, 2009).

Besides saline water, another great potential in the cultivation of microalgae is the possibility to use wastewater (sewer) as a medium of cultivation and to recycle the water that was used. These opportunities will be handled in the next section as they are closely related to the nutrients that are needed for the algae cultivation.

2.3.1.3. Nutrients

Microalgae cultivation requires a constant supply of several inorganic nutrients, such as nitrogen (N), phosphorous (P), and potassium (K) to maintain high algae yields. One of the concerns regarding future algae large-scale cultivation is the high requirement of nitrogen. Depending on how the cultivation process is managed, this high nitrogen requirement can either have positive or negative impacts on the nitrogen cycle, as nitrogen can be recycled and/or supplied by a waste source (Miller, 2010).

In this context, not only nitrogen requirements take advantage from using wastes, as using municipal wastewaters (sewer) for making up for water and nutrients (C, N, P, etc.) in the cultivation phase can be of great importance in the overall environmental sustainability of microalgae biofuels (Sheehan et al., 1998). Life cycle assessments often point out that much of the life cycle burden associated with microalgae biofuels comes from the production of nutrients, which occurs upstream of the algae-to-energy facility (Liu, 2013; Clarens et al.,2011). Therefore, nutrients are a perennial challenge to large-scale algae bioenergy deployment and maximizing nutrient use efficiency would be a significant element for enhancing the overall life cycle assessment.

In the other hand, providing biological cleaning in the municipal wastewater could be of great help on lowering environmental impacts and water treatment costs in communities, a win-win situation in which it would decrease the need for nutrients in the algae cultivation while providing a useful service for society. Sewage effluent and industrial nitrogenous waste, such as that from aquaculture and manure from animal farms could also be mitigated and remediated through the use of microalgae growth (Mcgraw, 2009). A significant advantage of algal employment in wastewater treatment over the conventional chemical-based treatment methods is the potential cost saving and the lower level technology that is used, therefore making this approach more attractive to developing countries (Pittman et al., 2011). While the use of wastewater for algal biomass cultivation could help minimize algal nutrient requirements it could also decrease algae biofuels water footprint (Yang et al., 2011).

Another interesting practice already used in many industries, is to recycle the water used in the process. In this way, apart from using much less water in the overall process, harvested water recycling can significantly reduce the nutrient usage (Yang et al., 2011). Yang et al. (2011) LCA study shows that when the harvest water is 100% recycled, the usage of these nutrients decreases by approximately 55% and the need of water is reduced 84%. Furthermore, the study shows that using sea water as culture medium also decreases water requirement, and eliminates the need of all the nutrients except phosphate as shown in Figure 10.

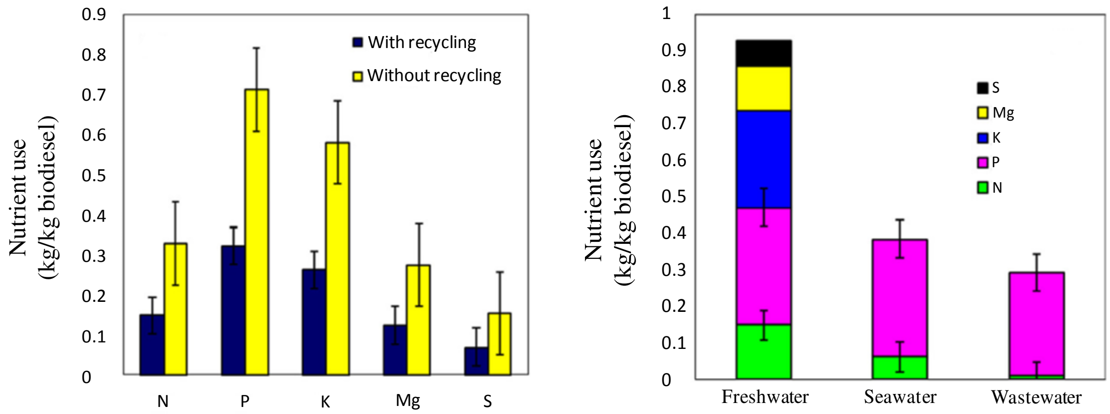


Figure 10: Life cycle use of nutrients in freshwater medium with/without harvest water recycling (left) and life cycle use of nutrients in sea and wastewater medium with 100% harvest water recycling (right). (Yang et al., 2011)

Thus, the use of sea and wastewater resources may be a viable means to enhance the environmental sustainability of algal biofuel production, by providing a dual use process, an effective growth medium for algal cultivation and freely available nutrients (Pittman et al., 2011).

2.3.1.4. Air

In the majority of microalgae cultivation, carbon dioxide must be fed constantly during daylight hours, in fact CO_2 supply is essential for high productivity. In this way, algae facilities can potentially use some of the carbon dioxide that is released in power plants by burning fossil fuels or other industrial processes. This CO_2 is often available at little or no cost (Chisti, 2007). This sort of fixation is already being made in some large algae companies in a trial basis; though, there is a lack of public data of the results yet. Although this is a very promising future possibility, and some species have proven capable of using the flue gas as nutrients, there are few species that survive at high concentrations of NO_x and SO_x present in these gases (Brown, 1996). In the same manner, algae can even capture other pollutants from combustion gas, so whenever possible, algae cultivation should be co-located with CO_2 emitting industries (Iersel and Flammini, 2010).

Considering recent LCA studies, Liu et al. (2013) presented promising results concerning the overall GHG emissions and Energy Return on Investment (EROI) performance of producing biofuels from algae. This study is based on the results of a hydrothermal liquefaction (HTL) pilot-scale facility in which they also presented lab scale and a future full scale results. This study is of great importance because it was based on pilot-scale data, while most of algae research so far are based on laboratory-scale research and theoretical studies.

Liu et al. (2013) results demonstrate that the deployed algae-to-energy production processes in the pilot-scale scenario have energy burdens and GHG emission profiles that are comparable to or better than conventional biofuels, cellulosic ethanol and soybean biodiesel. The GHG emissions comparison with other algae fuels processes are also lower than other existing algae-to-energy processes based on transesterification as captured in the Meta-Model of Algae Bio-Energy Life Cycles (MABEL) (Liu et al., 2013). Their results are shown in Figure 11.

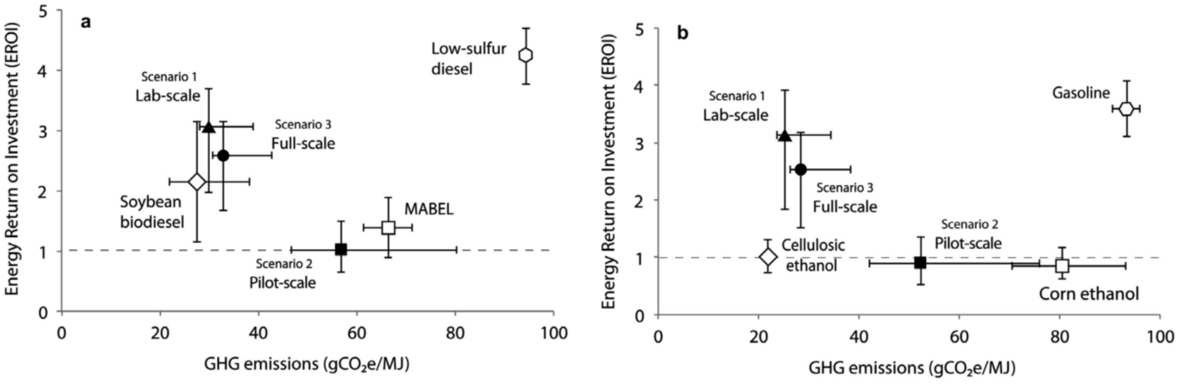


Figure 11: The EROI ratio and GHG emissions/MJ of (a) algae-derived diesel and (b) algae-derived gasoline produced using HTL (Liu et al.,2013).

The results are benchmarked against commercialized biodiesel or bioethanol as well as petroleum-derived versions of the drop-in fuels. Better outcomes are in the upper left hand corner of the plots (i.e., high EROI, low GHG emissions). Error bars correspond to 90% confidence intervals from the Monte Carlo simulations carried out here. The estimates came from (Hill et al., 2006) for soybean biodiesel; (California Air Resources Board, 2009; Wang, 2009) for cellulosic ethanol; (Frank et al., 2011; Wang, 2009; Farrell et al., 2006) for corn ethanol; and (Liu et al.,2012) for MABEL.

For analyzing the graph, the lower the life cycle GHG emissions the better and the higher the EROI the better, making it desirable fuels that appear in the top left hand side of both graphs. A separate analysis of the presented results show that the pilot-scale EROI is approximately 1, however, with the increase in efficiency and scale the full-scale scenario could reach an EROI between 2.5 and 3, using the described technology. Nonetheless, it is important to stress that EROI metrics ignores market factors that would make some energy outputs (e.g., liquid fuels) more desirable than others (e.g., CH_4) (Liu et al., 2013).

It is also important to notice that the soybean biodiesel results presented does not incorporate indirect land use effects, which are important factors influencing the carbon accounting of 1st generation biofuels. Although, these effects were also not considered for algae, it is expected that algae's indirect land use carbon impacts will be much smaller than those of other crops because algae can be cultivated on marginal land as already discussed in Section 2.3.1.1.

Others LCAs accounted for microalgae biofuels production GHG emissions and EROI, with different results. Regarding GHG emissions, in Zaimes and Khanna (2013) results, life cycle GHG emissions accounted for -46.2 to 48.9 g CO_2 eq/MJ-biomass, while Campbell et al. (2011) GHG emissions ranged from -27.6 to 18.2 g CO_2 eq/MJ-biomass. Batan et al. (2010), considering a pond-to-pump system boundary, found net GHG emissions comparable to the net GHG emissions for soy biodiesel, and much more favorable than the net GHG emissions for conventional diesel. Sander and Murthy (2010) also using the pond-to- pump system boundary, found GHG emissions both greater and lesser than those for conventional gasoline depending on different algae processing steps. Clarens et al. (2010) base case found that GHG emissions were much greater than canola, corn, and switchgrass feedstocks, although cultivation using waste CO_2 and wastewater nutrients could reduce those burdens. Passell et al. (2013) results for the base case and the future case show a Global Warming Potential (GWP) of 2.9 and 0.18 kg CO_2-equivalent, respectively. In comparison, petroleum diesel and soy diesel and GWP of 0.12 and 0.025, respectively. Frank et al. (2012) results from the baseline scenario produced 55400g CO_2 equivalent per MBtu of algae biodiesel compared to 101000g for low-sulfur petroleum diesel. Their analysis considered the potential for greenhouse gas emissions from anaerobic digestion processes commonly used in algal biofuel models.

Regarding energy use, Clarens et al. (2010) found that energy use were much higher when compared to canola, corn, and switchgrass feedstocks. However, Clarens et al. (2011) built upon their earlier study and found a net positive energy balance for various combinations of algae biodiesel production coupled with use of waste CO_2 and wastewater nutrients when compared to terrestrial feedstocks. Zaimes and Khanna (2013) EROI results for microalgae biomass vary from 0.38 to 1.08. Jorquera et al. (2010) analyzed algae biomass production (but not extraction, separation, or conversion to biodiesel) and found positive energy balances for production in both flat plate photo-bioreactors and open ponds. Frank et al. (2012) study shows a total energy use for algal biodiesel three times higher than petroleum low-sulfur diesel.

Another metric to analyze the energy performance is the use of the cumulative Net Energy Ratio (NER), and is defined as the energy in algal biofuel divided by the cumulative energy demand of the process. It is a common tool used to show how 'efficient' that technology is in terms of providing energy to society. The greater the Net Energy Ratio (NER), the better.

Batan et al. (2010) results of NER for microalgae biodiesel were less than 0.93. Lardon et al. (2009) provide NER values of 1.96, 1.04, 1.47, and 0.74 depending on the production and oil extraction processes. Frank et al. (2011) provide an NER of 2.58. Sander and Murthy (2010) found NERs greater than 1 across a range of analyses, depending on different algae processing steps. Vasudevan et al. (2012) NERs are 0.3 and 2.5, depending on the extraction process.

As seen so far, the processes used to cultivate and produce the biofuels is determinant to the overall environmental performance of microalgae biofuels. In the same way, Stephenson et al. (2010) compared open raceway ponds with closed air-lift tubular bioreactors for producing biodiesel regarding to environmental impacts. Their study has shown that open ponds would have a GWP ~80% lower than fossil-derived diesel (on the basis of the net energy content), and if compared to bioreactors, the GWP would be ~273% higher than the energetically equivalent amount of fossil-derived diesel. The energy results also has shown that open cultivation performs better, 85% lower energy requirements than fossil-derived diesel; where with closed PBRs there is 362% higher energy needs. In their study, raceways would be energetically self-sufficient, with the heat and power requirement of the process being provided by combusting the methane generated from the anaerobic digestion of the residual algal biomass (Stephenson et al., 2010).

Taking into account all exposed in this section, a discussion about all the possibilities and environmental impacts is presented in the next section.

2.3.1.5. Discussion

From all the aspects presented, so far it is not possible to say that using microalgae as a feedstock for producing biofuels is environmentally sustainable. It is plausible to state that it can be environmentally sustainable, depending on which cultivation processes are chosen. Microalgae's life cycle energy balance and GHG impacts are highly dependent on cultivation and harvesting parameters.

In order to reach the ideal scenario, a high level of logistics must be taken place. Therefore, the location of the algae farm facility must take into account a somewhat near source of saline water, non-agricultural land, a source of wastewater and a source of available CO_2. Moreover, the employment of processes comparable to the use of biogas for both heat and electricity via a combined heat and power (CHP) system would reduce GHG and are also where biggest attractiveness lies. Apart from that, new technologies, which require less energy, need to be explored to enable the overall process to be more energy efficient.

CO_2 supply is an important upstream burden that influences the overall life cycle of algae cultivation. Microalgae facilities could significantly improve their overall GHG footprint if they could switch from using industrial CO_2 (i.e., produced via natural gas scrubbing or from dedicated wells) to newer CO_2 capture technologies (e.g., capture from the air or as a byproduct of other industrial processes). Anyway, a lot of CO_2 sources are available and algal ponds could be co-located with CO_2 sources, or even vice-versa (Sheehan et al., 1998).

Regarding water requirements, many wastewater and saline water resources may be available and suitable for microalgae production, while compensating for the input of many nutrients. Wastewater use could offset nutrient and CO_2 demands and enhance the environmental assessment of algal biofuels. In the same manner, non-agricultural land is hardly a limitation, making resource limitations not a feasible argument against microalgae biofuel systems.

Another very important topic is oil yields, since the environmental performance of microalgal biodiesel is highly sensitive to the oil content, esterification rate and drying rate. The amount of GHG decreases when the microalgae yield increases, therefore, it is important to achieve high yields of biomass and oil in the cultivation plant (Yanfen, Zehao and Xiaoqian, 2012).

However, finding strains of algae that could perform well within all the processes described above is not a straightforward task. Thus, the utilization of genetic modified organisms may represent a potential field to be studied, although it may generate undesired problems in the diffusion acceptance and in the overall environmental sustainability.

Moreover, even though the Energy Return on Investment (EROI) ratios of algae-to-energy production are not as favorable as petroleum fuels today, improvements in the short term tend to make algae liquid fuels competitive on an energy basis (Liu et al., 2013). In addition, projections suggest that algae-based biofuels are set to surpass advanced biofuels (e.g., cellulosic ethanol) in terms of both EROI and GHG emissions.

As far as our concern, using microalgae as a feedstock for biofuels can reach significantly GHG reductions in relation to fossil and other bio-based fuels and reach a better EROI with the use of appropriate technology and processes options. Therefore being a environmentally sustainable biofuel.

2.3.2. Economical assessment

This section presents the main findings from a comprehensive literature review carried out on algae-based biofuels production costs throughout the world. The search was conducted with a focus on available scientific papers to gather studies that have been published during the last two decades containing detailed information on the methodology, assumptions and data used.

2.3.2.1. Methods

The chosen papers were the ones that shared common characteristics, namely providing simultaneous information about the 9 elected costs and technical specific indicators. The selected studies main results are summarized in Table 3. Several other articles, although equally relevant, were withdrawn from our sample because they did not comply with our current data systematization and others were excluded due to lack of transparency or sufficient quantitative information. It is also important to notice that not all studies deliver the cost of production values in the same manner. Some present the costs of producing algal biomass and others deliver the costs of producing oil, as illustrated in Table 3. For some surveyed studies, the original outcomes were further calculated to express the results in dollars, kg and liters. A dataset was built accordingly to the above-mentioned methodology and comprised specific cost related indexes (Ribeiro and Silva, 2013), presented and analyzed in the next section.

2.3.2.2. Analysis of surveyed studies

2.3.2.2.1. Oil by Weight

Microalgae produce storage lipids in the form of triacylglycerols (TAGs). The percentage of lipids is strongly related to the species or on how the cultivation process is made, as many microalgae species can be induced to accumulate substantial quantities of lipids. In this study, not all reviewed studies expressed the percentage of oil by weight of biomass, but analyzing those that provide these numbers, it is clear the wide range of values that can be achieved. The percentages of oil by weight varied from 10% to 60% and there was not a clear correlation between price and oil by weight in the selected studies.

2.3.2.2.2. Oil Yield

Similarly, significant variations were verified among oil yields from different authors. This was an expected outcome due to the utilization of different species and cultivating techniques. In spite of being an expected result, it is an important data when comparing species, techniques and costs among the studies, for example to select the more adequate species for cultivation. On the other hand, these comparisons have to be made carefully, due to different units in which the results are presented.

2.3.2.2.3. Cost per liter of oil

This item is one of the main issues of algae biofuel nowadays, if not the most important one. Every effort is being made to reduce this figure, so that algae biofuel can be more competitive and can be a viable alternative in of transportation fuels market. The data vary widely from study to study, with conclusions stating that it is economically feasible or impossible to be competitive. The prices shown are not normalized for today prices, as they represent what authors found at that point of time. The economical feasibility of microalgae is one of the main drawbacks of this technology for producing biofuels. Algal biofuels have to be cheap to compete with other biofuels and also with the currently dominant fossil fuels. Given the long-term uptrend in crude oil prices, the real competitive price level for algal biofuels can be far higher and it could be nearer than predicted, although it is impossible to predict exactly when that will happen.

2.3.2.2.4. Cost per kg of dry algae biomass

The cost per kg of dry algae biomass is an alternative measure for evaluating the economically feasibility of this technology, as it is the raw material from where the oils are going to be extracted. Likewise to the cost per liter of oil, it was verified significant variations among different studies, depending on the processes and procedures used to obtain it.

2.3.2.2.5. Type of production and culture

The types of production found were open ponds, photobioreactors (PBRs) and using fermentors. Concerning the various algal species and strains, they vary from study to study, depending on location and culture techniques. For that reason it is not yet possible to predict what species or strain will be the best suited for commercial biofuel production, but it is most likely that it will differ from case to case, depending on the location, cultivation techniques chosen, processing technologies available, nutrients source, local climacteric conditions, among other potential factors.

2.3.2.2.6. Co-products

Many of the authors refer the possibility of commercializing co-products generated in the production of algae biofuels. As stated before, algae can also produce valuable co-products, such as proteins, natural colorants, and biomass after oil extraction, that can be used as animal feed, as medicines or as fertilizers (Brennan and Owende, 2010; Spolaore et al., 2006), or, additionally, can be fermented to produce ethanol, methane or other biofuels (Hirano et al., 1997). Although this possibility is widely reported, just a few studies (Benemann and Oswald, 1996; Moheimani, 2005; van Harmelen and Oonk, 2006; Dmitrov, 2007; Alabi et al., 2009; Williams and Laurens, 2010) looked deeply tino this issue and provided financial calculations on the feasibility of producing biofuel and co-products together. This could be a promising opportunity to make algae biofuel more economically feasible. With the production of many products in algae cultivation (as it is done in a petrochemical refinery for fossil), technical and in particular economical efficiency can arise in the joint production of two or more products. If the cost of producing two products by one firm is less than the cost of producing the same two products by two firms, the production process exhibits economies of scope (Rothwell, 2000). Thus, it is expected a reduction in the price of algae biofuels in the coming years, if this approach is followed. In Table 2, a broad analysis of some possible commercial markets is presented.

Table 2: Summary of microalgae commercial products market

Commercial Product	Market Size (tons/yr)	Sales Volume (Millions $US/yr)	Reference
BIOMASS			
Health Food	7,000	2,500	Pulz and Gross (2004)
Aquaculture	1,000	700	Pulz and Gross (2004); Spolaore et al. (2006)
Animal Feed Additive	N/A	300	Pulz and Gross (2004)
Poly-Unsaturated Fatty Acids (PUFAs)			
ARA	N/A	20	Pulz and Gross (2004)
DHA	< 300	1,500	Pulz and Gross (2004); Spolaore et al. (2006)
PUFA Extracts	N/A	10	Pulz and Gross (2004)
GLA	Potential Product		Spolaore et al. (2006)
EPA	Potential Product		Spolaore et al. (2006)
Anti-Oxidants			
Beta-Carotene	1,200	> 280	Pulz and Gross (2004); Spolaore et al. (2006)
Tocopherol CO2 Extract	N/A	100-150	Pulz and Gross (2004)
Coloring Substances			
Astaxanthin	< 300	< 150	Pulz and Gross (2004); Spolaore et al. (2006)
Phycocyanin	N/A	> 10	Pulz and Gross (2004)
Phycoerythrin	N/A	> 2	Pulz and Gross (2004)
Fertilizers/Soil Conditioners			
Fertilizers, growth promoters, soil conditioners	N/A	5,000	Pulz and Gross (2004); Metting and Pine (1986)

Source: U.S. DOE, 2010.
N/A: Not available

From the possibilities presented above, all these markets are currently growing and can be explored by the algae industry. Naturally, the conceivable co-products to be produced depend on the type of processes employed and algae strains. For example, the use of flue gases or wastewater rich in heavy metal contaminants could impact the suitability of using residual biomass for co-products like human food and animal feed. Yet, when producing other co-products such as protein in conjunction with substantial amounts of biofuels, it is a potential threat the saturation of potential markets, due to the large amounts produced (Dmitrov, 2007).

2.3.2.2.7. CO_2 paid/free/revenue

The input of CO_2 needed for most of the processes could be provided for free, with no financial counterpart, it could be bought (paid) or some company that produces a considerable amount of CO_2 could pay the algae biofuel producer to process this CO_2. So far, this last option is just a possibility for future financial calculations, as all the studies surveyed or accounted CO_2 for free or paid for this gas. The existing and future Carbon Markets, coupled with more stringent limits of the emissions, may lead to companies increasingly paying to dispose off of their CO_2 emissions, and this may represent a reduction in the productions costs, resulting in lower microalgae fuel prices. Thus, the fixation of the waste CO_2 of other sorts of business could represent another source of income to the algae industry.

2.3.2.2.8. Commercial

Most of the studies available in the open literature are based on small-scale laboratory experiments, not commercial facilities already selling algae biomass and/or biofuels. As most of the algae biofuel production so far was made in experimental facilities with low capacity of fuel production, and with many companies expanding their facilities, it is expected that this will lead to economies of scale, now that production is increasing and average costs of cultivating algae are falling (and marginal costs are below average cost) (Alabi et al., 2009). In this context, it is also expected that the efficiency of such companies rise. In this regard it is possible to differentiate "technical efficiency" and "economical efficiency". Technical efficiency implies that the maximum output has been produced with a given set of inputs, giving that the most adequate technologies and processes are used. Economical efficiency implies that the maximum output has been produced at a given (opportunity) cost, or that a minimum (opportunity) cost has been achieved for a given level of output (Alabi et al., 2009). With a large set of alternatives of inputs and outputs within a developing market such as the algae one, it can be complex and hard to achieve the technical and economical efficiency in the near future, but as the time goes by and the technology matures, better trends in production will arise.

Table 3: Costs for algal biomass and biodiesel production: relevant data, processes and key results

Authors	Year	Oil by Weight	Oil yield	Cost per liter of oil (L^{-1})	Cost per Kg of dry algae biomass (Kg^{-1})	Type of Production	Culture	Co-products	CO2 paid/free /revenue	Commercial	Country
Gladue and Maxey	1994	50%	20g.L^{-1}.d^{-1}	NM	$12	Fermentor	N. alba	No	NM	No	USA
Benemann and Oswald	1996	50%	30g.m^{-2}.d^{-1}	$0.43	$0.24	Open	NM	Yes	Paid	Yes	USA
Sheehan et al.	1998	40%	67,5 mt/ha/yr	$0.63-1.01	NM	Open	NM	No	Paid	No	USA
Lee	2001	NM	25g.m^{-2}.d^{-1}	NM	$8-15	Open	NM	No	NM	Yes	Singapore
Benemann et al.	2002	NM	33g.m^{-2}.d^{-1}	NM	$0.10	Open	NM	No	Free	No	USA
Molina Grima et al.	2003	10%	1,25Kg.m^{-3}.d^{-1}	NM	$32.16	PBR	*Phaeodactylum*	No	Paid	No	Spain
Behrens	2005	NM	5,8g.L^{-1}.d^{-1}	NM	$2.01	Fermentor	NM	No	NM	Yes	USA
Moheimani	2005	NM	15,6-20 and 20g.m^{-2}.d^{-1}	NM	$7.87. $11.23 and $9.87	Open	*P. carterae and D. salina*	Yes	Paid	No	Australia
Harmelen and Oonk	2006	30%	27g.m^{-2}.d^{-1}	$1.06	$0.29	Open	NM	Yes	Free	No	Netherlands
Chisti	2007	30%	72 and 35g.m^{-2}.d^{-1}	$1.41 and $1.81	$0.47 and $0.60	PBR and Open	NM	No	Free	No	New Zeland
Dmitrov	2007	15%-25%	0,14-0,33 L/m^2/yr	$5.38	NM	PBR	NM	Yes	Free	No	USA
Li, Xu and Wu	2007	44%-48%	12,8-15,5g.L^{-1}.d^{-1}	$2.40	NM	Fermentor	*Chlorella protothecoides*	No	NM	No	China
Alabi, Tampier and Bibeau	2009	15%, 25% and 50%	9,38, 15,3.m^{-2}.d^{-1} and 50g.L^{-1}	$14.44. $24.6 and $2.58	$2.66. $7.32 and $1.54	Open, PBR and Fermentor	NM	Yes	Free	No	Canada
Pate	2009	Vary	Vary	$2.38 - 4.49 and $5.28 - $10.30	Vary	PBR and Open	NM	No	Vary	Vary	USA
Williams and Laurens	2010	15%-50%	18-37g.m^{-2}.d^{-1}	$0.79 - $3.08	$0.36 - $0.65	Hybrid Open/PBR	NM	Yes	Free	No	UK
Davis, Aden and Pienkos	2011	25%	25.m^{-2}.d^{-1} and 1.25Kg.L^{-1}	$2.25 - $4.78	$0.36 - $0.65	Hybrid Open/PBR	NM	Yes	Free	No	UK

*For conversion, a barrel was calculated as 159 liters, a US gallon 3,78 liters and currency conversions are: $ Aus/$ US=1,05 and €/$ US= 1,4.

** NM: Not mentioned

The sample of surveyed results was displayed chronologically, in order to assess the existence of any type of progress in the indicators values over a time frame of almost 20 years. However, there is no evident evolution in the outcomes along the years, what reinforces the need for more research focused in the economical aspects of microalgae production. Few cost estimates are also available, what justifies the apparent shortness of our database. However, it can be concluded that to reach commercial viability, costs will need to be substantially reduced. Given the early stage of this technology and its rapid development, cost reductions may indeed be possible.

2.3.2.3. Discussion

The basic economic motivation for biofuels resides in the fact that they are a convenient, low-priced, domestically producible and a substitute for oil. In the presented survey it became clear that algae are now being intensively researched as a potential biofuel feedstock. Although many testing and start-up companies are in operation in several countries, cost information is scarce.

The problems concerning large-scale production of biofuels from algal farms include inconsistent and insufficient algal productivities, uncertain capital and operating costs, volatile market prices and unknown levels of government support. This survey permits to conclude that although intensive work is being done on many technological issues, economic studies and respective data are scattered, incomplete and divergent. Also, this paper provided both, a chronological perspective and an updated analysis of the production and economic conditions that are certainly going to have a profound effect on the success of this important alternative fuel production process. From our assembly of nine elected indicators, cost per liter of oil clearly appears to be a key determinant for eventual market success, in spite of the discrepancy of its proposed values and no clear trend of findings over time.

By assessing the costs of different algae cultivation techniques, it is apparent that the current economic situation standpoint towards large-scale production of algae biodiesel has not yet seemed to be viable as a solution to displace petroleum-based fuels. In the present situation, the technology to efficiently produce biodiesel from microalgae is not competitive with more advanced and emerging renewable technologies. However, the currently fast rate of development of algae biofuel technology and the actual rising of petroleum-based fuels prices are encouraging algae-based biofuels feasibility in the next few years.

Moreover, with policy support and incentives, it is expected that the algal biofuel industry will continue to develop and assuming that this technology follows renewable energy cost trends, costs will decrease to eventual economic viability. In parallel, processes must be developed to reduce costs and increase production.

2.3.3. Social assessment

Not much is found in the literature regarding the social impacts of a microalgae biofuel future. However, from the overall technical, environmental and economical assessments it is possible to believe that algae farming have the potential to stimulate the economy, provide jobs, and alleviate poverty. In developing countries, the potential job creation could provide social and economic benefits (Mcgraw, 2009).

Taking the advanced biofuels industry as a comparative of jobs created, it is possible to present the following data on Table 4.

Table 4: Prediction of jobs created from 27 U.S. advanced biofuel new facilities coming online in 2015

	Capacity	Direct	Construction	Indirect	TOTAL
Reported	643.49	1,443	4,408	2,564	8,415
Per Million Gallon		2.24	10.29	14.66	
Total Estimated (low)	676.95	1,518.03	6,965.61	9,924.52	18,408
Total Estimated (high)	1,756.78	3,939.50	18,076.67	25,755.45	47,772

Source: Solecki et al. (2012).

Of the 27 commercial U.S. advanced biofuel facilities that are scheduled to come online by 2015, 24 reported permanent operation job estimates, 12 reported peak construction job estimates, and 7 provided indirect job estimates (Solecki et al., 2012). Using this data, Solecki et al. (2012) looked at job estimates on a per gallon basis and concluded that a million gallons of production capacity generates 2.24 permanent jobs, 10.29 construction jobs, and nearly 15 indirect jobs on average. Multiplying these averages against their low and high-end production scenarios for commercial facilities, they found the data presented on Table 4. Both direct and indirect jobs are permanent positions. Biofuel producers report that fuel production jobs will be full-time skilled and unskilled positions, starting around US$30,000 to 40,000 per year. Solecki et al. (2012) estimates do not include permanent and temporary jobs created in related industries, such as technology, equipment manufacturing, or transportation. Nor does it account for PhD level research and development jobs, which according to Bio-era (2009) could reach 12,100 by 2022.

Still according to Bio-era (2009), U.S. direct job creation from advanced biofuels production could reach 94,000 by 2016 and 190,000 by 2022. Total job creation, accounting for economic multiplier effects, could reach 383,000 in 2016 and 807,000 by 2022.

Beyond job generation impacts, since microalgal biofuels do not need "geographical proven reserves", they may allow for increased independence on foreign energy and increase the energy security of many countries, as developing domestic sources of energy are key to promoting energy security. Moreover, for developing countries with high levels of poverty, the relationship of increased consumption of energy and well-being is stronger. Providing economic stimulus for such countries, algal biofuel production would provide jobs, energy availability and security, while encouraging infrastructure development and social development such as better health services (Mcgraw, 2009).

Tackling the food *versus* fuel problem make it possible for countries to better manage its agricultural and non-agricultural land, increasing food plantation lands and decreasing hunger. Finally, overall environmental positive effects could lead to lower pollution, better population health and better quality of life.

2.3.4. Comparing feedstocks for biofuel

Biofuel production could be made from several sources. Among crops, it could be obtained from corn, sugar cane, switch grass, soybeans, rapeseed, canola, etc. Each crop has its own impacts and land-use requirements as identified in Table 5.

Table 5: Comparison Of Biofuel Feedstock Environmental Impacts For Transportation Fuels

Crop type	Used to Produce	Use of resources during growing, harvesting and refining of fuel				Pros & Cons
		Water	Fertilizer	Pesticide	Energy	
Corn	Ethanol	High	High	High	High	Technology ready and relatively cheap; reduces food supply.
Sugar cane	Ethanol	High	High	Med	Med	Technology ready; limited as to where it will grow; reduces food supply.
Switch grass	Ethanol	Med-low	Low	Low	Low	It will not compete with food crops; technology not fully ready.
Wood residue	Ethanol, Biodiesel	Med	Low	Low	Low	Technology ready; reduces food supply.
Soybean	Biodiesel	High	Low-med	Med	Med-low	Technology ready; reduces food supply.
Rapeseed, Canola	Biodiesel	High	Med	Med	Med-low	Technology ready; reduces food supply.
Algae	Biodiesel, Ethanol, Gasoline, Bio-oil	Med	Low	Low	Med-High	Potential for huge production levels; technology not fully ready for scale up.

Data source: Adapted from Groom et al., 2007.

Comparing to other sources of feedstock to produce biofuels, algae-based biofuels have several advantages. These advantages are: (1) microalgae are capable of producing oil during all year long, therefore the oil productivity of microalgae is higher when compared to the most efficient crops; (2) microalgae can be produced in brackish (salt) water and on not arable land (Searchinger et al., 2008); not affecting food supply or the use of soil for other purposes (Chisti, 2007); (3) microalgae have a fast growing potential and several species have 20 to 50% of oil content by weight of dry biomass (Chisti, 2007); (4) Regarding air quality, production of microalgae biomass can fix carbon dioxide (1 kg of algal biomass fixes roughly 1.83 kg of CO_2) (Chisti, 2007); (5) Nutrients for the cultivation of microalgae can be obtained from sewage, therefore there is a possibility to assist the municipal wastewater treatment (Cantrell et al., 2008); (6) Growing algae do not need the use of herbicides or pesticides (Rodolfi et al., 2009); (7) Algae can also produce valuable co-products, as proteins and biomass after oil extraction, that can be used as animal feed, medicines or fertilizers (Spolaore et al., 2006; Brennan and Owende, 2010), or fermented to produce ethanol or methane (Hirano et al., 1997); (8) Biochemical composition of algal biomass can be modulated by different growth conditions, so the oil yield can be significantly improved (Qin, 2005); (9) microalgae are capable of performing the photobiological production of "biohydrogen" (Ghirardi et al., 2000) and (10) Low sulfur and relative heavy metals-free algal biocrude could also be produced and mixed with fossil oil in existing oil refineries (Liu et al., 2013).

The above combination of the potential for biofuel production, CO_2 fixation, wastewater treatment and the possibility of production of biocrude highlight the potential applications of the microalgae cultivation. Compared to other biofuel technologies, the most favorable factors for the cultivation of microalgae for the production of biofuels is that they can be grown in brackish water, on non-fertile land and the oil yield production is far superior.

2.3.5. Challenges of algae-based biofuels

Despite its vocation as a potential source of biofuels, many challenges have hindered the development of biofuels technology from microalgae to become commercially viable. Among them, and based on recent literature, we elect as the most important: (1) the selection of species must balance the requirements for biofuel production and extraction of valuable by-products (Ono and Cuello, 2006) and still reach environmental and economical sustainability; (2) achieve greater photosynthetic efficiency through the continuous development of production systems (Pulz and Scheinbenbogan, 1998); (3) develop techniques for growing a single species, reducing evaporation losses and diffusion of CO_2 (Ugwu et al. 2008); (4) few commercial cultivating "farms", so there is a lack of data on large-scale cultivation (Pulz, 2001) and standard processes; (5) impossibility of introducing flue gas at high concentrations, due to the presence of toxic compounds such as NO_x and SO_x (Brown, 1996); (6) choosing algae strains that require fresh water to grow can be unsustainable for operations on a large scale and exacerbate fresh water scarcity (Mcgraw, 2009); (7) price is still too high to compete with fossil fuels; (8) Current harvest and dewatering are still too energy intensive (Chen et al., 2009); (9) Some recent life cycle analyses project algae biofuels as having poor energy or greenhouse gas benefits (Clarens et al., 2010); (10) Depending on the processes, PBR systems can consume more energy than they produce (Slade and Bauen, 2013); (11) Possible scarcity of sites with favorable climate, land, water, and CO_2 resources, all required in one place (Benemann, 2012; Clarens et al., 2010; Slade and Bauen, 2013); (12) CO_2 supply is relatively expensive, due to high capital and operational costs for piping CO_2 to, and transferring it into, the ponds (Benemann, 2012) and (13) Large-scale cultivation of algal biomass will require a lot of nitrogen and phosphorus; recycling nutrients from wastewater and seawater could potentially provide some of the nutrients required (Slade and Bauen, 2013).

Although, as often mentioned throughout this work, there are multiple challenges related to the development of microalgae biofuels technology, many policies are being prepared focusing on this new source of feedstock for biofuels as it is stated in the chapter 3.

3. BIOFUEL MARKET DIFFUSION AND POLICIES

Up to now it has been shown that it is scientifically and technically possible to derive energy products from algae in the laboratory. Economic feasibility is believed to be currently the main hurdle to overcome for this technology. Current costs associated to both the state of the science and technologies are sizeable and represent a main factor working against development.

This characteristic is not unique for algae biofuels as high costs often prevent the market diffusion of novel and efficient energy technologies. As microalgae biofuel is not a mature technology, it becomes important to provide a revision of technological innovation and diffusion aspects to enlighten some available options that may help overpass the barriers found by innovative technologies. Thus, this chapter stresses the importance of public policies in the diffusion of emerging technologies.

3.1. Market diffusion

The current economic situation points towards large-scale production of algae biofuel not being viable as a solution to displace petroleum-based fuels (Ribeiro and Silva, 2013). The technology to efficiently produce and disseminate biofuels from microalgae is not yet competitive with more mature transportation energy options, and the high costs prevent the market diffusion of novel energy technologies.

It is widely recognized that modern economic analysis of technological innovation originates fundamentally from the work of Joseph Schumpeter (1934), who stressed the existence of three necessary conditions for the successful deployment of a new technology: invention, innovation and diffusion. Each of these keywords represents different aspects, in particular: invention includes the conception of new ideas; innovation involves the development of new ideas into marketable products and processes; and diffusion, in which the new products and processes spread across the potential market.

Emergent technologies are relatively expensive at the point of market introduction but eventually become cheaper due to mechanisms such as learning-by-doing, technological innovation and/or optimization, and economies of scale. The combined effects of these mechanisms are commonly referred to as technological learning. Over the last decades, learning theories combination with evolutionary economics have led to the innovation systems theory that expands the analysis of technological innovation, covering the entire innovation system in which a technology is embedded. In particular, "An innovation system is thereby defined as the network of institutions and actors that directly affect rate and direction of technological change in society" (Junginger et al., 2008; p.39).

In the emerging energy technologies field, there is a strong need to influence both the speed and the direction of the innovation and technological change. With that in mind, policymakers are putting their efforts on lowering the costs of renewable energy sources to support the development of renewable technologies, either through direct means such as government-sponsored research and development (R&D), or by enacting policies that support the production of renewable technologies. It is well documented (Johnstone et al. 2010; Popp, 2002) that both higher energy prices and changes in energy policies increase inventive activity on renewable energy technologies. As noted by Popp et al. (2011), the higher costs of renewable energy technologies suggest that policy intervention is necessary to encourage investment. The impact of the lack of public policies favoring the development of renewable energy is that production costs remain too high and renewable energy does not represent an option in replacing fossil fuels.

Policies to foster innovation should not only focus on the creation and supply of new technologies and innovations, but also on the diffusion and take-up of green innovations in the market place. Such policies need to be well designed to ensure that they support and do not distort the market formation, and should be aligned with competition policies and international commitments (OECD, 2011). With this purpose, several government policies have been introduced in the energy markets worldwide in an effort to reduce costs and accelerate the market penetration of renewables (U.S. DOE, 2010).

In Section 3.2, some of the U.S. policies that could enhance the development of microalgae biofuels are, therefore, revised.

3.2. United States policies

In this section, special focus is devoted to biofuels policies, because they include major drivers for biofuel technology deployment. The U.S. policies were chosen due to its representative share of algal biofuel producing companies. The United States show a level of 78% of all algal biofuel producing companies around the world (Singh and Gu, 2010).

There are many objective aims in U.S. biofuels policies (De Gorter and Just, 2010). Firstly, there is a strong desire to decrease the dependence of the United States on foreign oil. The 2008 spike of fossil fuel prices is a lively reminder that fluctuations in such levels can have sizeable impacts on U.S. welfare. In addition, there is an increasing motivation in developing alternative, environmentally friendly and more secure energy sources. The idea is that using biofuels might alleviate the environmental impacts of oil energy consumption. At last, increasing biofuels production has the added implication of increasing the demand for agricultural production and thus is consistent with a long-standing U.S. commitment to support its farm sector (Lapan and Moschini, 2012).

In order to boost the adoption and development of biofuels, the key instruments widely adopted have been mandatory blending targets, tax exemptions and subsidies. Supplementary to those, governments have intervened on the production chain by supporting intermediate inputs (feedstock crops), subsidizing value-adding factors (labor, capital, and land) or granting incentives that target end-products. Import tariffs have also played a significant role by protecting national industries from external competition (Sorda et al., 2010).

A vivid example of the utilization of these policies is the steeply rise of the U.S. corn-based ethanol production, going from 1.62 billion gallons in 2000 to 13.31 billion gallons in 2013 (U.S. EIA, 2014). It is clear that this expansion of ethanol production owes much to the implementation of critical support policies. The corn ethanol industry has received a great share of subsidies over the past 20 years. Through federal tax credits, loan guarantees, grants and other subsidies, billions of dollars have been invested in this industry. While the biofuels industry as a whole was intended to help achieve American energy independence, reduce greenhouse gas emissions, and spur rural economic development, the corn ethanol industry has fallen short of achieving these goals and generated unintended consequences and long-term liabilities (Yang et al., 2012; Pimentel, 2003).

Regarding emerging biofuels, the U.S. Environmental Protection Agency suggested revisions to the National Renewable Fuel Standard program (RFS). The proposed rules intended to address changes to the RFS program as required by the Energy

Independence and Security Act of 2007 (EISA). The revised statutory requirements establish new specific volume standards for cellulosic biofuel, biomass-based diesel, advanced biofuel, and total renewable fuel that must be used in transportation fuel each year. The regulatory requirements for RFS will apply to domestic and foreign producers and importers of renewable fuel (U.S. EPA, 2010). This rule proposes to establish the revised annual renewable fuel standard (RFS2) and to make the necessary program modifications as set forth in EISA. The required volume modifications made under RFS2 are shown in Table 6, eventually reaching 36 billion gallons by 2022.

Table 6: U.S. Renewable Fuel Volume Requirements for RFS2

Year	Cellulosic biofuel	Biomass-based diesel	Advanced biofuel	Total renewable fuel
2008	n/a	n/a	n/a	9.0
2009	n/a	0.5	0.6	11.1
2010	0.1	0.65	0.95	12.95
2011	6.6*	0.80	1.35	13.95
2012	8.65*	1.00	2.0	15.2
2013	6.0*	1.28	2.75	16.55
2014**	17.0*	1.28	2.2***	18.15
2015	3.0	a	5.5	20.5
2016	4.25	a	7.25	22.25
2017	5.5	a	9.0	24.0
2018	7.0	a	11.0	26.0
2019	8.5	a	13.0	28.0
2020	10.5	a	15.0	30.0
2021	13.5	a	18.0	33.0
2022	16.0	a	21.0	36.0
2023+	b	b	b	b

Volumes in billion gallons, unless otherwise stated.
Source: U.S. EPA, 2010.
a: To be determined by EPA through a future rulemaking, but no less than 1.0 billion gallons.
b. To be determined by EPA through a future rulemaking.
* Million Gallons
** Proposed Rule (U.S. EPA, 2013).
*** Reduced from 3.75 billion gallons. (U.S. EPA, 2013).

Based on the table above for all renewable fuel categories, the applicable standards for 2010 onwards were proposed, each representing the fraction of a refiner's or importer's gasoline and diesel volume which must be renewable fuel.

The proposed specific targets for 2014 in the U.S. include 0.010% from cellulosic biofuel, 1.16% from biomass-related diesel, 1.33% from advanced biofuel, and 9.20% from total renewable fuels. As defined by the Energy Independence and Security Act of 2007 (p.28),

"advanced biofuels are renewable fuels, other than ethanol derived from corn starch, that

> have lifecycle greenhouse gas emissions that achieve at least a 50 percent reduction over baseline lifecycle greenhouse gas emissions. Advanced biofuels may include ethanol derived from cellulose or lignin, sugar or starch (other than corn starch), or waste material, including crop residue, other vegetative waste material, animal waste, and food waste and yard waste; biomass-based diesel; biogas produced through the conversion of organic matter from renewable biomass; butanol or other alcohols produced through the conversion of organic matter from renewable biomass; and other fuel derived from cellulosic biomass."

While cellulosic ethanol is expected to play a large role in meeting the 2007 EISA goals, a number of next generation biofuels, especially those with higher-energy density than ethanol, show significant promise in helping to achieve the 36 billion gallon goal. Of these candidates, biofuels derived from algae, particularly microalgae, have the potential to help the U.S. meet the new RFS while at the same time moving the nation ever closer to energy independence (U.S. DOE, 2010). Algae-based fuels could be considered under the advanced biofuel or bio-based diesel portion of the RFS, according to the proposed rule (U.S. EPA, 2013).

To accelerate the deployment of biofuels produced from algae, President Obama and Secretary of Energy Steven Chu announced on May 5th, 2009 the investment of US$800 Millions new research on biofuels in the American Recovery and Renewal Act (ARRA). This announcement included funds for the Department of Energy Biomass Program to invest in the research, development, and deployment of commercial algal biofuel processes (U.S. DOE, 2010).

Meanwhile, the Algal Biomass Organization (ABO) are focusing its efforts on achieving three main goals for the algae biofuels technology: (1) Financial parity: Algae Fuels must receive the same tax incentives, subsidies and other financial benefits that are currently accorded to other biofuel feedstocks. (2) Regulatory parity: Algae must be recognized as an effective medium for the "beneficial reuse" of carbon dioxide, and a significant part of the solution to the American overall carbon reduction strategy. Federal agencies should develop regulations that treat algae's growth and production similarly to other biofuel feedstocks and carbon sequestering technologies. (3) RFS parity: Because algae are not cellulosic, low-carbon algae-based fuels were not counted towards the 16 billion gallon cellulosic biofuel carve-out within the RFS's advanced biofuel mandate. Consequently, all non-cellulosic biofuels, including algae-based fuels, were left to compete among themselves to meet the threshold within the mandate (ABO, 2014). However, in the Family and Business Tax Cut Certainty Act of 2012 bill, the definition of qualified cellulosic biofuel production was expanded to include algae-based fuel (U.S. Senate, 2012). The bill would also extend the cellulosic biofuel tax credit to algae-based fuel for the first time.

As the main region so far for algae biofuel production, The U.S. is leading policies concerning this technology. Although it is expected much more advances in this field in the next few years, research on the welfare economics of renewable energy policy is still in its infancy and the economic effects of biofuel policies are not only complex and difficult to understand, but are ultimately ambiguous in theory (De Gorter and Just, 2010).

In the next section, the European policies are presented since EU presents 13% of all algal biofuel producing companies around the world (Singh and Gu, 2010).

3.3. European Union policies

In order to promote the use of energy from renewable sources, The European Parliament published on April 2009, the Directive 2009/28/EC which

> “establishes a common framework for the promotion of energy from renewable sources. It sets mandatory national targets for the overall share of energy from renewable sources in gross final consumption of energy and for the share of energy from renewable sources in transport. It lays down rules relating to statistical transfers between Member States, joint projects between Member States and with third countries, guarantees of origin, administrative procedures, information and training, and access to the electricity grid for energy from renewable sources. It establishes sustainability criteria for biofuels and bioliquids.” (E.U., 2009, p.27).

The Directive 2009/28/EC also establishes in its Article 4 that each Member State shall adopt a national renewable energy action plan. In a nutshell, the national renewable energy action plans shall set out Member States’ national targets for the share of energy from renewable sources consumed in 2020 and the policies and measures adopted to achieve those targets.

Concerning energy from biofuels, the Directive 2009/28/EC establishes in its Article 17, the sustainability criteria for these fuels, stating that biofuels that do not fulfil the sustainability criteria set out in this article shall not be taken into account. The main criteria are: (1) The greenhouse gas emission saving from the use of biofuels taken into account shall be at least 35 %. From January 2017, the greenhouse gas emission saving shall be at least 50 % and from January 2018 shall be at least 60%. (2) Biofuels shall not be made from raw material obtained from land with high biodiversity value, (3) from land with high carbon stock, (4) or from land that was peatland in January 2008, unless evidence is provided that the cultivation and harvesting of that raw material does not involve drainage of previously undrained soil.

By the end of 2010, a communication from the European Parliament has set the strategy for competitive, sustainable and secure energy by 2020. The Strategic Energy Technology (SET) Plan sets out a medium term strategy valid across all sectors. Yet development and demonstration projects for the main technologies (e.g. second generation biofuels) must be speeded up (E.U., 2007).

The European SET-Plan lists several energy technologies, which will be required to bring together economic growth and a vision of a decarbonized society. It states that advanced biofuels, namely microalgae, are supposed to play a significant role. EU energy policy aims to represents a green “new deal”, which will hopefully enhance the competitiveness of EU industry in an increasingly carbon-constrained world (E.U., 2007).

Among the projects to be launched, the €9 billion European Industrial Bioenergy Initiative aims to ensure quick market uptake of sustainable second-generation biofuels. Since implementing large-scale sustainable biofuel production is one of the targets to be achieved.

After reviewing some of the policies focused on this new source of feedstock for biofuels, chapter 4 presents what are the visions of microalgae experts for its future.

4. WORLD EXPERTS VISIONS THROUGH A DELPHI SURVEY

Currently, much experimental and even theoretical/simulation work is being done to ensure that biofuels from microalgae become a reality in the short to medium term. Some aspects were already identified as significant for the overall competiveness, such as: the microalgae should have high biomass and lipids productivities (Singh and Gu, 2010; Sander and Murthy, 2010; Pittman et al., 2011); the processing system should be highly efficient and integrated with other processes following the biorefinery concept (Pokoo-Atkins, 2010); there must be markets or valorization potential for the process byproducts or other high value products that may be obtained (Resurreccion et al, 2012); waste streams and/or remaining nutrients should be used to reduce operating costs and increase the process sustainability (Pittman et al., 2011); among others. Each of the previous possibilities have a positive impact on the competiveness of using microalgae as a feedstock for biofuels, but there is a lot of discussion in which one should focus efforts of research and development.

To fulfill this gap, this chapter presents a study based on the Delphi method to obtain more concrete information and predictions on how this area should be further developed. This way it will be possible to better define which lines of research should be supported, and what policy and funding instruments are more adequate. To the authors' awareness, no study can be found in the literature addressing these questions with this methodology, involving the usage of microalgae as feedstock for biofuels.

A related work is the National Algal Biofuels Technology Roadmap (U.S. DOE, 2010), the result of a two day workshop that brought together specialists from various areas, including engineers, scientists, policy makers, financiers, and others, to discuss the present and future of microalgae as a feedstock for biofuel production. The final document was intended to serve as a revision of the current state of the art in the area, and to identify which are the key challenges that must be considered to achieve a commercial scale production, serving as a guide to ongoing efforts. The study is rather comprehensive and extensive but fails to highlight which are the areas and aspects that are considered to be more important and should be considered first, from a cost-benefit point of view.

Also related, the EurEnDel project was a European wide Delphi study on the future developments in the energy sector, with a time horizon of 2030 based on the situation up to 2003. Its main goal was to provide advice on energy R&D activities in this key area. Hundreds of responses from experts in a wide range of topics were gathered, several future scenarios were developed, and in which concerns biofuels, there is a short-term need for new production processes and an increase in their market share (Wehnert et al, 2004 and 2007).

In 2009, a Delphi study was published dealing with the potential of biofuels in Alabama (Guthrie, 2009). The information gathered supported the idea that there are no simple and unique technology answers for the commercial implementation, and that local questions and an array of technologies and feedstocks is the most adequate strategy. Similar conclusions were reached by Celitkas and Kocar (2010) in their Delphi study of the renewable energy sector in Turkey, and by Lubieniechi and Smyth (2011) in their work on the barriers to biofuels in Canada.

4.1. Methodology

The Delphi method is a qualitative research aiming to support strategic future-oriented action, such as policy making in the areas of science and technology. It typically entails two or more survey rounds in which the participating experts are provided with the results of the previous rounds. The panel of experts is used as the source of information, and the questionnaires act as the medium of interaction. The key characteristics of a traditional Delphi study are iteration, participant and response anonymity, controlled feedback, and group statistical response. It is especially suitable in judgment and long-range forecasting (20-30 years) situations, when expert opinions are often the only source of information available, due to a lack of appropriate historical, economic or technical data (Blind et al., 2001; McLeod and Childs, 2007; Rowe and Wright, 1999).

The key objective of our Delphi study is to determine the prospects of using microalgae for biofuels production within a time scale extending to 2030. Before initiating the Delphi study, a brainstorming was organized by four microalgae specialists. In the brainstorming, the participants identified factors affecting production and competition of microalgae biofuels. Subsequently, the factors were categorized into sentences as presented in the Delphi study later on. The brainstorming participants also suggested panelists for the Delphi survey. Based on this meeting, the statements for the first Delphi survey round were formed by the researchers. The questionnaires were sent to the Delphi experts via e-mail, enquiring about their willingness to participate in the study. In the first Delphi survey round, all statements were presented to the panelists at the same time. In the second survey round, the respondents similarly had the opportunity to comment on the critical factors voted on in the first round (Ribeiro et al., 2014).

Our Delphi study included three survey rounds (the workshop and two Delphi rounds), which made it possible to understand the features that may develop or hold back this technology in the future. All three rounds were carried out during three months (from May 2012 to July 2012). From all the experts inquired, there were 55 respondents in the first round, reaching a response rate of 36.7 %, and, in the second round, when only were questioned those 55 experts that answered the first round, the response rate was 54.5 %. The Delphi participants were selected based on their expertise on the subject matter, as it is required in-depth knowledge about the microalgae biofuel markets and processes from all the experts (Ribeiro et al., 2014).

Overall, the panelists represented 10 countries (United States, Portugal, the Netherlands, Italy, Norway, United Kingdom, Spain, Uruguay, Brazil and Australia). The experts can be categorized into three groups based on the field they represented: Academy (38.5 %), Government (23.1 %), Business (28.8 %), Academy/Business (7.7 %) and Academy/Business/Government (1.9 %) (Figure 12). The main focus of this Delphi study was to gather insights from specialists that symbolized distinctive fields, and not specifically the strategies of each country.

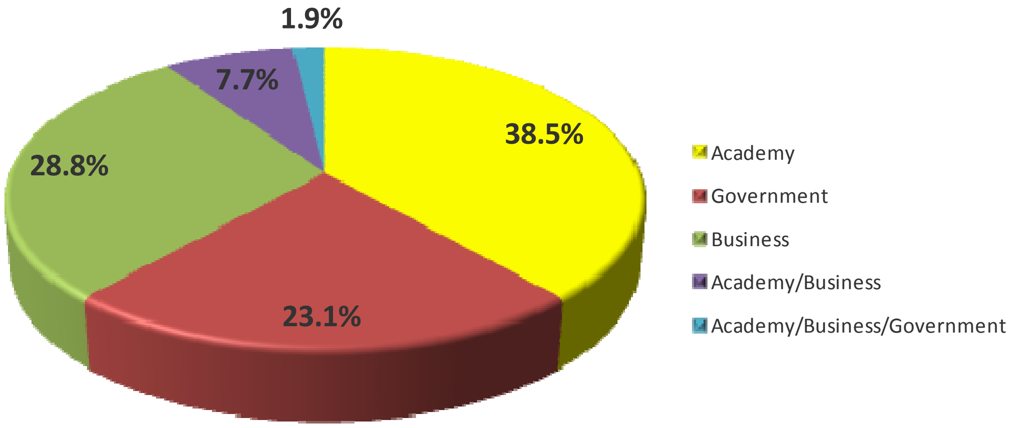


Figure 12: Survey experts' fields of work.

In the workshop, participants raised several factors that could affect competition in this particular market and they were categorized into four main themes. The first theme concerned microalgae biofuel economics as it plays a crucial role in establishing well-functioning and competitive market. The second theme studied some future trend hypothesis to be rejected or accepted by participants on the Delphi survey. The third key element in the study dealt with environmental sustainability, which directly affects confidence-building in the development of the microalgae biofuel market. The final group of statements focused on policies and on forecast concerning the future.

The 1st round questionnaire consisted of 50 statements. Those that did not reach an overall consensus (more than 66 % agree or disagree) shaped the basis of the second round, which included open-ended fields for further explanations or suggestions. The second round focused on clarifying the answers of the first round. All the questionnaires were pre-tested, and the panelists were given feedback after the first round with all the participants' answers from the first round. The participants in the study were likewise encouraged to provide arguments supporting their views and opinions.

4.2. Results and discussion

Once all the respondents had completed the first round, each answer was examined. The statements that, in the view of the experts, did not achieve an overall consensus formed the footing for the questions of the second round.

In Appendix A, the statements of the first three themes asked in the survey are shown. The question asked in Themes 1, 2 and 3 was "Please rate how strongly you agree or disagree with each of the following statements by placing a check mark in the appropriate box." The respondents could choose in a seven-level Likert scale from "Totally Disagree, Strongly Disagree, Disagree, Neither agree nor disagree, Agree, Strongly Agree and Totally Agree". The full questionnaire sent to the experts is presented in Appendix B. After the first round of answers, the aggregated results of the economics Theme 1 is shown Table 7.

Table 7: Delphi survey Theme 1 cumulative overall results

Statement	Respondents	Agree (%)	Neither Agree nor Disagree (%)	Disagree (%)	Variance
1.1	55	94,5	3,6	1,8	1.14
1.2	54	68.5	24.1	7.4	1.94
1.3	55	63.6	20.0	16.4	2.53
1.4	54	42.6	22.2	35.2	2.87
1.5	54	85.2	9.3	5.6	1.97
1.6	55	94.5	3.6	1.8	1.08
1.7	54	66.7	14.8	18.5	2.90
1.8	55	81.8	10.9	7.3	1.92
1.9	55	78.2	16.4	5.5	1.88
1.10	53	83.0	9.4	7.5	1.83
1.11	54	79.6	7.4	13.0	2.21
1.12	52	94.5	3.8	1.9	0.99
1.13	54	83.3	9.3	7.4	1.46
1.14	53	67.9	22.6	9.4	2.17
1.15	53	84.9	7.5	7.5	1.51

In the economics theme, expressive consensus were achieved on statements 1.1, 1.6 and 1.12 (above 90 %), in a way that experts consider that there is plenty of room for innovative and more effective production processes that could lead to economic feasibility, considered one of the main challenges facing large-scale deployment of biofuels from microalgae.

Statements 1.5, 1.8, 1.10, 1.13, 1.15 also revealed a high consensus level (above 80 %). From those, it is important to highlight the awareness that R&D subsidies and supporting programs will be needed to promote improvements in the technology in order to reduce the costs of algal biofuels and speed up development. Moreover, an interesting issue relates the perception that the increase in the overall consumption of biofuels, and the expected growing pressures on currently used feedstocks can be a key factor to the economic viability of microalgae.

The experts also reached an agreed consensus on statements 1.2, 1.7, 1.9, 1.11 and 1.14, but with less intensity (from 66 % to 80 % agree) of which, it is important to highlight the interest in other co-products outside the transportation sector, such as nutraceuticals and compounds for the pharmaceutical and/or fine chemistry industries. The commercialization of theses co-products could assist industries to reach economic feasibility of microalgae biofuel.

Questions 1.3 and 1.4 did not reach a clear consensus and were asked again in the 2nd round for further analysis. From the results, 1.3 has a clear tendency on agreement (63.6% agree), however, we could not conclude a clear overall consensus, since the sample that agreed now (69.0 %) had already agreed on the 1st round (70.0 %). Some of the experts' answers are presented as follows and could lead to an understanding why this statement did not achieve a consensus.

Statement 1.3: "Microalgae biofuel will become a co-product of future large-scale facilities, where other high-value products are generated."

> "High-value products may be co-products of any successfully large-scale biofuel production from algae, but co-products may not be possible at the scale of biofuels, which will be huge" (Strongly Disagree).
>
> "This is akin to a petrochemical complex, generates less residues, and ensures that there is a lower risk in the microalgae base industry as there is less dependence on just one product" (Strongly Agree).
>
> "Depends on the commercialization strategy of the facility; a near-term, "1st of a kind" facility may rely primarily on other high-value products to generate required revenue with algal oil/biofuel as a co-product, and could transition to a larger emphasis on algal biofuel as a principal product as the technology matures" (Neither Agree nor Disagree).

On the other hand, Statement 1.4 did not reach any consensus (26.7 % disagree / 33.3 % neither agree nor disagree / 40.0 % agree).

In Theme 2 (Table 8), expressive consensus was reached only on statement 2.8, which reached 92.2 % of agreement. Therefore, experts strongly agree that no single microalgae strain will be the dominant one, and that different strains of microalgae will be used depending on the nutrients and/or waste streams available, and particular local climatic and water availability conditions.

Table 8: Delphi survey Theme 2 cumulative overall results

Statement	Respondents	Agree (%)	Neither Agree or Disagree (%)	Disagree (%)	Variance
2.1	52	78.8	15.4	5.8	1.58
2.2	52	73.1	11.5	15.4	2.08
2.3	51	47.1	25.5	27.5	2.28
2.4	52	84.6	7.7	7.7	1.41
2.5	52	75.0	15.4	9.6	2.05
2.6	50	70.0	14.0	16.0	2.99
2.7	50	66.0	18.0	16.0	2.67
2.8	51	92.2	7.8	0.0	0.86
2.9	49	40.8	24.5	34.7	3.08
2.10	51	82.4	13.7	3.9	1.57
2.11	51	82.4	9.8	7.8	1.41

High consensus was observed on declarations 2.4, 2.10 and 2.11. In this way, the reduction of oil imports dependence and the potential development of local and national economies is a relevant factor for the development of microalgae biofuels. Experts also believe that biofuels from microalgae will be produced commercially, but only in the mid to long term. This conviction was better described on Theme 5 of this study.

Mild agreement was reached on 2.1, 2.2. 2.5, 2.6, and 2.7 (from 66 % to 80 % agree). Two factors related to the economic feasibility of algae biofuels are noteworthy to point out. They relate to the sense that not only higher petro-oil prices, but also a more developed, globalized and comprehensive Carbon Market could foster microalgae biofuel to become more economically feasible.

Questions 2.3 and 2.9 did not reach a clear consensus and were asked again in the 2nd round for further enlightenment. Neither an achieved consensus was obtained on the 2nd round nor were some reasons clarified by the experts, for instance:

Statement 2.3: "Algal biofuels will be developed, but will play only a minor role in the future mix, in particular for the transportation sector."

> "Algal biofuels have the potential to play a major role in the future mix relative to many other biofuel pathways, but it depends on cost and time scale" (Disagree).
>
> "Too early to reach conclusions" (Neither Agree nor Disagree).
>
> "Hard to make predictions know. Depends on the evolution of other biofuels, technological advances, development of other biofuels... This is one is tough..." (Neither Agree nor Disagree).

Since this prediction involves several factors, it was difficult for experts to reach a consensus (47.1 % agree / 25.5 % neither agree nor disagree / 27.5 % disagree).

Statement 2.9: "Open pond cultivation, or similar, will dominate the future production systems, although for small production involving the processing of waste streams the close cultivation systems will be also used."

> "Open pond cultivation represents 90% of the world production... now and in the future also..." (Agree)
>
> "Only closed systems with industrial scale will make algae biofuels possible. Pond systems do not scale up for biofuels." (Strongly disagree)

Here again the respondents struggled with the fact of predicting the future and no consensus was reached (33.3% agree / 33.3% neither agree nor disagree / 33.3% disagree).

The Sustainability theme was the most controversial one (Table 9). In which, eight from twelve statements did not show consensus (3.1, 3.2, 3.3, 3.4, 3.6, 3.7, 3.10 and 3.11). All these were asked again in the 2nd round of the survey.

Table 9: Delphi survey Theme 3 cumulative overall results

Statement	Respondents	Agree (%)	Neither Agree or Disagree (%)	Disagree (%)	Variance
3.1	50	38.0	28.0	34.0	3.20
3.2	50	60.0	18.0	22.0	2.60
3.3	46	15.2	41.3	43.5	2.87
3.4	47	27.7	42.6	29.8	3.23
3.5	48	72.9	12.5	14.6	1.94
3.6	48	47.9	29.2	22.9	1.84
3.7	49	59.2	10.2	30.6	3.58
3.8	49	79.6	18.4	2.0	1.86
3.9	48	79.2	14.6	6.3	1.78
3.10	46	32.6	32.6	34.8	2.11
3.11	49	61.2	22.4	16.3	2.12
3.12	49	81.6	12.2	6.1	2.17

The highest consensus was achieved on 3.12 (82 % agree) that said, "The potential to use waste streams and/or easily available renewable nutrients is a key factor in the overall system sustainability."

Agreement was also reached on 3.5, 3.8 and 3.9, but with lower intensity (from 66 % to 80 % agree). All these statements had in common "carbon emissions", where experts agree that the need to reduce world's CO_2 emissions is a key advantage for microalgae biofuels; and that the actual overall life cycle carbon balance is key aspect to consider in the microalgae biofuel production. They think that being carbon neutral is a key factor concerning microalgae biofuel production sustainability.

From the ones asked on the 2nd round, it is interesting to highlight that because biofuels of this origin do not have a well-known industrial process (there are different methods for producing them) and microalgae are not yet being cultivated commercially for this purpose, it was difficult for the experts to answer questions related to sustainability. Some of the comments to these questions were:

Statement 3.3: "Open pond cultivation is more environmentally friendly than PBRs cultivation."

> "More information and practical data is needed to answer this one." (Neither agree nor disagree).
>
> "There is not sufficient evidence in the literature to support or negate this statement." (Neither agree nor disagree).
>
> "That depends on the nutrient source, direct and indirect land use and other issues specific to each site." (Disagree).

Although there is a tendency on disagreement, no clear consensus was reached (10.3% agree / 34.5% neither agree nor disagree / 55.2% disagree),

Statement 3.6: "The production of algae biofuels in large scale could generate potential impacts on local ecosystems from new algal species."

> "All these statements are dependent on other factors, therefore difficult to respond with just a simple agree/disagree."; (Disagree)
>
> "The "potential" is certainly there for affecting local ecosystems; the issue comes down to containment and safety contingency planning." (Agree)
>
> "if genetically modified organisms are used, that could be an issue." (Agree)

No consensus was reached (34.5% agree / 31.0% neither agree nor disagree / 34.5% disagree).

Statement 3.10: "Some potential undesired environmental aspects may arise from microalgae cultivation, as for example, increased emissions of NO_x and/or methane."

> "Depends on the processes utilized for product and co-products generation/use." (Neither agree nor disagree)
>
> "Possible situation, in particular if the cultivation systems are not well designed or adjusted." (Agree)
>
> "Only if actions to minimize/restrict those impacts are not taken." (Disagree).

No consensus was reached (20.7% agree / 37.9% neither agree nor disagree / 34.5% disagree).

Theme 4 concerned "Policies", where several prospects of policies were presented and the respondents were asked to choose "How important is each policy below to the success of microalgae biofuels?" The answers were presented in a seven-level Likert scale ranging from "Unimportant" to "Extremely Important". The policies presented are displayed in Table 10.

Table 10: Delphi survey Theme 4 statements and results

	Theme 4: POLICIES	**Mean**
4.1	Mandatory country objectives;	**5.52**
4.2	Sustainability standards (Emissions, production, etc.);	**5.70**
4.3	Public Investment in R&D;	**6.09**
4.4	Tax incentives and subsidies;	**5.71**
4.5	Certification schemes, in particular those concerning raw materials or the entire fuel life cycle;	**5.48**
4.6	Specific legislation or international agreements (such as European Directives) aimed specifically to biofuels or to specific environmental questions (such as carbon emissions) where biofuels have a pivotal role;	**5.70**
4.7	Development strategies aimed to renewable resources, either research, utilization and integration in existing systems.	**5.91**

All policies were seen by experts as important, in which the sum of "Important", "Very Important" and "Extremely Important" in all items were above 80% of valid responses. In an attempt to rank, which were the most important ones, values were set from 1 to 7 to "Unimportant" through "Extremely Important". Consequently, it was possible to estimate the most important policies in the view of the experts interviewed. For that purpose, an overall mean was computed for each policy and is presented in Table 10. Analyzing this data, experts believe that "Public Investment in R&D" is the most important mechanism to develop microalgae biofuels. However, the other mechanisms were also important for this purpose and it is a sum of efforts that makes the development to go on.

In order to better specify which policies were the most important ones, in the 2nd round the same set of policies were given, but this time, the respondents were asked to rank them (from 1-most important to 7-least important) without repeating numbers. The results were similar to the ones from the first survey: public investment in R&D was elected as the most important one, with a statistic mode of 1 (most important) chosen by 34.5% of the respondents and ranked in the top 3 to other 27.6% of the respondents. This policy was followed by "developing strategies aimed to renewable resources, either research, utilization and integration in existing systems"; "tax incentives and subsidies"; and "mandatory country objectives", subsequently. The results from Theme 4 in the 2nd round are presented in Table 11.

Table 11: Delphi survey Theme 4 2nd round policies priorities

	Theme 4: POLICIES	1st	2nd	3rd	4th	5th
4.1	Mandatory country objectives;	27.6%	6.9%	10.3%	10.3%	10.3%
4.2	Sustainability standards (Emissions, production, etc.);	0.0%	17.2%	6.9%	24.1%	24.1%
4.3	Public Investment in R&D;	34.5%	13.8%	13.8%	13.8%	10.3%
4.4	Tax incentives and subsidies;	6.9%	20.7%	20.7%	17.2%	6.9%
4.5	Certification schemes	0.0%	6.9%	3.4%	13.8%	17.2%
4.6	Specific legislation or international agreements	10.3%	13.8%	20.7%	10.3%	20.7%
4.7	Development strategies aimed to renewable resources	20.7%	20.7%	24.1%	10.3%	10.3%

Theme 5 was named "Future" where the question asked was "When do you think the following would happen in microalgae biofuels industry?" The outcomes are shown in Figure 13.

The graph of Figure 13 shows that most of the experts think that production of microalgae for biofuels will achieve full commercial scale until 2020. From 2021 to 2030 it is believed to represent from 1 % to 5 % of the total worldwide fuel consumption and from 2030 onwards it could reach figures of 10 % to 25 %. However, almost half of the experts (47 %) do not believe it could ever reach 25 % of worldwide fuel consumption.

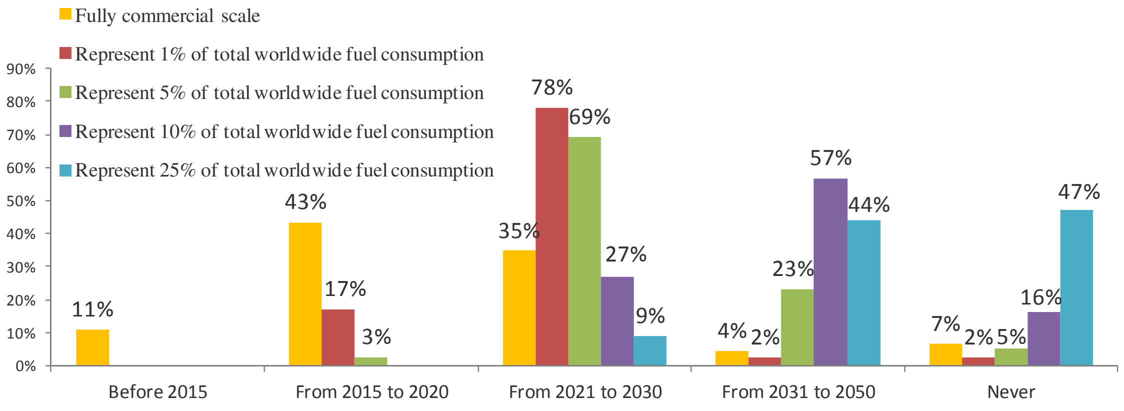


Figure 13: Delphi survey results about the future of microalgae biofuels.

Therefore, one of the key findings is that most of the experts believe that the production of microalgae for biofuels will achieve full commercial scale until 2020 and from that period on, it could represent an important share of the total worldwide fuel consumption. In order to boost development, experts agree that public investment in R&D is the most important policy to be adopted by countries. Developing strategies aimed to renewable resources; applying tax incentives and subsidies; and issuing mandatory country objectives were also encouraged.

Although this Delphi Survey research has reached its aims, the outcomes might not represent the majority of the microalgae experts’ opinion due to the limited sample size. In the same manner, after analyzing the results, some questions did not reach a consensus and could be further explored in a supplementary study or in a third round. All the results obtained in the survey are presented in Appendix C.

The Delphi method proved to be a successful research method when expert opinions are the main source of information available, due to a lack of appropriate historical, economic or technical data and the outcomes herein provided clearly outline the main issues of microalgae biofuels' market at present and in the future. In particular, the two-round survey revealed the most important issues affecting this emerging market and also, recommended ways to influence future policies and development of this biofuel.

With all the information gathered in the microalgae literature review, public policies and in this Delphi survey, a model was developed in order to analyze possible diffusion pathways of microalgae biofuels. This is presented in the next Chapter.

5. MODELING POLICIES IMPACTS ON BIOFUELS MARKET DIFFUSION

To analyze the impact of different policies in the transportation fuel market share, a computational model using Stochastic Automata Networks (SANs) was built. First, a basic model reflecting the scenario without policies was constructed and then different policies were added. The objective was not only to investigate the effect of each specific policy alone, but also the interplay among the different policies. The basic model is parameterized by the prices of fuels and their availability (taking into account not only the availability of the fuel itself for end-consumers, but also of vehicles using this fuel). The policies model is an extension of the basic model including 4 different policies that tackle: subsidies, taxes, R&D investments and mandates. Diverse U.S. transportation scenarios were analyzed in the period from 2010 to 2040. The analysis consists of searching for the equilibrium state (steady state) in each scenario. This equilibrium state represents the market share that results from the given parameters of the scenario.

In the following, after a short introduction to SANs, the construction of the basic and policy models are presented, and then the results of the analysis of some scenarios are discussed.

5.1. Stochastic Automata Network

In the Stochastic Automata Network (SAN) formalism (Plateau, 1985; Baldo et al., 2005), a system is modeled by interacting subsystems, which are represented by automata. An automaton is composed by states and transitions labeled with event names. These automata may evolve independently with local events (that may affect only the local state of the automata participating in this event), or by synchronizing events that are used to model joint evolution of two or more automata. With the association of distribution probabilities to the events, the labeled transition system generated by a SAN gives rise to a Markov Chain and it is possible to calculate the steady state probability of each state of a SAN. More precisely, to each event there is an occurrence rate associated. The inverse of the occurrence rate is the mean value of the exponential distribution function that regulates the time interval between two occurrences of the event.

A SAN defines the set of events that are used to synchronize the different automata during the execution. The state changes of SANs are possible when all different automata that may be engaged in some event are in some state in which a transition labeled with this event is possible. Note that since there may be different transitions labeled with the same event, there may be different reachable states starting with the same state and executing the same event.

SAN has been employed to flexibly model and analyze different kinds of systems, such as: prediction of geological stratal stacking patterns (Assunção et al., 2013); performance evaluation of software development teams (Fernandes et al., 2011); process scheduling for NUMA machines (Chanin et al., 2006); master/slave parallel programs (Baldo et al., 2005); ad hoc wireless networks (Dotti et al., 2005); production line (Fernandes et al., 2013); quality of service assessment in multi-tier web services (Czekster et al., 2011); spatial distribution of mobile nodes (physical mobility models) (Dotti et al., 2011), to cite a few.

5.1.1. Comparing SAN with other modeling techniques

This section presents a comparison of recent studies analyzing the impacts and consequences of biofuel policies using different model generators techniques. Some of these techniques are: TIMES-MARKAL, ESIM, AGLINK-COSIMO, CAPRI, IMPACT and GTAP models (Loulou et al., 2005; Taheripour, et al., 2008; Banse et al., 2010; OECD, 2006; Britz and Witzke, 2012; Rosegrant et al., 2012). The purpose of this review is to illustrate the variety of output that could be obtained from such techniques, to discuss the pros and cons of the different models, and to provide some insights that may be useful when comparing the results reported later in this study. It is to mention, that the selection of techniques is not comprehensive. The main selection criteria are that the study involving the technology should be recent, and that its objective should be relevant to that of the current study.

There are many ways in which a mathematical model can be built to describe the reality to be studied. A fundamental difference among modeling techniques is whether the model is constructed based on an external or on an internal perspective. External means that the result of observations gives rise to the model. Typically, such model captures relations among the variables that are relevant to the system (like e.g. equations), and are called analytical models. Having an internal perspective means that the way the system behaves is captured by the model, that is, the cause/effect relation is used to build the model. These are termed computational models. The emphasis here resides not only to model that some relationship among inputs and results are obtained, but rather on why they are obtained. Building a computational model requires thus a deeper understanding of the system being modeled. But, once there is a computational model that closely describes a reality, it is possible not only to analyze which equilibrium states are reached (like it is the case of analytical methods), but also to reason about the process of reaching such states. In many situations, understanding the process may be even more important than knowing the result of the process. Synthesizing, a computational method emphasizes the process being modeled, whereas analytical methods emphasize the result of this process.

An example of computational model is the agent-based computational economics (ACE), which is the computational study of economies modeled as evolving systems of autonomous interacting agents (Tesfatsion, 2002). An important characteristic of ACE is interactions of autonomous agents, as described by Tesfatsion (2002; p.23):

> “The dynamics of the ensuing economic process are governed by agent-agent interactions, not by exogenously imposed systems of equations, and the state of the economy at each point in time is given by the internal attributes of the individual agents that currently populate the economy. ”

The SAN model presented in the next sections can be described as a partial equilibrium model governed by agent-agent interactions, where the agents are the users of fuels that compose the U.S. transportation market. But, unlike a pure agent system, a network of automata is used allowing the computation of equilibrium states (steady states).

Regarding other model generators, a well-known system that is often used for modeling energy scenarios is TIMES (The Integrated MARKAL-EFOM System). TIMES is an analytical model whereas SAN is a computational model. This means that in TIMES the reality is described by some of its properties (in TIMES, the equations of the linear programming model). Finding an equilibrium in TIMES means to find values for the interest variables of the equations, such that they are all satisfied in an optimum way (Loulou et al., 2005). This equilibrium is in terms of variables that denote consumers and producers (or, said in another way, in terms of prices and quantities). In a computational model, like SANs, a system is described by its behavior, that is, by the actions or events that may take place. A SAN typically models a complex system as a set of different subsystems that may interact and influence each other. If, at some moment in time, more than different future is possible, this can be modeled in SANs by giving different rates to transitions denoting these different evolutions of the system. These rates may vary over time since they may depend on the state of the system. An equilibrium state in a SAN (called steady state) describes that the modeled system converges to situation in which the relationships among all its subsystems is constant. This equilibrium state may be found analyzing all possible states of the system (this is performed by solving a Markov model, in SANs the solution is optimized such that it is not necessary to consider states that would never be reached).

SAN is a general purpose modeling formalism and, as such, it could be possible to construct many different SAN models to describe different aspects of a system. Here, a model that describes the behavior of consumers (users of transportation) is built, given different kinds of energy and their corresponding prices and availabilities of different energy sources. The aim is not to find the prices of fuel that would bring a system to some equilibrium, but rather to understand how the users may move from one fuel to another, given as input the prices and availabilities. The result of a run of the model is the market share induced by these inputs. Policies may alter prices and/or availability of items, thus they may be given as inputs as well, and will influence the market share by making it more or less likely that users opt for some kind of fuel.

In both models, calibration of the reference model is crucial, and means, in the case of TIMES, to find the right values of the parameters to build the equations that model reality, and in the case of SANs, finding the right rates for the transitions that make the system evolve.

TIMES is a very sophisticated tool to model energy systems, taking into account hundreds of different parameters. This is necessary because analytical models describe a system by its observations and thus the more parameters and equations we have, the more accurate the model will be. However, this may make models very large and difficult to fully understand. Moreover, the fact that non-commercial immature technologies do not have a well-known process of production makes it difficult to insert all the inputs needed for an accurate model.

SANs model reality in a simpler way, but knowledge on the intrinsic behavior of the system is required. For each transition that the system may perform, it is necessary to exactly state what is the situation that triggers the transition and what its effect is. Moreover, in a stochastic model, the probability that this transition happens must also be given. This means that a deeper understanding of the system is needed to build a SAN. But if it is possible to construct and calibrate a SAN to depict some reality, the analysis that can be done is far richer because we can analyze not only the final state but the whole process (for example, we may investigate not only the final state of the system, but analyze how this state can be reached). Moreover, by having an explicit behavior model the results can be better understood and explained.

There coexist also additional analytical representations that were used to model policies in the scope of biofuels. They possess many similarities to TIMES and thus, the comparison with SANs is analogous. The main difficulty to use these modeling techniques resides in the facts that it is not possible to include microalgae biofuels or advanced biofuels, since most of them already come with a fixed set of possible biofuel feedstocks in the system. In the following paragraph, some of these modeling tools are described.

GTAP is a multiregional, multisectoral, computable general equilibrium model with perfect competition (Taheripour, et al., 2008). One of the latest versions of GTAP, known as GTAP-E, has been extended to deal with substitution between biofuels and fossil fuel for transport use and climate change policies. However, only three different feedstock for biofuels are explicitly modeled: maize-based ethanol, sugar-cane-based ethanol and biodiesel. Advanced Biofuels are not supported (Taheripour, et al., 2008; Fonseca et al., 2010).

The ESIM model is a partial equilibrium multi-country model of the agricultural sector (Banse et al., 2010). Since it is mainly designed to simulate agricultural markets in the EU, policies are modeled only for these countries. Concerning biofuels, it only contains explicit supply and demand functions for biodiesel and ethanol (Banse et al., 2010; Fonseca et al, 2010).

Similar to ESIM model, AGLINK-COSIMO (OECD, 2006), CAPRI (Britz and Witzke, 2012) and IMPACT (Rosegrant et al., 2012) are economic models for the agricultural sector. They incorporate a wide range of agricultural and trade policies for several countries and regions. They are mainly used for food market related issues, measuring alternative futures for global food supply, demand, trade, prices, and food security (Britz and Witzke, 2012; Rosegrant et al., 2012; OECD, 2006). They possess 1st generation feedstocks for biofuels production. Microalgae are not supported as a feedstock.

Analyzing all these modeling tools, the main drawback related to microalgae biofuels or advanced biofuels is that they are closed systems and these emerging technologies cannot be inserted easily. Apart from that, they were not tailored to model energy sources, but instead food markets (with the exception of TIMES), and this could mislead the focus of the research.

The TIMES model was the only one among them in which it was possible to insert new technologies, such as microalgae as a feedstock for biofuels, and much more emphasis was given to this possibility. However, to insert a new technology, a production process has to be given, with all the inputs related to this process. Complex data regarding the inputs characterization, quantities, emissions and costs are necessary. It would be possible to choose one microalgae process and fulfill these requirements. Yet, as abovementioned, cultivating microalgae is still an immature technology and there are hundreds of pathways to produce different types of fuels and co-products. These distinctive processes generate diverse emissions, quantities of biofuels and can possess very different costs. Therefore, it would be misleading to choose one single microalgae process for producing biofuel and use it for modeling different policies. A simpler model without the need of these complex inputs would be a superior choice for the purposes of this thesis. With this in mind, a SAN-based model with this autonomy was developed from scratch, in order to model this emerging technology without the need of fixing a production process that is yet not well established for the case of microalgae fuel.

5.2. Modeling policies

The United States transportation market was chosen due to its representative share of algal biofuel producing companies nowadays and because of the potential for future growth. Therefore, all the results presented in this chapter rely on the U.S. transportation sector.

In order to develop a full scenario (from 2010 to 2040), each year inputs have to be defined and ran separately using the software SAN Lite Solver, and then the results of each year are aggregated to build a curve. The inputs and basic assumptions are presented in the next section.

5.2.1. Model assumptions

In order to reduce the uncertainty and simplify the model, the Advanced Biofuels share is considered as a sum of cellulosic biofuel, biomass-based diesel and advanced biofuel shares of the RFS2. This basic assumption was made due to the difficulty to analyze each of these emerging biofuels separately, and forecast their market diffusion.

The reference scenario considered the years from 2010 to 2040 and the only policy used was 1st generation biofuels mandate, because it already affects the market share greatly. Since in this study Biofuels, Gasoline/Diesel and Advanced Biofuels are expressed in units that have the same energy content (MBtu per gallon), we are assuming that these fuels are perfect substitutes. The main variables that need to be set for each year and for each of the energy sources are price, availability and policies. An energy-equivalent price was computed relying on EIA reference prices (U.S. EIA, 2013). The availability ranges from 0 to 100, as 0 being no availability and 100 being total availability. This variable takes into account the availability of resource, fueling stations and vehicles that run with that energy source. The availability and change costs are described as follows but were defined through a rigorous step of calibration presented in Section 5.2.4.

The model consists of 5 automata representing the users of each considered energy source: Petrol, Gas, Biofuels, Advanced Biofuels and Electricity. The basic assumptions made for each of these automata are described as follows.

5.2.1.1. Petrol Share

Gasoline and Diesel together represent the Petrol share of the model. Aviation fuels and other petrol derivatives were not considered in this study. Future prices of Gasoline were based on EIA reference case study (U.S. EIA, 2013) and converted to an energy-equivalent basis (Dollars per MBtu). The Petrol prices used as inputs for each year in the model are presented in Table 12. Diesel prices were not taken into account. Concerning Petrol availability, it was set to a maximum (100) because it is widely available in gas stations all over the U.S. and it is quite easy acquire a car that runs on gasoline or diesel.

Table 12: Reference case Petrol prices used.

2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
$23.18	$28.70	$29.14	$27.02	$26.37	$25.99	$26.00	$26.25	$26.69	$27.22	$27.84
	2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
	$28.32	$28.72	$28.92	$29.13	$29.26	$29.51	$29.75	$30.01	$30.37	$30.73
	2031	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
	$31.07	$31.44	$31.97	$32.41	$32.99	$33.59	$34.19	$34.79	$35.47	$36.18

* Source: U.S. EIA (2013). Prices in 2011 dollars per million Btu.

5.2.1.2. Gas share

Natural gas in the model was considered as Compressed Natural Gas (CNG). Future prices of CNG were based on EIA reference case study (U.S. EIA, 2013) and converted to an energy-equivalent basis (Dollars per MBtu). The Natural Gas prices used as inputs for each year in the model are presented in Table 13. Since regular cars need to be adapted to run with gas, there is a cost for adapting a car to use CNG that was considered as well. The adaptation costs vary from 10 to 100 units, in which 10 means that the user needs to buy a new car and 100 denotes that the same car can be used with no changes. Since to consume gas a car must be adapted, but it is not demanded to buy a new one, the adaptation cost for natural gas was set to 20 units. The availability of this type of fuel is somewhat available in petrol stations but it is not found everywhere. Thus, the availability for the reference case was set to 25 units.

Future scenarios of Natural Gas use in transportation could vary due to policies and new resource discoveries, however, as it was not one of the objectives of this study, these different Natural Gas scenarios were not modeled. Nevertheless, it is conceivable to use this model to develop different Natural Gas scenarios by altering prices, availability and policies related to this source of energy.

Table 13: Reference case Natural Gas prices used.

2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
$16.51	$16.14	$14.59	$15.85	$15.73	$15.74	$16.15	$16.35	$16.63	$16.78	$16.87
	2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
	$17.02	$17.30	$17.55	$17.77	$17.97	$18.22	$18.37	$18.58	$18.75	$18.90
	2031	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
	$19.06	$19.18	$19.31	$19.57	$19.86	$20.20	$20.51	$20.85	$20.98	$21.20

Source: U.S. EIA (2013). Prices in 2011 dollars per million Btu.

5.2.1.3. Biofuels share

Due to the fact that the vast majority of biofuels sold in the U.S. is ethanol (even if through blending), the Biofuels share is composed by ethanol. Future prices of the Biofuels share were based on ethanol prices of EIA reference case study (U.S. EIA, 2013) and are shown in Table 14.

The availability to buy directly ethanol (not mixed in gasoline) is low and most of the ethanol is sold mixed in gasoline due to mandate policies. Therefore, the availability for the reference case was set to 8. There is no cost for adapting a car to use biofuels. The users do not give preference to any fuel due to environmental issues.

In order to model the insertion in the market of biofuel blending mandates, a mathematical policy was set. As this is not an option of the users, because they buy gasoline (petrol) and receive ethanol blended with it, this policy worked as a percentage of Petrol. Thus, a factor of 0.1 (10%) is multiplied by the overall Petrol users, subtracted from the Petrol share and added to the Biofuels share already modeled.

Table 14: Reference case Biofuels prices used.

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
$25.56	$25.30	$33.64	$31.12	$24.81	$24.94	$24.51	$24.77	$25.84	$26.81	$29.64
	2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
	$29.38	$28.22	$28.25	$27.15	$27.27	$27.52	$26.36	$26.24	$26.60	$26.94
	2031	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
	$27.29	$27.67	$28.19	$28.63	$29.19	$29.79	$30.40	$30.99	$31.67	$30.58

* Source: U.S. EIA (2013). Prices in 2011 dollars per million Btu.

5.2.1.4. Advanced Biofuels share

Analyzing the diffusion of Advanced Biofuels depending on different policies is the main objective of this model. In order to reduce the uncertainty and simplify the model, the Advanced Biofuels share is considered as a sum of cellulosic biofuel, biomass-based diesel and advanced biofuel shares of the RFS2.

Since it is difficult to forecast future prices of Advanced Biofuels share, as referred in the economical assessment of microalgae (Section 2.3.2), various prices were tested. Regarding Advanced Biofuel prices, two scenarios were taken into account; one, in which price drops from 42 dollars per MBtu in 2020 by 1% per year, and another, with fixed price 42 dollars per MBtu in 2020 onwards. These options were made to model two different situations, one that the prices of Advanced Biofuels drop with advances in technology and production and another one where the price reaches a limit that cannot be further reduced.

The availability to buy directly advanced biofuels (not mixed in gasoline) is low. Therefore, the availability for the reference case was set to 7 and it rises depending on the investment of R&D that is applied. With the increase of R&D in emerging advanced biofuels, it is expected that the resource availability grows. In this manner, with low R&D investment, in the reference case, the availability grows 2.5% per year from 2015 onwards. Likewise, the availability increases yearly with medium and high investments in R&D in 4.0% and 6.5%, respectively.

As said previously, advanced feedstock for fuels can produce a great variety of fuels, such as ethanol, biodiesel, biogasoline or bio-oil (considered perfect petroleum substitute). Therefore, in this model, no cost for adapting cars to use advanced biofuels was accounted for.

In the scenarios where advanced biofuels mandates are modeled, the same methodology of 1st generation biofuels blending mandates was used. If the RFS2 mandates of Table 6 are considered to be met, a factor of 0.04 (4%) in 2015 is multiplied by the overall Petrol users, subtracted from the Petrol share and added to the Advanced Biofuels share already modeled. These values increase by 0.02 until 2022, when they remain constant.

5.2.1.5. Electricity share

The electricity share of the model was represented by what is already used nowadays plus the incorporation of electric cars. Future prices of the electricity share were grounded on a projection of electricity for transportation from U.S EIA (2013). These future prices are offered in Table 15.

Electric cars have a greater efficiency than combustion engine cars, and because of this characteristic, there is a lower energy need to travel the same distance with fuel electric cars. To model this, the electricity price was multiplied by a factor of 0.35 so that the energy equivalent is cheaper and the price is in tune with reality.

Table 15: Reference case Electricity prices used.

2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
$33.91	$32.77	$31.12	$30.59	$30.13	$29.84	$30.01	$29.95	$29.97	$29.76	$29.60
	2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
	$29.45	$29.42	$29.66	$30.04	$30.40	$30.71	$30.93	$31.21	$31.33	$31.53
	2031	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
	$31.74	$31.92	$32.19	$32.43	$32.84	$33.35	$33.76	$34.21	$34.76	$35.07

* Source: U.S. EIA (2013). Prices in 2011 dollars per million Btu.

The availability to buy an electric car is increasing each year due to technological advances in this field. Several limitations still halt the mass diffusion of this kind of transportation (e.g. autonomy, battery life, recharging time and stations, vehicle cost, etc.). However, it is expected a rise in electric and hybrids sales and thus, the availability for the reference case was set to 2 but it increases in 0.1 yearly over time from 2015 onwards. As commented before, in order to the user change to/from this energy source, there is the need of buying a new car, therefore, the cost for changing to/from electricity is 10.

Similarly to natural gas, many different scenarios could be modeled regarding different future paths for electric cars. However, since electric cars are not the main objective of this study, just one pathway was considered. The reference baseline for hybrid and electric cars was based on EIA (2013), and set to 20 million cars on the market in 2040 (accounting for cars and light trucks). These numbers contrast to 240 million conventional cars and light trucks in 2040 in the U.S. using gasoline and diesel (EIA, 2013). Therefore, in this scenario, it is not expected elevated electricity consumption and diffusion of the Electricity Share of the model. As stated earlier, another reason for this low level of diffusion is that electric cars are more efficient than conventional cars and will use less energy to travel the same distance, and the overall transportation market diffusion of this model is presented in an energy unit basis. More optimistic assumptions regarding electric vehicles market diffusion in the future of transportation can be modeled by changing prices, availability and change costs for this energy source.

With all the assumptions presented, in the next section it is described how each year was modeled and the equations that were used.

5.2.2. Modeling each year

The model consists of 5 automata representing the users of each considered energy source (Petrol, Gas, Electricity, Biofuels and Advanced biofuels). The structure of automata are analogous (Figure 14).

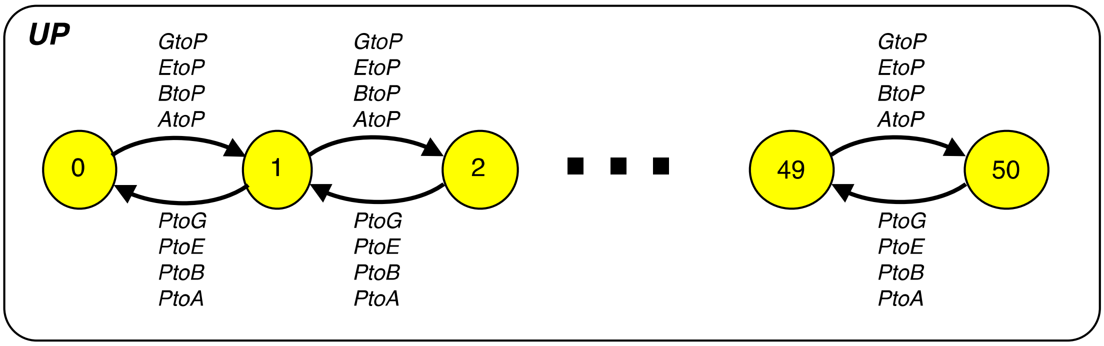


Figure 14: Automaton Users Of Petrol

Automaton ***UP*** (Users of Petrol) has 51 states, each representing a range of 2% of users. For example, if this automaton is in state 1, there is 1 to 2% of users of Petrol, if it is in state 49, users of Petrol are 97 to 98% of the total users of transport energy fuels. The increase/decrease of the number of users of Petrol occurs according to the transitions.

Transitions are triggered by events. For example, in ***UP*** it is possible to change from state 0 to state 1 if one of the following events occur: *GtoP* (Gas to Petrol), *EtoP* (Electricity to Petrol), *BtoP* (Biofuels to Petrol), *AtoP* (Advanced Biofuels to Petrol). The intuitive meaning is that there can only be an increase in the number of Petrol users if the user of some other fuel changes to Petrol. Figure 15 shows part of the automata ***UP*** and ***UG*** (Users of Gas). There we can perceive that the same event name is used in both automata. This means that these events are synchronized, that is, must occur at the same time, assuring that the users really move from one fuel to the other.

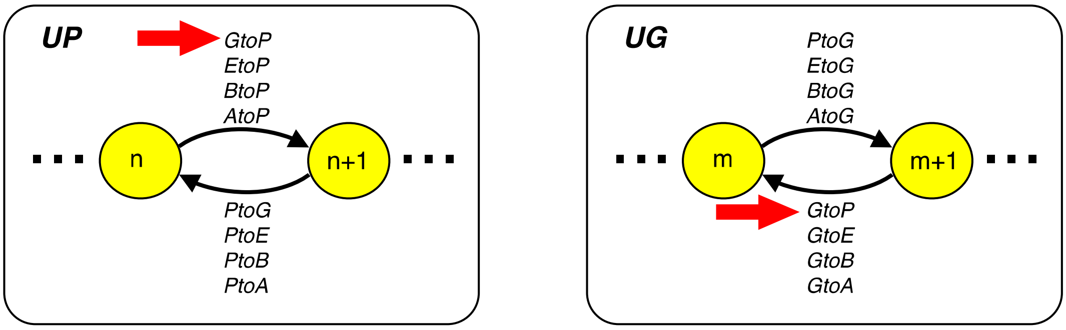


Figure 15: Synchronized Events

Moreover, each event has its own occurrence rate that governs how often the event will happen. These rates are thus the essential component of the model. Rates are values ranging from 0 to 1, where higher rates represent that it is more likely that the transition between the corresponding states occurs. The basic parameters (without considering policies) that are used to define the rates of transitions are, for each fuel X:

PRICE_X: price of fuel X. The price is given in Dollars per MBtu.

AVAIL_X: the availability of fuel. This may range from 1 to 100, and is a bound limiting the number of users of fuel X (if AVAIL_X is 10, at most 10% of users may use X). We consider the value of 100 as unlimited availability.

The mathematical expression that gives the rate of event XtoY (changing from a fuel X to fuel Y) is basically a weighted harmonic mean. The mathematical expression (Equation 1) should be understood as follows: if there is still availability of fuel Y, the rate to change from X to Y is the weighted harmonic mean considering the cost of converting the car (if necessary), with weight one, the availability of Y, with weight 2 and the price difference, with weight 3.

$$rateXY = available\_Y \times \frac{6}{\frac{1}{changeCost\_XtoY}+\frac{2}{(AVAIL\_Y/100)}+\frac{3}{priceDiff\_XtoY}} \quad \textbf{(1)}$$

where

available_Y: denotes whether fuel Y has not yet reached its limit. The value of this variable is zero if the number of users of this fuel is equal or greater than the availability of this resource, and one otherwise. In our model, an availability of 100 means that there is no limit, and, thus, in case fuel Y has availability 100, available_Y is one.

changeCost_XtoY: this represents the cost of changing from fuel X to fuel Y regarding car adaptations that are necessary. We work with three values for this variable: 1, when no adaption is necessary; 0.4 when some adaption is necessary (like in the case of adapting a car to use gas); and 0.1 when a car change is necessary.

priceDiff_XtoY: This variable gives the distance between the prices of fuel X and Y. We use a unity-based normalization using as interval the distance between the minimum cost in all scenarios (10) and the maximum cost (50). If prices of X and Y are the same, priceDiff_XtoY is 0.5. If Y is cheaper than X, priceDiff_XtoY will be greater than 0.5 (the greater the difference in price, the more this variable approximates to 1). Analogous to this, if Y is more expensive than X, priceDiff_XtoY will be smaller than 0.5.

Four kinds of policies were modeled: subsidy (policy 1), taxes (policy 2), mandates (policy 3) and R&D investment (policy 4). To simulate the effects of these policies in the model, the following parameters must be set for each fuel X:

Policy1_X: Subsidy is modeled by decreasing the price of a fuel by a factor (subsidy factor), ranging from 0 to 1.

Policy2_X: Taxes are modeled analogously, but with factors that are greater than 1. In this way, the price of fuel X that is considered in each model is obtained by multiplying the actual cost of X by the subsidy and tax factors.

Policy3_X: Mandates are also modeled by factors from 0 to 1 that represent the percentage of a fuel (Bio or Advanced Biofuel) in Gasoline.

R&D investment (policy 4) was modeled by increasing the availability of the resource, since the expected medium to long term effect of such investment is to improve the efficiency of the technology for production and use of these biofuels.

By solving the Markov chain associated to each scenario we find the equilibrium state, that is the distribution of users in states to which the system would converge. In this way, altering all the inputs and running in the SAN Lite Solver it is possible to model one year. The model template of the source code developed is presented in Appendix D. With the yearly results a scenario can be modeled. This step is presented in following section.

5.2.3. Modeling a scenario

The time span to be modeled is divided into 31 periods of equal length, corresponding to the years of 2010 through 2040. Since the change in energetic sources take a long time to reach penetration, such time horizons tend to cover several decades, being in this study until 2040.

In order to make a scenario, each individual year must be ran as described previously and the results compiled together, so that a curve can be attained. For example, Figure 16 (in section 5.2.4) is created from 31 "dots" arising from each energy source, representing their respective each year market shares based on the parameters established for each year. In this way, depending on prices fluctuations, availability changes or policies employed, the equilibrium state and the distribution of users of each year will be different, and the overall scenario will differ as well.

So, it was possible to create different scenarios to represent the future of transportation fuels in the U.S. depending on the policies adopted. However, for this model to represent realistic scenarios, it had to be calibrated and validated. More information about these steps is presented in the subsequent section.

5.2.4. Calibrating and validating the model

The challenge was to calibrate this model to make it a realistic representation of the U.S. transportation market shares, such that it would be worthwhile to use it to perform analysis of future scenarios. The calibration involved the choices of harmonic mean, weights of the harmonic mean components, factors of change cost, unity based normalization for price differences, and availability values of resources.

The choice for weighted harmonic mean was made to penalize low values. In this way, if a fuel is very cheap but has no availability, it will never achieve high market share, only if it increases its availability. Similarly, if a fuel is widely available but the price is too high, the weighted harmonic mean penalizes this fuel, as occurs in reality.

The factors of changing from an energy source to another were based on the reality whereas there is no change in infrastructure to change from gasoline/diesel to ethanol/biodiesel. Although ethanol is not recommended for older cars (prior to 2001) with gasoline engines, newer ones can use up to 15% (E15) of ethanol blended in their gasoline. Newer flex fuel cars are already been sold and can even use E100. In this way, changing costs for Petrol fuels to Biofuels and Advanced Biofuels were set to 100 (none). On the other hand, natural gas car adaptations were set to 40 and the purchase of an electric car set to 10. These numbers were achieved in the calibration process whereas the right set of inputs was needed so that the real transportation market shares were reached, as described further.

Regarding energy price differences, a unity-based normalization using as interval the distance between the minimum cost in all scenarios ($10.00) and the maximum cost ($50.00) was applied. Setting these parameters was necessary to achieve values ranging from 0 to 1, without having inaccuracies due to possible differences among scenarios. For example, if it were normalized solely with minimum and maximum values within the studied scenario, given year could present a minimum price of $30.00 and a maximum of $35.00 among all the energy sources. This would lead to a total range of only $5.00, and the fuel costing 35.00 would be greatly penalized, although it is not much more expensive than the others. In order to prevent these inaccuracies, all price differences were calculated based on a maximum range of $40.00, as stated before ($50.00 minus $10.00).

Availability is one of the key parameters in the model. In order to define the availability of each energy source, a relation with the real market was made as described in the assumptions section. Therefore, Petrol fuels were defined as widely available (100) and the other fuel availabilities were defined through the calibration process.

After the model was calibrated, the validation of the model was performed in three ways: (1) by considering real U.S. transportation market shares data of existing years, (2) by analyzing threshold situations, and (3) by analyzing a reference scenario.

The years 2010 and 2013 were chosen as references and the market shares resulting from the solution of the model should be very approximate to the real values of the considered years. In this way, with all the same inputs, except for price (based on real ones), the modeled years 2010 and 2013 results must be very similar to the real values. In order to accomplish that, the values for availability and prices used are shown in Table 16.

Table 16: Availability and price calibration (2010 and 2013 inputs).

Energy sources	**2010**		**2013**	
	Availability	**Price**	**Availability**	**Price**
Petrol	100	23.18	100	27.02
Natural Gas	25	16.51	25	15.85
Biofuels	8	25.56	8	31.12
Advanced Biofuels	7	50.00	7	50.00
Electricity	2	33.91	2	30.59

Prices in US$ per Million Btu.

It is important to highlight that with only an alteration of prices, that was based on the real ones (U.S. EIA, 2013) except for Advanced Biofuels, and using the same availability for each source, the market shares resulting from the solution of the model were very close to the real values of the selected years (Table 17).

Another characteristic of this model is that it points out tendencies. For example, if the price of Natural Gas drops vigorously for a given year, the market share of gas is bound to raise in the model. However, in the real world market, a transition among different energy sources takes time, and it is not probable to witness strong changes from one year to another. Due to this reality, the Natural Gas share was particularly difficult to calibrate because the price decreased from 2010 to 2013 (U$16.51 to U$15.85) and just a small raise in market share was observed (3.03% to 3.36%). Consequently, the model results presented a higher raise in Natural Gas market share, due to lower prices.

Table 17: Real transportation U.S. values versus model results from years 2010 and 2013.

Energy sources	Real	Model	Real	Model
	2010	**2010**	**2013**	**2013**
Petrol	88.80%	88.78%	87.81%	87.91%
Natural Gas	3.03%	2.53%	3.36%	3.40%
Biofuels	7.94%	8.02%	7.94%	7.94%
Advanced Biofuels	-	0.33%	0.52%	0.36%
Electricity	0.23%	0.32%	0.37%	0.36%

* Petrol represents a sum of fossil Gasoline and Diesel. Aviation fuels and petrol derivatives were not considered. Market shares are represented in % of Mbtu used.

Furthermore, the analysis of limit situations showed the robustness of the model. The model behaves as expected considering, among others, circumstances where all fuels had the same price and/or all the same availability. A total of 32 limit tests were performed with the final version of the model. A list of some of these limit tests are shown below and the test results are presented in Table 18. Note that all the tests were based on 2010 reference values and only the changes made are listed.

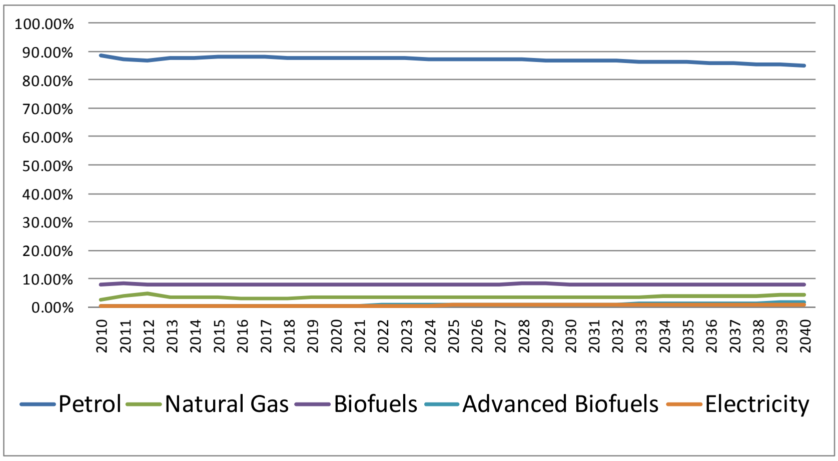
- **Test 1:** Advanced Biofuels availability = Petrol = 100
- **Test 2:** All sources availability = 100
- **Test 3:** Advanced Biofuels availability = 100 and Price 10.00
- **Test 4:** Advanced Biofuels availability = 100 and Petrol price = Adv. Bio = 23.18
- **Test 5:** Advanced Biofuels price = 20.00
- **Test 6:** Natural Gas availability = 100
- **Test 7:** Electricity availability = 50
- **Test 8:** Electricity availability = 100 and Biofuel Price = Adv. Bio = 25.56
- **Test 9:** Advanced Biofuels price = Petrol = 50.00
- **Test 10:** Advanced Biofuels price = Petrol = 20.00

Table 18: Limit situations test results.

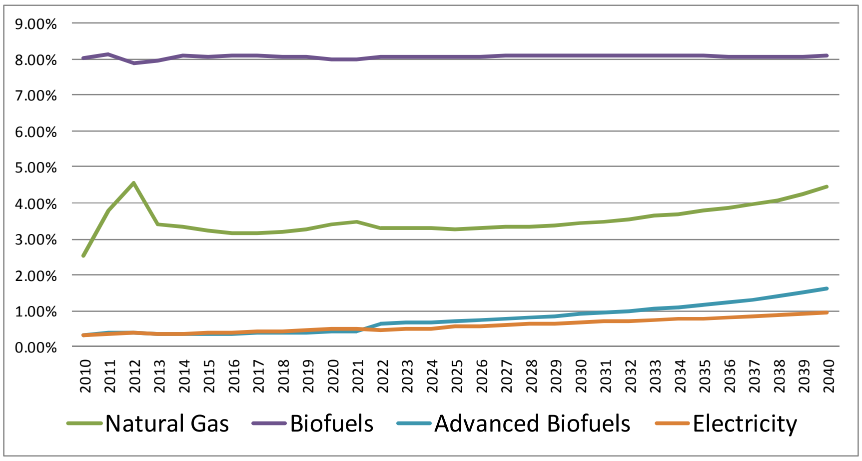
Energy sources	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**	**Test 7**	**Test 8**	**Test 9**	**Test 10**
Petrol (%)	88.36	9.51	3.58	45.29	88.73	82.37	73.77	51.55	65.43	89.40
Natural Gas (%)	2.76	6.51	1.26	2.40	2.45	9.74	2.98	2.85	23.45	2.08
Biofuels (%)	7.84	7.95	1.20	4.82	7.93	7.47	6.98	5.44	10.07	7.91
Advanced Biofuels (%)	0.87	0.60	93.82	47.32	0.74	0.25	0.25	0.51	0.65	0.46
Electricity (%)	0.15	75.41	0.11	0.14	0.13	0.14	15.99	39.62	0.38	0.12

The results from Table 18 are reached to analyze if the resulting market share behaves as expected with the given inputs. For example, Test 4 changes the availability of Advanced Biofuels to 100, and the price is set as the same as Petrol. In this fictitious scenario, it is expected from the users to be divided mainly between these two fuels. That is, in fact, what occurs, with a slight difference from the biofuels mandate policy 3 that subtracts some of the users of Petrol. Thus, this same analysis is continually performed to all 32 tests.

After calibrating the model and analyzing the test sequences, a full scenario could be built. For that, each year inputs for every energy source were inserted in the model and ran separately. With all data from all years done, the resulting reference U.S. transportation market share can be seen in Figure 16.



(a)



(b)

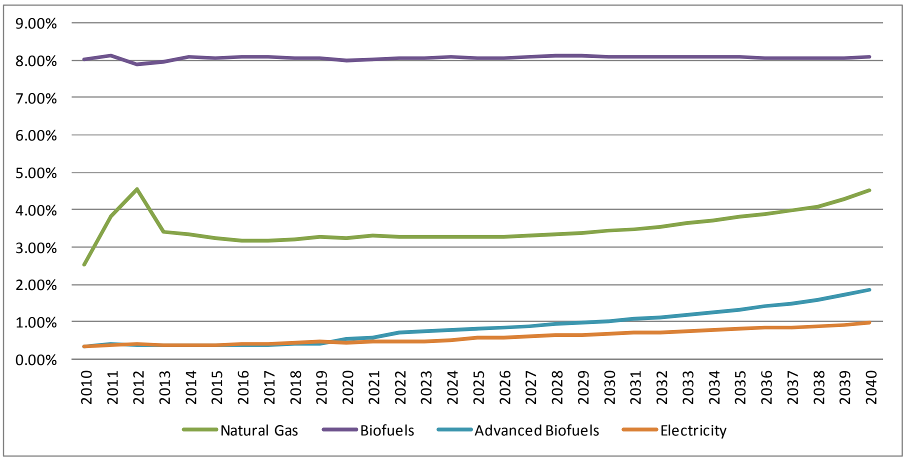
Figure 16: U.S. Transportation market share diffusion reference scenario (a) and a graphic zoom in non-petrol fuels (b).

From this reference scenario, it is possible to notice only a minor decrease in the users of Petrol if no other policies are in effect, since the only policy used in the reference model was the 1st generation biofuels mandates. In the Figure 16 (b), there is a slight yearly increase in electricity, natural gas and advanced biofuels use. Other scenarios can be created by altering the assumed policies . This will be made in the next section.

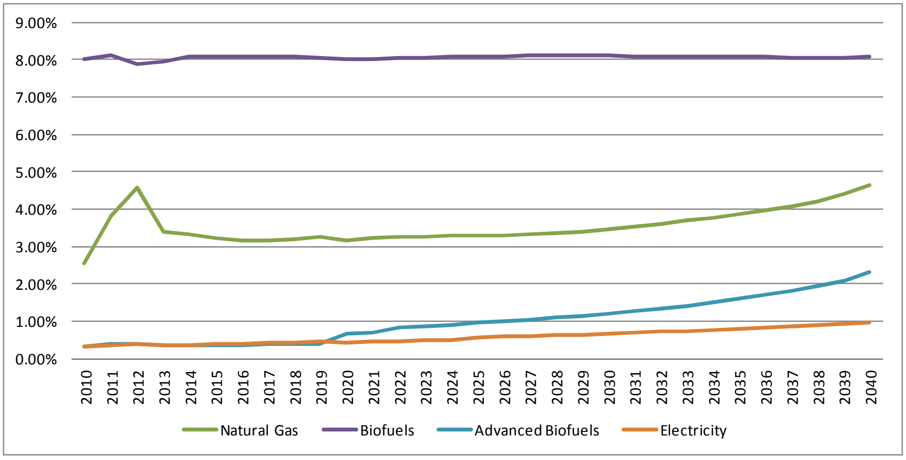
5.3. Results and analysis

After the steps of calibrating and validating the model, many scenarios were calculated from 2010 to 2040 with different policies configurations. Initially, a price subsidy of Advanced Biofuels was modeled (Policy 1) from 2020 onwards. This price subsidy scenario, based on the reference scenario, reduced the final price of Advanced Biofuels in 10%, 25% and 50% with no alterations made in the reference availability of

Advanced Biofuels (low investment on R&D). The results can be met in Figure 17. It is only shown the graphic zoom in the non-Petrol fuels due to the very high market shares of Petrol (84.6, 84.0 and 82.2% in 2040, respectively).



(a)



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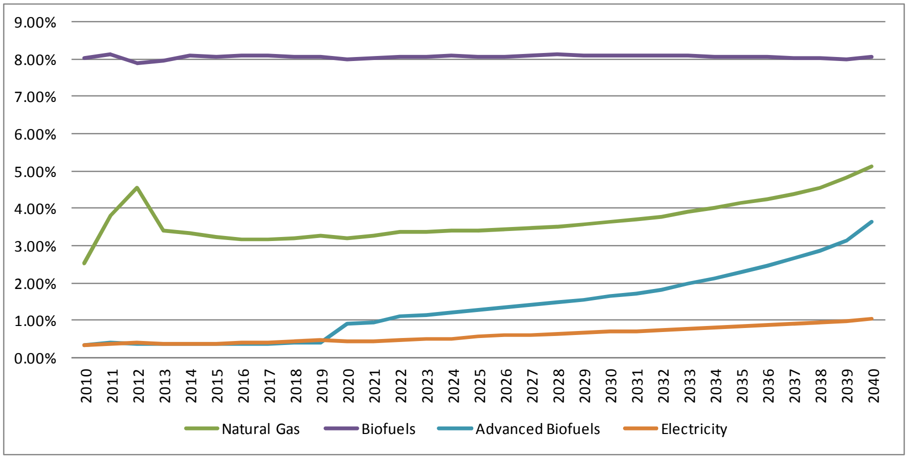
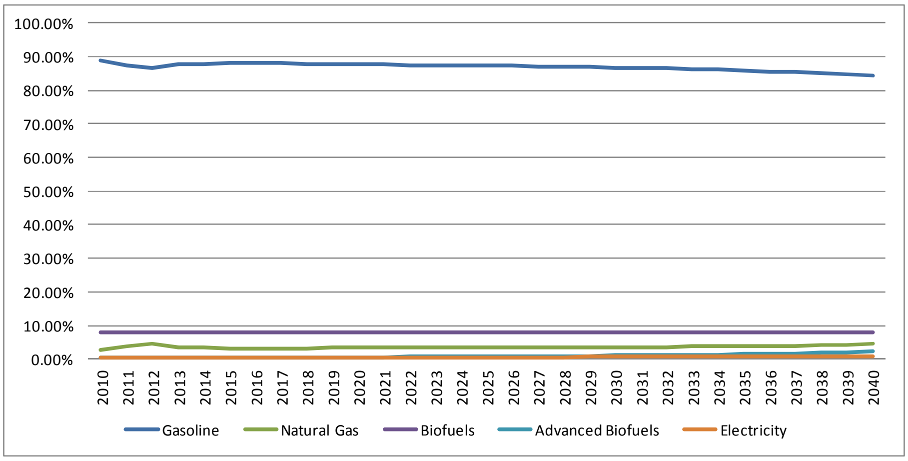


(c)

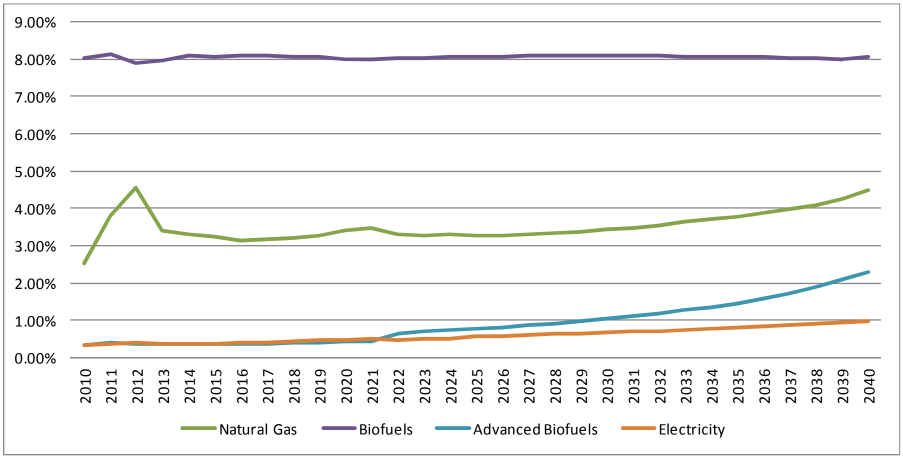
Figure 17: U.S. Transportation market share diffusion of reference scenario with low investment in R&D and 10% (a), 25% (b) and 50% (c) Advanced Biofuels price subsidy.

From the above graphs it is possible to realize that with low investment in R&D, no mandates and solely price subsidies, slight is the effect on the future diffusion of Advanced Biofuels, since in the strongest 50% subsidy scenario (c), the Advanced Biofuels share does not reach 4% in the market share by 2040.

With the purpose of assessing the impact of Research & Development, a medium investment on R&D was modeled without subsidies and with the same Advanced Biofuels price subsidies already used. The new reference scenario is shown in Figure 18.



(a)



(b)

Figure 18: U.S. Transportation market share diffusion reference scenario with medium Advanced Biofuels R&D investment (a) and a graphic zoom in non-petrol fuels (b).

Comparing the medium and low R&D investment scenarios for Advanced Biofuels, it is possible to witness a small increase of market shares by the end of 2040 (1.6% to 2.3%). In the same manner, the Petrol share decreases from 84.9% to 84.2% of the total market share in 2040. The scenarios with Advanced Biofuels subsidies and medium R&D investment are presented in Figure 19. The Petrol share are not represented in this figures, but they achieved 83.7, 82.7 and 79.4% in 2040, respectively.

(a)

(b)

(c)

Figure 19: U.S. Transportation market share diffusion of reference scenario with medium investment in R&D and 10% (a), 25% (b) and 50% (c) Advanced Biofuels price subsidy.

Analyzing these graphs, it is interesting to point out that the market diffusion outcomes obtained from a price subsidy coupled with a medium investment in R&D are more effective regarding Advanced Biofuels, when compared with the low R&D

investments scenarios. In Figure 19(c) it is possible to see that not only the Advanced Biofuels share made progress in the final market share, but also the Natural Gas share raised as well (2040 Reference Natural Gas from 4.46% to 5.21%), even if no policies or different availabilities were applied in this energy source.

To conclude this section of R&D investments, a high investment in Advanced Biofuels was modeled according the same pattern presented in the previous ones. The results of the overall market diffusion with no subsidies are shown in Figure 20.

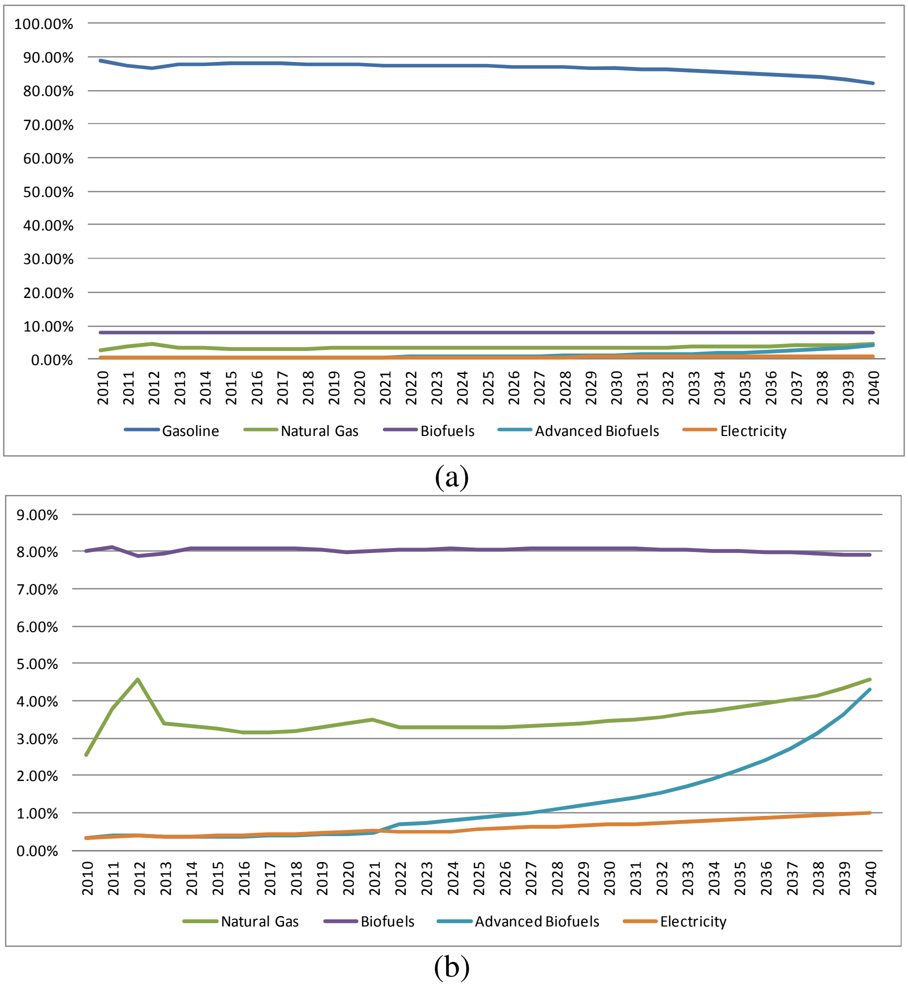
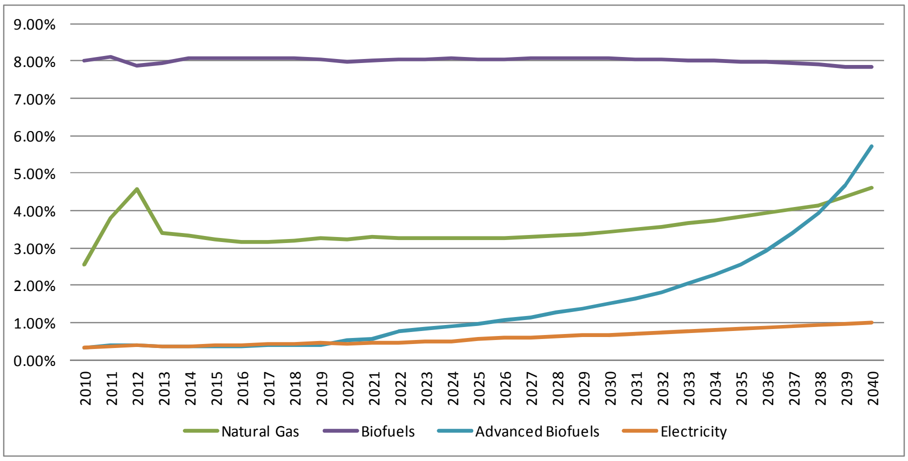


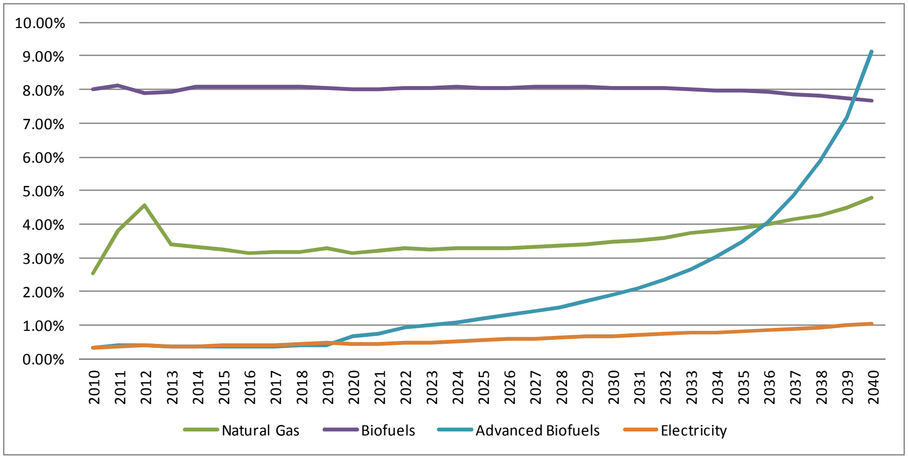
Figure 20: U.S. Transportation market share diffusion reference scenario with high Advanced Biofuels R&D investment (a) and a graphic zoom in non-petrol fuels (b).

The Advanced Biofuels share is reasonably higher in this scenario, achieving 4.31% of the overall U.S. transportation market share in 2040. When this higher investment in R&D is combined with price subsidies, the results are far more promising.

Figure 21 displays the results of Advanced Biofuels high investment in R&D and price subsidies of 10 and 25%.



(a)



(b)

Figure 21: U.S. Transportation market share diffusion of reference scenario with high investment in R&D and 10% (a) and 25% (b) Advanced Biofuels price subsidy.

From Figure 21 it is clear that with high investment in R&D and with price subsidies, Advanced Biofuels market diffusion can become an important market player in the future. In Figure 22 it is shown the great impact on the overall U.S transportation market diffusion with a high investment in R&D and high subsidies for Advanced Biofuels.

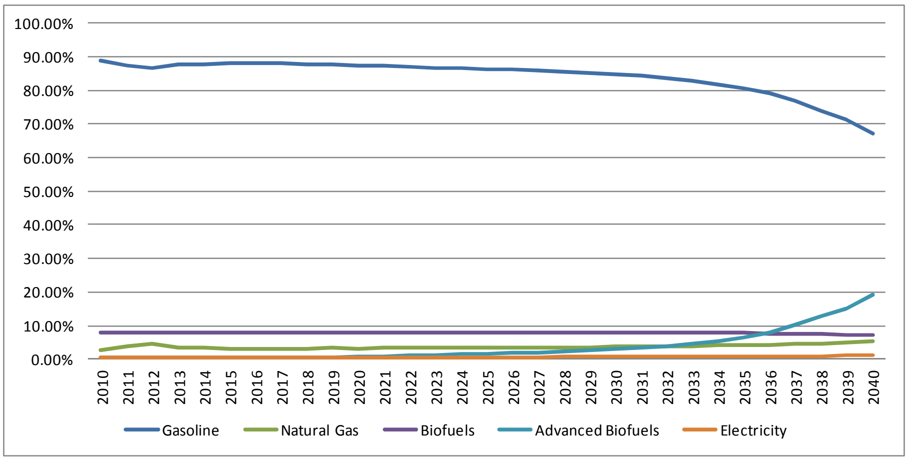


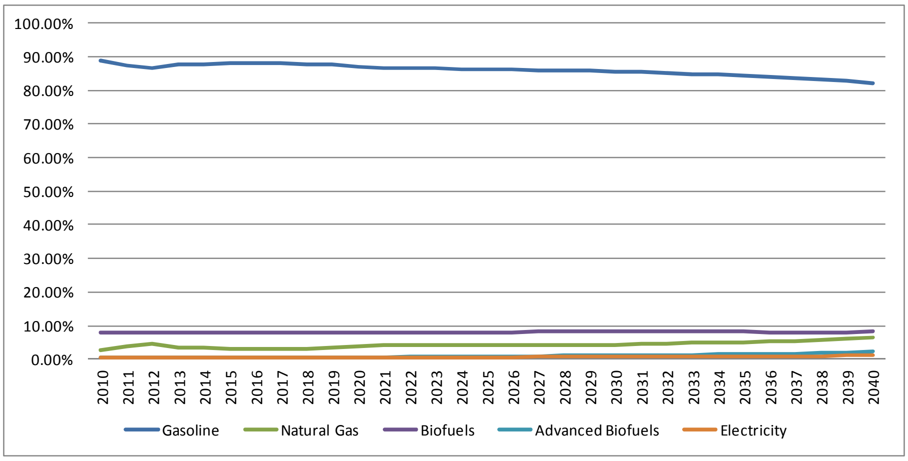
Figure 22: U.S. Transportation market share diffusion reference scenario with high R&D investment and 50% price subsidy for Advanced Biofuels.

Although it is unlikely that such a high subsidy is to be implemented by any government, it is valid to model this feature for academic purposes. In this figure, it is interesting to witness a sensible growth in the Advanced Biofuels share, reaching 19.03% in 2040. On the other hand, the Petrol share decreases from 87.87% nowadays to 67.33% of U.S. transportation market share in 2040.

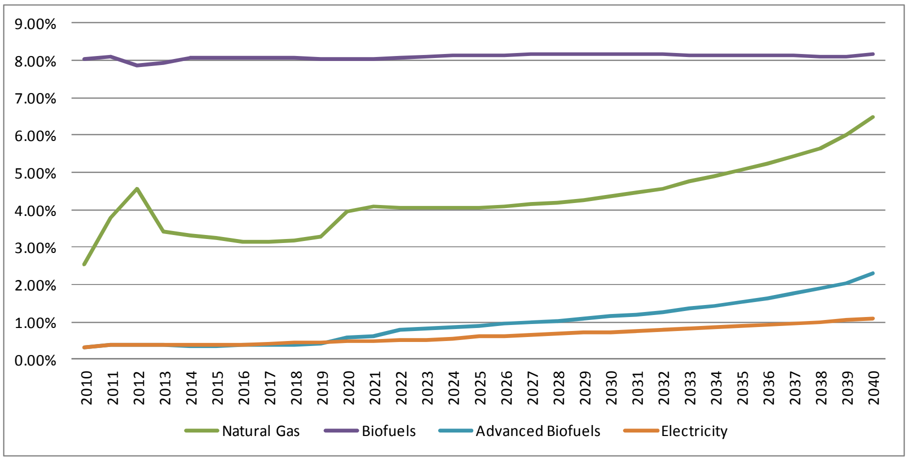
The importance of R&D investment as a policy was mentioned in the Delphi survey (Section 4.2) by the algae experts and proved to be successful on the scenarios modeled. In this way, R&D investment not only in the algae industry but also in all advanced biofuels one can be crucial to the development of these technologies.

In the next step of modeling scenarios, price taxes on the Petrol share were applied attempting to achieve even higher market diffusion for Advanced Biofuels. In a similar method, other sources of energy would benefit from higher prices of the Petrol share, and an increase of the Natural Gas and Electricity shares were also expected.

The same models with Advanced Biofuels price subsidies (10%, 25% and 50%) were coupled with Petrol taxes that increased the price of Petrol in 10%, 25% and 50%. These 9 scenarios were recalculated with low, medium and high R&D investments, performing a total of 27 new scenarios to be analyzed. Some of these scenarios are presented as follows (Figure 23). A complete table with all the results achieved in each scenario is displayed in Appendix E. A 10% Petrol tax was applied from 2020 onwards in the next scenarios.



(a)

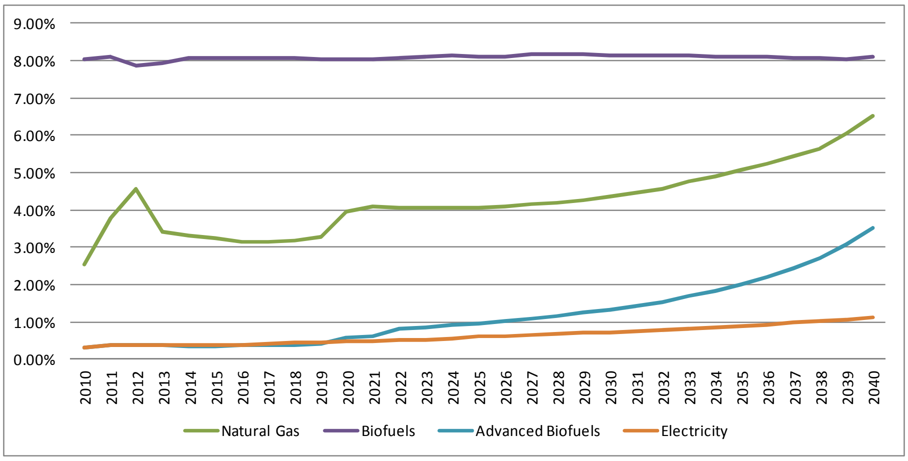


(b)

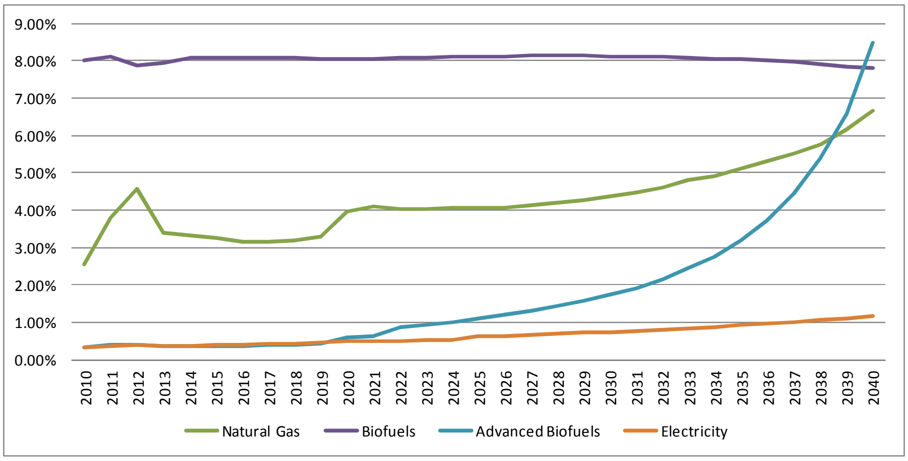
Figure 23: U.S. Transportation market share diffusion of reference scenario with low investment in R&D, 10% Advanced Biofuels subsidy and 10% Petrol tax (a) and a graphic zoom in non-petrol fuels (b).

From these graphs it is noteworthy the growth of other energy sources when a 10% Petrol Tax is applied. The Natural Gas share ascends from 4.46% to 6.49% in 2040, while the Electricity share slightly climbs from 0.96% to 1.10% in this new scenario. The Advanced Biofuels share shows an increase from 1.63% to 2.29% based on the reference scenario.

When medium and high investments in R&D in Advanced Biofuels are considered, it is noted a higher rate of market diffusion of Advanced Biofuels, as expected (Figure 24).



(a)



(b)

Figure 24: U.S. Transportation market share diffusion graphic zoom in non-petrol fuels of reference scenario with 10% Advanced Biofuels subsidy, 10% Petrol tax and medium (a) and high (b) investment in R&D.

With a higher penetration of Advanced Biofuels, a small drop in 1st generation biofuels is observed (Figure 24b). The reason for this decrease is that almost 99% of the volume of ethanol is sold through blending mandates, sold simultaneously with gasoline (U.S EIA, 2013). In this way, when users increase their use of Advanced Biofuels, Electricity and Natural Gas, they decrease their utilization of gasoline (75.9% of users in 2040), consequently reducing the amount of biofuels sold through blending.

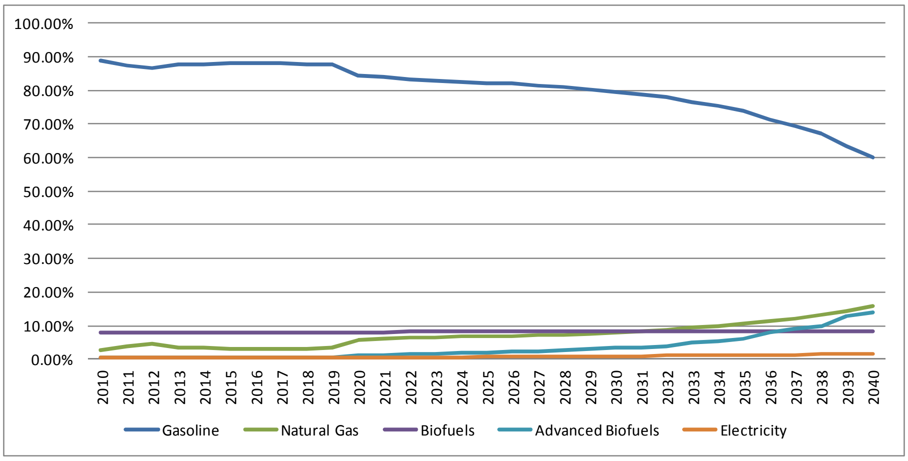
Analogously, these scenarios were developed with different policies and Table 19 presents the final results (in 2040) of Advanced Biofuels and Petrol shares in % of total U.S. transportation. In this table, results are summarized for four different policies: Research & Development (R&D) investment in Advanced Biofuels (low, medium and high), advanced biofuels price subsidies (10%, 25%, and 50% price abatement), Petrol taxes (10%, 25%, and 50% price increase) and 1st generation biofuels mandates (already in the reference model).

Table 19: U.S. Transportation Market Shares In 2040 Depending On Different Policies.

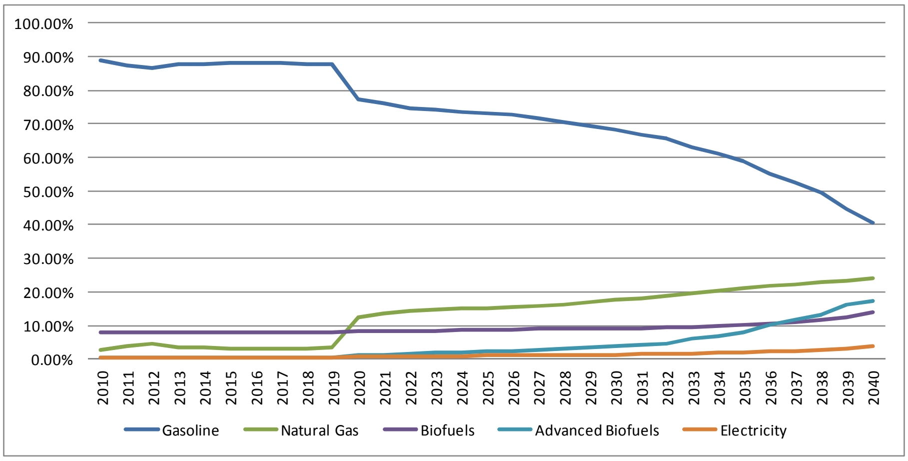
Reference: Advanced Biofuels share				**Petrol (Gasoline + Diesel) share**		
R&D	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Reference	1.6%	2.3%	4.3%	84.9%	84.2%	82.2%
Price subsidy 10%	1.9%	2.7%	5.7%	84.6%	83.7%	80.8%
Price subsidy 25%	2.3%	3.6%	9.1%	84.0%	82.7%	77.4%
Price subsidy 50%	3.6%	6.4%	19.0%	82.2%	79.4%	67.3%
With 10% Petrol Tax						
Price subsidy 10%	2.3%	3.5%	8.5%	82.0%	80.8%	75.9%
Price subsidy 25%	2.9%	4.9%	13.8%	81.0%	79.1%	70.4%
Price subsidy 50%	4.9%	9.0%	23.4%	78.0%	73.9%	59.9%
With 25% Petrol Tax						
Price subsidy 10%	3.4%	5.8%	16.3%	74.1%	71.8%	61.3%
Price subsidy 25%	4.7%	8.3%	22.1%	72.0%	68.3%	54.6%
Price subsidy 50%	8.2%	14.1%	27.0%	65.9%	59.9%	46.9%
With 50% Petrol Tax						
Price subsidy 10%	9.6%	15.2%	27.5%	50.3%	44.3%	30.7%
Price subsidy 25%	12.1%	17.3%	28.5%	46.2%	40.7%	28.2%
Price subsidy 50%	14.7%	19.1%	29.4%	40.5%	36.2%	24.5%

As commented previously, the greatest difference in final market diffusion of Advanced Biofuels depends on how intense is the R&D investment. Price subsidies also help the diffusion of Advanced Biofuels, however, with little investment in R&D the scale of production do not raise sufficiently and, consequently, a low percentage of users can change to this biofuel. Thus, a combination of investment in R&D with price subsidies showed better results.

Taking into account the implementation of Petrol taxes, it is significant to highlight that not only the Advanced Biofuels share increased, but users of all other sources of energy also enhanced. This is shown in Figure 25.



(a)



(b)

Figure 25: U.S. Transportation market share diffusion of reference scenario with medium investment in R&D, 50% Advanced Biofuels subsidy and 25% Petrol tax (a); and 25% Advanced Biofuels subsidy, 50% Petrol tax (b).

In these scenarios a much more balanced situation, regarding the sources of energy used in transportation, is achieved. For example, in Figure 25b, Advanced Biofuels, Natural Gas and Electricity reach in 2040 17.32%, 24.09% and 3.79% of the transportation market share respectively, while the use of Petrol fuels declines to 40.71%. However, it is imperative to make clear that such elevated petrol taxes are unlikely to happen in reality, at least nowadays, but for scientific purposes it revealed to be important to project these scenarios.

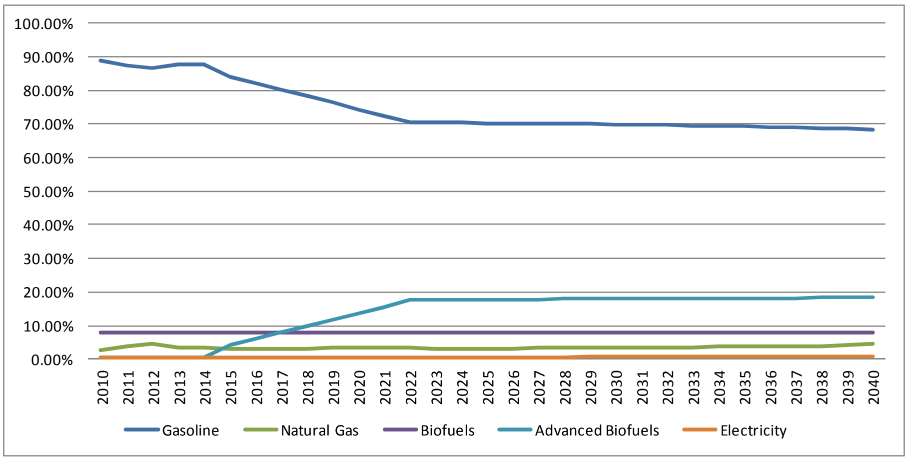
It is essential to recap that with an 1% yearly decrease in Advanced Biofuels price as reference (from 2023 onwards), the final price, without taxes or subsidies, was cheaper than the Petrol (in which gasoline prices were used) US$ 35.05 *versus* US$ 36.18 per MBtu in 2040. Recognizing that it could be difficult to lower prices only due to better industry efficiency and economies of scale, all these scenarios were run again with fixed advanced biofuels prices of US$ 42 per MBtu, in an attempt to mimic a scenario that advanced biofuels industry reach its minimum feasible price. The results are shown in Table 20.

Table 20: U.S. Transportation Market With Fixed Price U$ 42.00 per Mbtu Share in 2040 Depending on Different Policies.

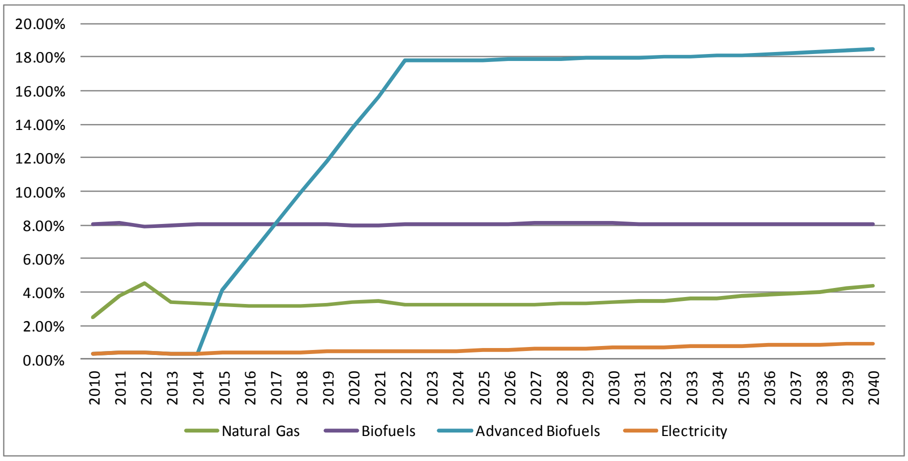
Reference: Advanced Biofuels share				**Petrol (Gasoline + Diesel) share**		
R&D	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Reference	1.3%	1.7%	2.6%	85.2%	84.8%	83.7%
Price subsidy 10%	1.5%	2.0%	3.5%	85.0%	84.5%	83.0%
Price subsidy 25%	1.9%	2.7%	5.7%	84.6%	83.7%	80.8%
Price subsidy 50%	3.0%	5.0%	14.8%	83.1%	81.1%	71.7%
With 10% Petrol Tax						
Price subsidy 10%	1.8%	2.5%	4.8%	82.6%	81.9%	79.5%
Price subsidy 25%	2.3%	3.5%	8.5%	81.9%	80.7%	75.9%
Price subsidy 50%	3.9%	7.0%	20.1%	79.5%	76.4%	63.7%
With 25% Petrol Tax						
Price subsidy 10%	2.5%	3.8%	9.1%	75.4%	74.1%	68.7%
Price subsidy 25%	3.4%	5.8%	16.3%	74.0%	71.8%	61.3%
Price subsidy 50%	6.5%	11.7%	25.7%	68.8%	63.5%	49.5%
With 50% Petrol Tax						
Price subsidy 10%	6.5%	11.4%	25.1%	68.8%	49.5%	34.6%
Price subsidy 25%	9.6%	15.3%	27.5%	50.3%	44.3%	30.7%
Price subsidy 50%	13.9%	18.5%	29.1%	42.5%	37.8%	25.9%

In order to assess how the mandates influence the advanced biofuels diffusion in the transportation sector of the U.S., the next scenario is made based on RFS2 mandates of Table 6 from 2015 onwards. It is significant to highlight that although these mandates are in place, the actual produced volumes differ greatly from what was previously predicted. Regarding cellulosic biofuels, for example, the volume for 2014 established in 2010 was 1.75 billion gallons (U.S. EPA, 2010), but this amount was changed in 2013 to 17 million gallons (U.S. EPA, 2013). Thus, although the volume amounts used in this next scenario were based on that table, these amounts are probably going to be altered by the U.S. Environmental Protection Agency in the next years to values consistent with reality.

In Figure 26, a representation of how the RFS2 mandates for advanced biofuels would affect the market shares if they could accomplish the 36 billion gallons goal as it was planned (U.S. EPA, 2010). The problem with this approach is that the mandates only do not have the power to make these fuels available, and the real production is well below to what was established.



(a)



(b)

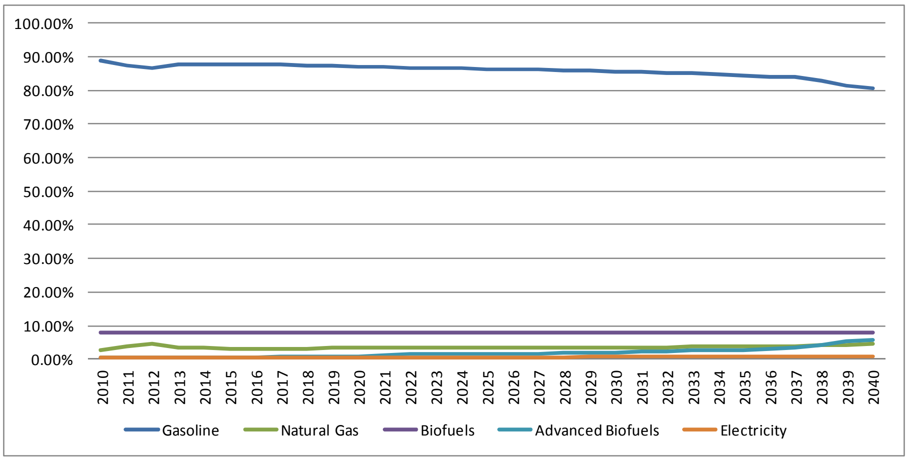
Figure 26: U.S. Transportation market share diffusion of reference scenario with low investment in R&D and Advanced Biofuel Mandates based on RFS2(a); and a graphic zoom in non-petrol fuels (b).

Regarding the first years of the RFS2 mandates, real production is not following the path established. The U.S. EIA (2013) states that the consumption of 36 billion gallons ethanol equivalent established on EISA 2007 RFS target will not be reached in 2022 since the RFS program does not provide sufficient incentives to promote significant new ethanol capacity in this pricing environment. Thus, with the purpose of generating a better representation of the advanced biofuels mandates so far, data from U.S. EIA (2013) projection was used to develop this new scenario of mandates. Table 21 presents these possible future scenarios from U.S EIA (2013) and Figure 27 presents a representation of those values developed from the model.

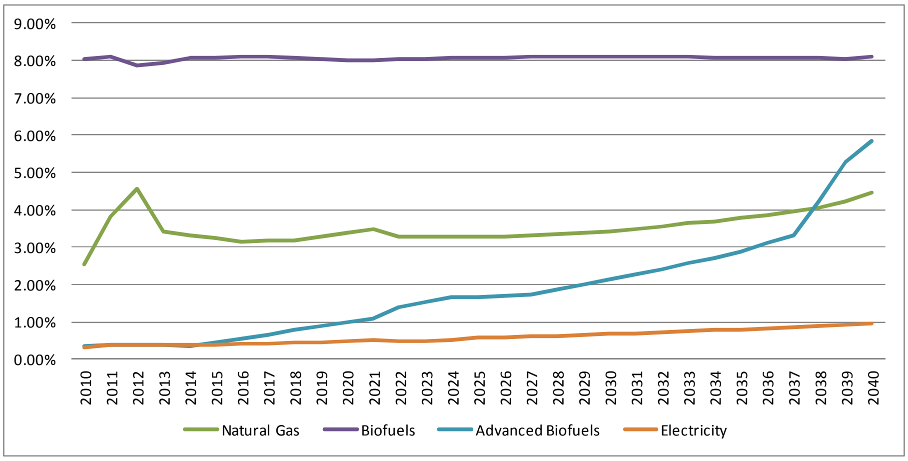
Table 21: Altered EISA2007 RFS2 mandate from 2011-2040 (billion gallons ethanol eq.)

	Advanced Ethanol	Biomass-based Diesel	Cellulosic drop-in fuels	TOTAL
2011	0.05	0.30	0.00	**0.35**
2012	0.13	1.49	0.02	**1.64**
2013	0.25	1.92	0.02	**2.18**
2014	0.34	1.91	0.05	**2.29**
2015	0.34	1.91	0.08	**2.33**
2016	0.35	1.91	0.14	**2.40**
2017	0.35	1.91	0.16	**2.42**
2018	0.35	1.89	0.18	**2.42**
2019	0.36	1.90	0.21	**2.47**
2020	0.36	1.90	0.25	**2.51**
2021	0.36	1.91	0.28	**2.55**
2022	0.36	1.91	0.33	**2.59**
2023	0.35	1.92	0.38	**2.65**
2024	0.35	1.91	0.44	**2.71**
2025	0.35	1.91	0.52	**2.78**
2026	0.35	1.91	0.61	**2.87**
2027	0.35	1.91	0.72	**2.98**
2028	0.35	1.91	0.85	**3.11**
2029	0.35	1.91	1.01	**3.26**
2030	0.34	1.91	1.20	**3.45**
2031	0.34	1.90	1.46	**3.70**
2032	0.34	1.91	1.78	**4.02**
2033	0.34	1.90	2.17	**4.41**
2034	0.34	1.91	2.65	**4.90**
2035	0.34	1.91	3.25	**5.49**
2036	0.34	1.91	3.98	**6.23**
2037	0.34	1.91	4.88	**7.13**
2038	0.34	1.91	5.99	**8.24**
2039	0.34	1.91	7.36	**9.61**
2040	0.34	1.91	9.03	**11.28**

Source: U.S. EIA projection (2013)



(a)



(b)

Figure 27: U.S. Transportation market share diffusion of reference scenario with low investment in R&D and revised RFS2 Advanced Biofuel Mandates based on U.S. EIA (2013)(a); and a graphic zoom in non-petrol fuels (b).

As represented on Table 21, U.S. EIA (2013) states that domestic consumption of drop-in cellulosic biofuels will grow from 0.3 billion gallons to 9.0 billion gallons ethanol equivalent per year from 2011 to 2040 while production costs for biofuel technologies fall. In comparison, little raise is seen on advanced ethanol and bio-based diesel, mainly due to the uncertainty related to the scale production of microalgae. After some commercial microalgae plants start production in the next years, these values can be altered.

Finally, from the results presented some considerations can be drawn:

a) Investment in Research & Development in advanced biofuels plays a key role in the future diffusion of these fuels;

b) It is more interesting in terms of diffusion to create policies that enhance research and development of advanced biofuels that would lead to increased availability and lower future prices than to merely enable subsidies to make them readily competitive with other fuels;

c) Enabling Petrol taxes not only enhances the diffusion of Advanced Biofuels but also all other fuels in the market share; and if there are not enough biofuels to fulfill the demand, natural gas and electricity become key players in the market share;

d) If no public policy is enabled to enhance the Advanced Biofuels industry, it would play a minor role in the future of energy transportation. This scenario could dramatically change depending on the policies adopted and

e) Given the uncertainty of long-term crude oil prices, the real competitive price level for advanced biofuels can be far higher.

Although it is very unlikely to promote such taxation on petroleum products, it is interesting to study how strong fiscal impacts would affect the market diffusion of all fuels until 2040. Moreover, with policy support and incentives, the algal biofuels industry (and advanced biofuels) will continue to develop and assuming that this technology follows renewable energy cost trends, costs will decrease to eventual economic viability.

6. CONCLUSIONS

As several times mentioned throughout this work, the continued use of fossil fuels for energetic purposes is gradually becoming clearer to society that is unsustainable. Innovative technologies and sources of energy must then be developed to replace fossil fuels. However, alternative sources of biofuel derived from terrestrial crops such as sugarcane, soybeans, maize, rapeseed, among others, inflict a lot of pressure on the global food markets, contribute to water scarcity and precipitate the destruction of forests. Furthermore, many countries cannot grow most of the terrestrial crops due to climate factors or lack of fertile cultivation areas for energetic purposes. In this context, using microalgae as a feedstock for biofuels is strongly believed to make a contribution for the future world sustainability.

Algae biofuel technological advances in cultivation and extraction of oil are scientifically well known, and should continue to move forward in the coming years with increasing investment in R&D in this area. However, as shown in this thesis, many are the challenges for this technology to be successful and produce biofuels in a sustainable manner. Therefore, **what are the main drivers that influence the overall sustainability of microalgae biofuels, considering economic, social and environmental impacts?**

Consensus among the algae experts was reached in many of the prospects and bottlenecks of this technology. The Delphi method proved to be a successful research method when expert opinions are the main source of information available, due to a lack of appropriate historical, economic or technical data. The outcomes provided a clear outline of the main issues of microalgae biofuels' market at the present and in the future. In particular, the two-round survey revealed the most important issues affecting this emerging market and also, recommended ways to influence future policies and development of this biofuel.

Environmental sustainability can be directly affected by several issues in microalgae cultivation, such as poor energy balance, water scarcity or greenhouse gas benefits if some processes are not adopted in the cultivation and production. Some of the key processes are anaerobic digestion to generate energy for the process, recycling nutrients from wastewater and seawater, and using a source of CO_2 from emitting industries. The need of finding locations with favorable climate, in non-agricultural land, with feasible water supply and CO_2 resources are also key aspects concerning environmental sustainability of microalgae biofuels. However, as shown in the sustainability assessment, it is possible to produce biofuels from microalgae while being environmentally sustainable depending on the cultivation processes that are chosen.

Social equity presents a favorable panorama. The possibility to produce fuels with no need of "proven geographical reserves" renders to this technology a strong social characteristic, in which many countries have the possibility to produce it. This allows increased independence on foreign energy and increase the energy security of producing countries, as developing domestic sources of energy are key to promoting energy security. Moreover, for developing countries with high levels of poverty, the relationship of increased consumption of energy and well-being is stronger. Therefore, beyond job generation impacts, providing economic stimulus for such countries, algal biofuel production would provide energy availability and security, while encouraging infrastructure and social development, without the dire effects of the food *versus* fuel issue of 1st generation biofuels.

Economical viability still is uncertain as the cost of producing biofuels from algae still generates divergence among experts and it is unknown, so far, if it could compete equally with other fuels in the market. Thus, for the establishment of a credible market, steady and with a growing demand, experts agree that microalgae biofuels need to be stimulated, as many of the implementation stages of emerging technologies can face limitations that can lower the possibility of success. Therefore, with policy support and incentives, the algal biofuel industry could continue to develop and assuming that this technology follows renewable energy cost trends, costs would decrease to eventually reach economic viability. This leads to the second question, **which policies currently affect microalgae biofuels industry?**

Although the idea of a global carbon offset is already affecting all renewables market, concerning particularly microalgae biofuels, depending on the region different policies are found. In the United States, the Energy Independence and Security Act of 2007 establishes annual renewable fuel standard (RFS and RFS2) and is an important mechanism of energy sources change, aiming to reach 36 billion gallons of renewable fuel by 2022. Besides that, investment in microalgae R&D in cultivation and deployment of commercial processes through the American Recovery and Renewal Act (ARRA), Department of Energy Biomass Program and the U.S Ministry of Defense are also important measures to be highlighted.

In the European Union, the Directive 2009/28/EC sets mandatory national targets for the overall share of energy from renewable sources in gross final consumption of energy and for the share of energy from renewable sources in transport. Although, it does not mention algae fuels directly, it also establishes sustainability criteria for biofuels and bioliquids. In the other hand, the Strategic Energy Technology (SET) Plan sets out a medium term strategy valid across all sectors stating that development and demonstration projects for the main technologies must be speeded up. The SET-Plan lists several energy technologies, which will be required to bring together economic growth and a vision of a decarbonized society. It states that advanced biofuels, namely microalgae, are supposed to play a significant role.

Although It is expected much more advances in this field in the next few years, research on the welfare economics of renewable energy policy is still in its infancy and the economic effects of biofuel policies are not only complex and difficult to understand, but are ultimately ambiguous in theory. Thus, in an attempt to clarify a part of this matter the last question emerges: **What policies could enhance the diffusion of microalgae in the transportation market share in the future?**

Experts consent that public investment in R&D is the most important policy to be adopted by countries and this was confirmed through the development of a model. Modeling using SAN formalism proved to be an effective research method and offered useful future scenarios regarding the advanced biofuels market. It emphasized what the experts had already agreed upon, and also revealed the potential impact of advanced biofuels subsidies and petrol taxes. Mandates were are also considered of great importance, although the model failed to predict how is the real impact of such policy in the diffusion. These results can serve as recommendations concerning public policies to be enacted through policy makers.

Cultivating microalgae to produce biofuels has, consequently, a strong potential in multiple domains, such as energy, food and agriculture, national security and sustainability. The task that remains is how to disentangle the puzzle of a sustainable (technical, economical, social and environmental) production process, with all the obstacles that were herein presented. Nonetheless, according to our analysis, it is believed to be feasible. It will, thus, require innovative dimensions of political will and institutional cooperation to achieve the solution to this complex challenge.

6.1. Limitations and recommendations for future research

Although this research has reached its aims, some tests ahead still remain. In this section, the main limitations of this work and some recommendations for future research are addressed.

First of all, the sample size of the Delphi survey could have been larger and, thus, more representative in statistical terms. The author is aware that the outcomes might not represent the majority of the microalgae experts' opinion. In the same manner, after analyzing the results, some questions that did not reach a consensus could be further explored in a supplementary study or in a third round of survey. More robust statistical calculations could have been done with the data obtained. However, due to the small sample size, this was not possible.

Regarding the model developed, some limitations can also be highlighted. With the current model, it was arduous to mimic the impact of policy mandates, since the real effect of them in the market is not based in prices or quantity produced. Some studies consider them as binding policies, but, many times, it is not what happens in the real world, as we can see, namely, in the advanced biofuels field in the U.S.

Some other issues were not dealt with and could be interesting to develop further studies on them. For example, the GHG emissions were not considered in the model and with some adaptations it is possible to combine them with the current model. Other possibilities are to account for the difference of overall energy used throughout the years; to model the impacts of GHG policies and other pathways for natural gas and electricity; and to develop models for other regions such as Europe or even the entire World.

6.2. Contributions

The research presented in this thesis has lead to the following publications:

International Journal Publications:

- Ribeiro, L.A; SILVA, P.P.; Mata, T.; Martins, A.A., 2014. Prospects of Using Microalgae for Biofuels Production: Results of a Delphi Study. In: *Renewable Energy*. Accepted with minor revisions.

- RIBEIRO, L.A.; SILVA, P.P. Surveying techno-economic indicators of microalgae biofuel technologies. In: *Renewable and Sustainable Energy Reviews*, Vol. 25, Set., pp. 89-96, 2013.

- FERREIRA, A.F.; RIBEIRO, L.A.; BATISTA, A.P.; MARQUES, P.A.S.S.; NOBRE, B.P.; PALAVRA, A.M.F.; SILVA, P.P.; GOUVEIA, L.; SILVA, C. A. Biorefinery from *Nannochloropsis sp.* microalga – Energy and CO_2 emission and economic analyses In: *Bioresource Technology*, Vol. 138, Jun. pp. 235-244, 2013.

- RIBEIRO, L.A.; SILVA, P.P. Technoeconomic Assessment on Innovative Biofuel Technologies: The Case of Microalgae, In: *ISRN Renewable Energy* Vol. 2012, Article ID 173753, 2012.

- SILVA, P.P.; RIBEIRO, L.A. The role of microalgae in the deployment of biofuels: contrasting renewable energy technologies, In: *International Journal of Technology, Policy and Management (IJTPM)*, Vol.12, No.2/3, pp.158-176, 2012.

Book Chapters:

- RIBEIRO, L.A.; DIAS, P.; NASCIMENTO, L.F.M.; SILVA, P.P. Technological Issues: Algae Biofuels In: ***Liquid Biofuels: Emergence, Development And Prospects*,** Editors: Antonio D. PADULA, Manoela S. SANTOS, Omar, B. SANTOS, and Denis BORENSTEIN (Federal University of Rio Grande do Sul - Porto Alegre – Brazil), Vol. 24, Springer, 2014 (ISBN 978-1-4471-6481-4).

- RIBEIRO, L.A.; SILVA, P.P. Outlook on the Upcoming of Advanced Biofuels: Inputs from a Delphi Study In: *Energy Management of the Series Energy Science & Technology*, Editor: J.N. Govil, Vol. 12, 2014. Book in press.

- RIBEIRO, L.A. Biocombustíveis de Algas? In: *Sustentabilidade: resultados de pesquisas do PPGA/EA/UFRGS*, Editors: Luis Felipe NASCIMENTO and Patrícia TOMETICH – Porto Alegre: Grupo de Pesquisa em Sustentabilidade e Inovação – GPS, 2013 (ISBN 978-85-915531-0-5).

Conference Proceedings:

- RIBEIRO, L.A.; SILVA, P.P.; RIBEIRO, L.; DOTTI, F.L. *Modeling the impacts of policies on microalgae biofuel feedstocks diffusion*, "Proceedings of the 14th IAEE European Energy Conference on Sustainable Energy Policy and Strategies for Europe", October 28-31th, Rome, Italy, 2014.

- RIBEIRO, L.A.; SILVA, P.P. *Technology Experts Visions for Microalgae Biofuels: A Delphi Study*, "Proceedings of the Energy for Sustainability: Sustainable Cities: Designing for people and the planet", September 8-10th, Coimbra, Portugal, 2013.

- RIBEIRO, L.A.; SILVA, P.P.; MATA, T.M., MARTINS, A.A. *Prospects on employing microalgae into the production of biofuels: outcomes from a Delphi study*, "Proceedings of the ICEE Energy & Environment: bringing together Economics and Engineering ", May 9-10th, Porto, Portugal, 2013.

- RIBEIRO, L.A.; SILVA, P.P.; CONNORS, S. *Economical Evaluation of Emerging Biofuel Technologies: The Microalgae Case Study*, "*MIT Energy Club - Energy Night", June 1st*, Lisbon, Portugal, 2012.

- RIBEIRO, L.A.; SILVA, P.P. *Innovative biofuel Technologies: microalgae analysis*, "Proceedings of the 34th IAEE International Conference on Institutions, Efficiency and Evolving Energy Technologies", June 19-23th, Stockholm, Sweden, 2011.

- RIBEIRO, L.A.; SILVA, P.P. *Policies and Challenges for Advanced Biofuel Technologies: a look into microalgae*, "Proceedings of the SDEWES2011 6th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems", September 25-29th, Dubrovnik, Croatia, 2011.

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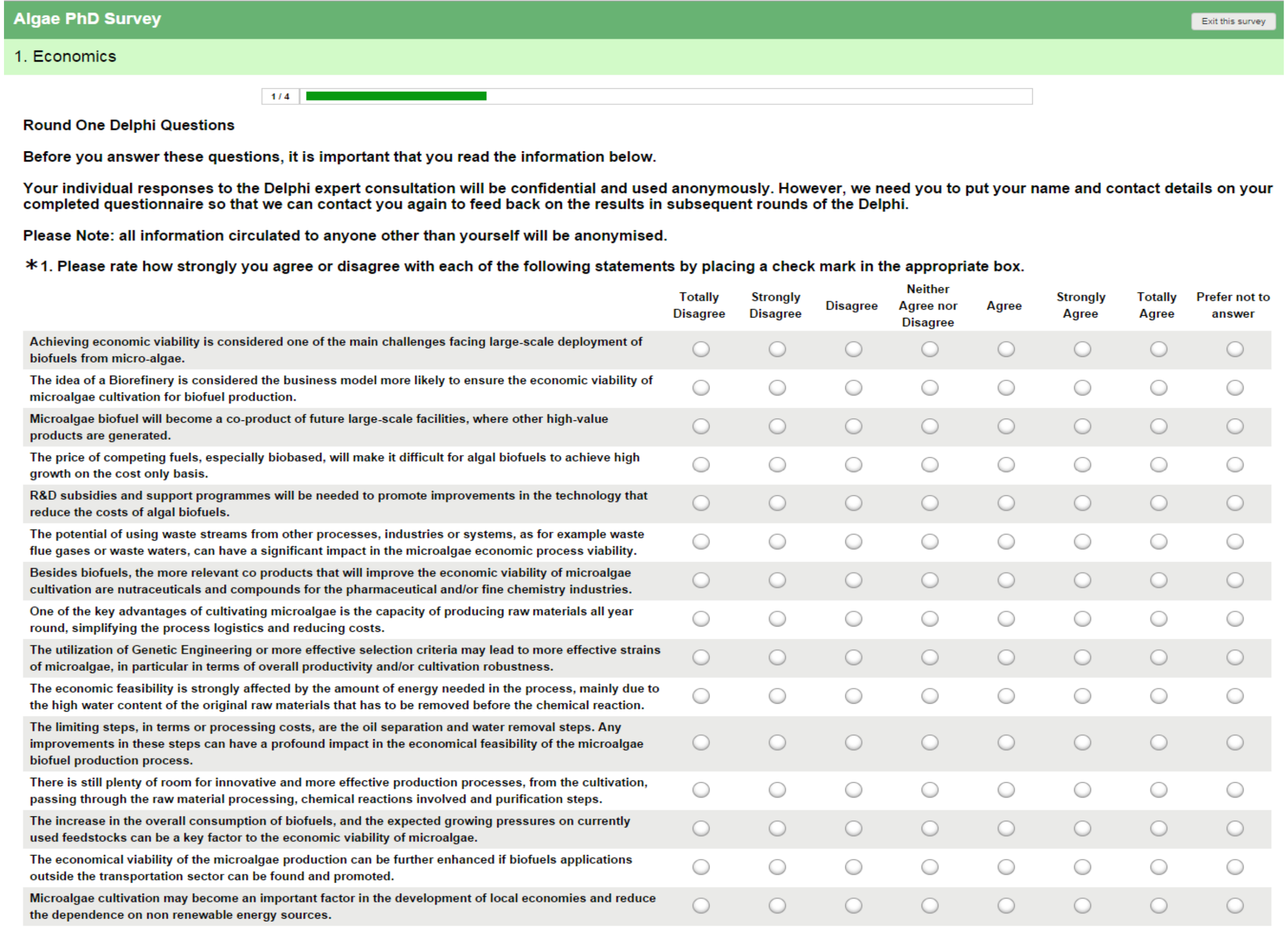
APPENDIX A: Statements of Themes 1,2 and 3.

	Theme 1: ECONOMICS
1.1	Achieving economic viability is considered one of the main challenges facing large-scale deployment of biofuels from microalgae.
1.2	The idea of a Biorefinery is considered the business model more likely to ensure the economic viability of microalgae cultivation for biofuel production.
1.3	Microalgae biofuel will become a co-product of future large-scale facilities, where other high-value products are generated.
1.4	The price of competing fuels, especially biobased, will make it difficult for algal biofuels to achieve high growth on the cost only basis.
1.5	R&D subsidies and support programmes will be needed to promote improvements in the technology that reduce the costs of algal biofuels.
1.6	The potential of using waste streams from other processes, industries or systems, as for example waste flue gases or waste waters, can have a significant impact in the microalgae economic process viability.
1.7	Besides biofuels, the more relevant co products that will improve the economic viability of microalgae cultivation are nutraceuticals and compounds for the pharmaceutical and/or fine chemistry industries.
1.8	One of the key advantages of cultivating microalgae is the capacity of producing raw materials all year round, simplifying the process logistics and reducing costs.
1.9	The utilization of Genetic Engineering or more effective selection criteria may lead to more effective strains of microalgae, in particular in terms of overall productivity and/or cultivation robustness.
1.10	The economic feasibility is strongly affected by the amount of energy needed in the process, mainly due to the high water content of the original raw materials that has to be removed before the chemical reaction.
1.11	The limiting steps, in terms or processing costs, are the oil separation and water removal steps. Any improvements in these steps can have a profound impact in the economical feasibility of the microalgae biofuel production process.
1.12	There is still plenty of room for innovative and more effective production processes, from the cultivation, passing through the raw material processing, chemical reactions involved and purification steps.
1.13	The increase in the overall consumption of biofuels, and the expected growing pressures on currently used feedstocks can be a key factor to the economic viability of microalgae.
1.14	The economical viability of the microalgae production can be further enhanced if biofuels applications outside the transportation sector can be found and promoted.
1.15	Microalgae cultivation may become an important factor in the development of local economies and reduce the dependence on non renewable energy sources.
	Theme 2: FUTURE TRENDS
2.1	Higher petro oil prices could make algae biofuel economically feasible.
2.2	A more developed, globalized and comprehensive Carbon Market could make algae biofuel more economically feasible.
2.3	Algal biofuels will be developed, but will play only a minor role in the future mix, in particular for the transportation sector.
2.4	Biofuels from microalgae will be produced commercially, but only in the mid to long term.
2.5	Advances in strain identification and process engineering are key factors in the development of the technology.
2.6	The nature of the cultivation system, closed or open, will depend on the production quantities, type of nutrients required, waste streams available and strains used.
2.7	The microalgae cultivation process will be increasingly used integrated in existing industrial processes, usually not related with energy production and for waste treatment and/or carbon capture purposes.
2.8	Different strains of microalgae will be used depending on the nutrients and/or waste streams available, and particular local climatic and water availability conditions. No single strain will be dominant one.
2.9	Open pond cultivation, or similar, will dominate the future production systems, although for small production involving the processing of waste streams the close cultivation systems will be also used.
2.10	The main aspects that have to be considered in the process development are improving its overall energy efficiency, the ability to produce other high value products, or the possibility to integrate it in other process under the biorefinery concept umbrella.
2.11	The reduction in the dependence in oil imports, and the potential development of local and national economies, is a relevant factor in the development of the area.
	Theme 3: SUSTAINABILITY
3.1	The environmental sustainability of microalgal derived biofuels is a potential problem.
3.2	The utilization of genetic modified organisms may represent a potential problem in the diffusion of algal biofuels.
3.3	Open pond cultivation is more environmentally friendly than PBRs cultivation.
3.4	Closed PBRs cultivation is more environmentally friendly than open pond cultivation.
3.5	The need to reduce world's CO_2 emissions is a key advantage for algae biofuels.
3.6	The production of algae biofuels in large scale could generate potential impacts on local ecosystems from new algal species.
3.7	The production of algae biofuels in large scale could generate potential impacts on water reserves.
3.8	Although microalgae can be used to capture CO_2, the actual overall life cycle carbon balance is key aspect to consider.
3.9	The potential of biofuels from microalgae to be carbon neutral is a key factor concerning their sustainability.
3.10	Some potential undesired environmental aspects may arise from microalgae cultivation, as for example, increased emissions of NO_x and/or methane.
3.11	The environmental impacts of energy consumption is the key factor concerning the sustainability of the microalgae cultivation.
3.12	The potential to use waste streams and/or easily available renewable nutrients is a key factor in the overall system sustainability.

APPENDIX B: Delphi Survey Questionnaire



1. Economics

Round One Delphi Questions

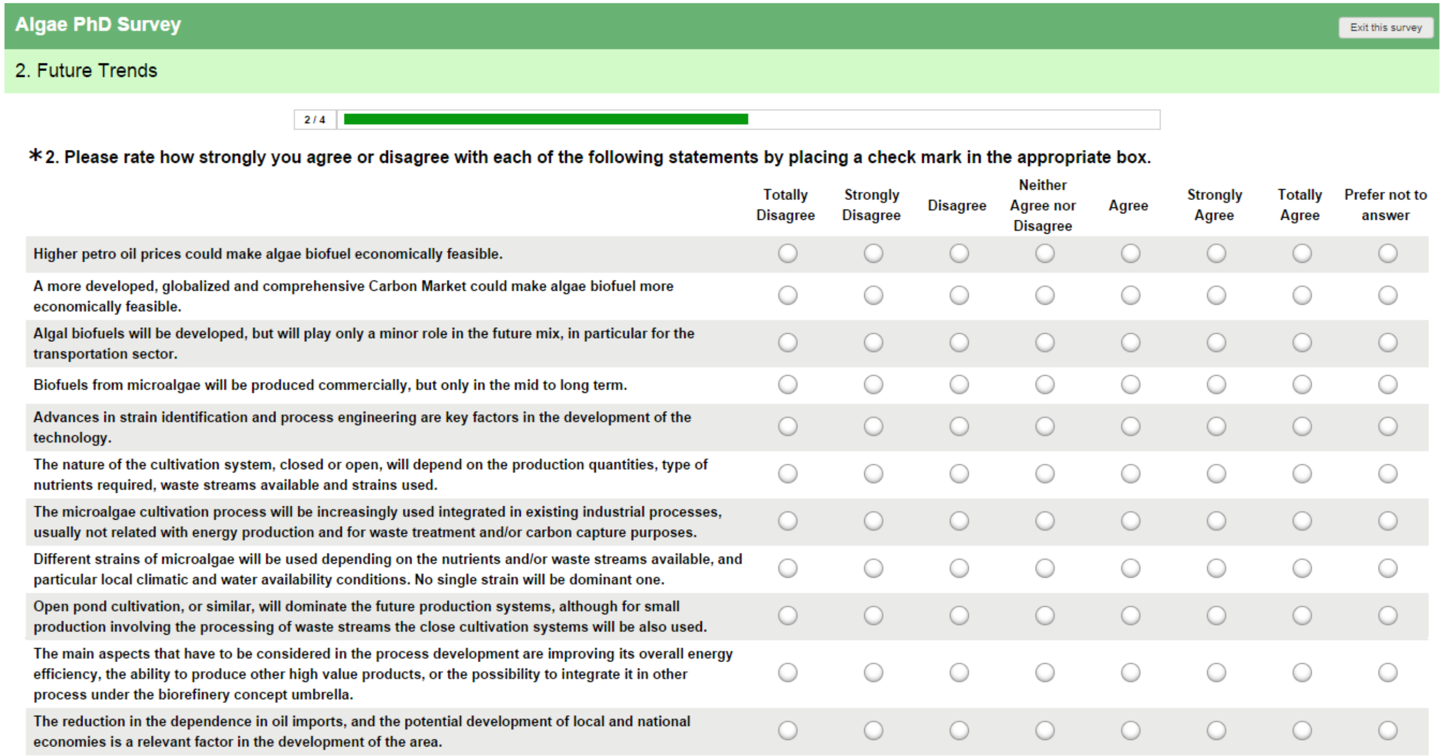
Before you answer these questions, it is important that you read the information below.

Your individual responses to the Delphi expert consultation will be confidential and used anonymously. However, we need you to put your name and contact details on your completed questionnaire so that we can contact you again to feed back on the results in subsequent rounds of the Delphi.

Please Note: all information circulated to anyone other than yourself will be anonymised.

***1. Please rate how strongly you agree or disagree with each of the following statements by placing a check mark in the appropriate box.**

	Totally Disagree	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree	Totally Agree	Prefer not to answer
Achieving economic viability is considered one of the main challenges facing large-scale deployment of biofuels from micro-algae.	○	○	○	○	○	○	○	○
The idea of a Biorefinery is considered the business model more likely to ensure the economic viability of microalgae cultivation for biofuel production.	○	○	○	○	○	○	○	○
Microalgae biofuel will become a co-product of future large-scale facilities, where other high-value products are generated.	○	○	○	○	○	○	○	○
The price of competing fuels, especially biobased, will make it difficult for algal biofuels to achieve high growth on the cost only basis.	○	○	○	○	○	○	○	○
R&D subsidies and support programmes will be needed to promote improvements in the technology that reduce the costs of algal biofuels.	○	○	○	○	○	○	○	○
The potential of using waste streams from other processes, industries or systems, as for example waste flue gases or waste waters, can have a significant impact in the microalgae economic process viability.	○	○	○	○	○	○	○	○
Besides biofuels, the more relevant co products that will improve the economic viability of microalgae cultivation are nutraceuticals and compounds for the pharmaceutical and/or fine chemistry industries.	○	○	○	○	○	○	○	○
One of the key advantages of cultivating microalgae is the capacity of producing raw materials all year round, simplifying the process logistics and reducing costs.	○	○	○	○	○	○	○	○
The utilization of Genetic Engineering or more effective selection criteria may lead to more effective strains of microalgae, in particular in terms of overall productivity and/or cultivation robustness.	○	○	○	○	○	○	○	○
The economic feasibility is strongly affected by the amount of energy needed in the process, mainly due to the high water content of the original raw materials that has to be removed before the chemical reaction.	○	○	○	○	○	○	○	○
The limiting steps, in terms or processing costs, are the oil separation and water removal steps. Any improvements in these steps can have a profound impact in the economical feasibility of the microalgae biofuel production process.	○	○	○	○	○	○	○	○
There is still plenty of room for innovative and more effective production processes, from the cultivation, passing through the raw material processing, chemical reactions involved and purification steps.	○	○	○	○	○	○	○	○
The increase in the overall consumption of biofuels, and the expected growing pressures on currently used feedstocks can be a key factor to the economic viability of microalgae.	○	○	○	○	○	○	○	○
The economical viability of the microalgae production can be further enhanced if biofuels applications outside the transportation sector can be found and promoted.	○	○	○	○	○	○	○	○
Microalgae cultivation may become an important factor in the development of local economies and reduce the dependence on non renewable energy sources.	○	○	○	○	○	○	○	○

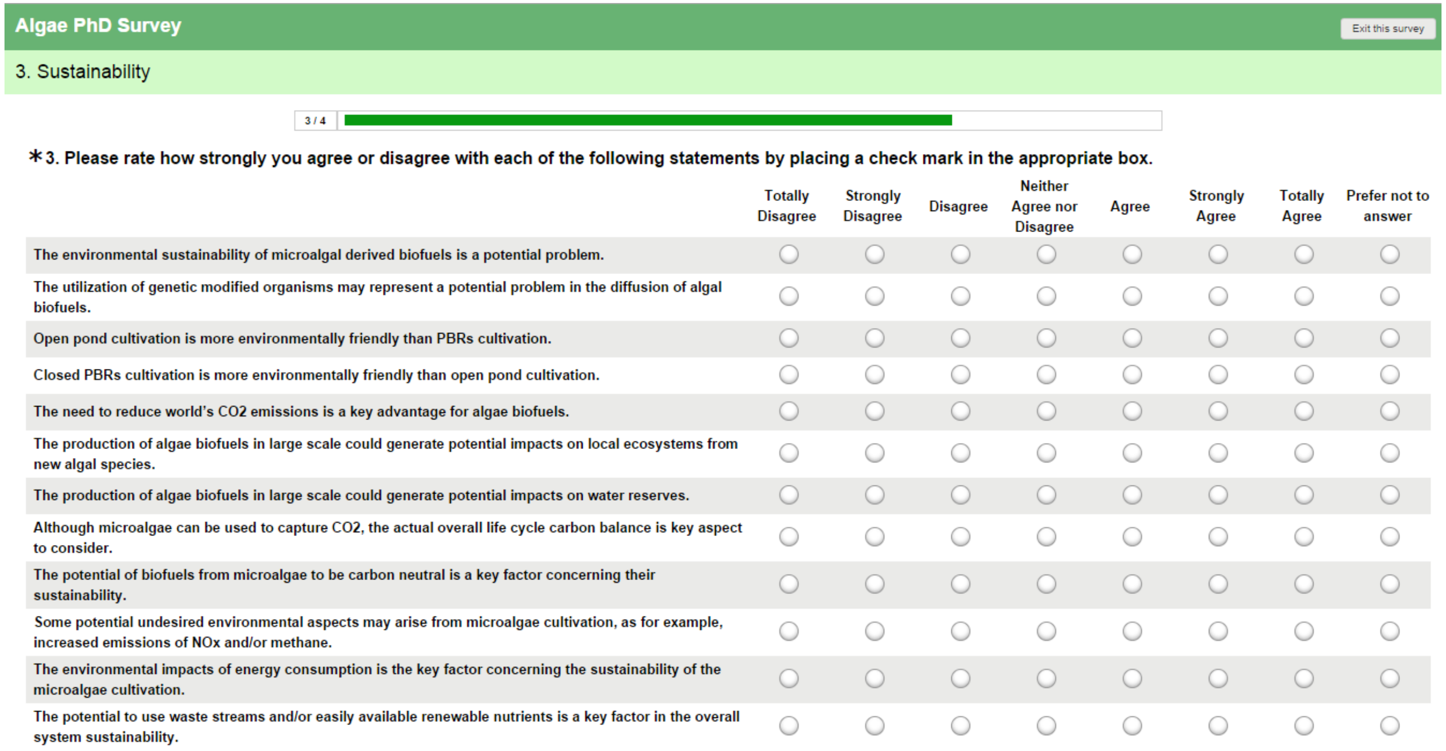


Algae PhD Survey

2. Future Trends

*2. Please rate how strongly you agree or disagree with each of the following statements by placing a check mark in the appropriate box.

	Totally Disagree	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree	Totally Agree	Prefer not to answer
Higher petro oil prices could make algae biofuel economically feasible.	○	○	○	○	○	○	○	○
A more developed, globalized and comprehensive Carbon Market could make algae biofuel more economically feasible.	○	○	○	○	○	○	○	○
Algal biofuels will be developed, but will play only a minor role in the future mix, in particular for the transportation sector.	○	○	○	○	○	○	○	○
Biofuels from microalgae will be produced commercially, but only in the mid to long term.	○	○	○	○	○	○	○	○
Advances in strain identification and process engineering are key factors in the development of the technology.	○	○	○	○	○	○	○	○
The nature of the cultivation system, closed or open, will depend on the production quantities, type of nutrients required, waste streams available and strains used.	○	○	○	○	○	○	○	○
The microalgae cultivation process will be increasingly used integrated in existing industrial processes, usually not related with energy production and for waste treatment and/or carbon capture purposes.	○	○	○	○	○	○	○	○
Different strains of microalgae will be used depending on the nutrients and/or waste streams available, and particular local climatic and water availability conditions. No single strain will be dominant one.	○	○	○	○	○	○	○	○
Open pond cultivation, or similar, will dominate the future production systems, although for small production involving the processing of waste streams the close cultivation systems will be also used.	○	○	○	○	○	○	○	○
The main aspects that have to be considered in the process development are improving its overall energy efficiency, the ability to produce other high value products, or the possibility to integrate it in other process under the biorefinery concept umbrella.	○	○	○	○	○	○	○	○
The reduction in the dependence in oil imports, and the potential development of local and national economies is a relevant factor in the development of the area.	○	○	○	○	○	○	○	○

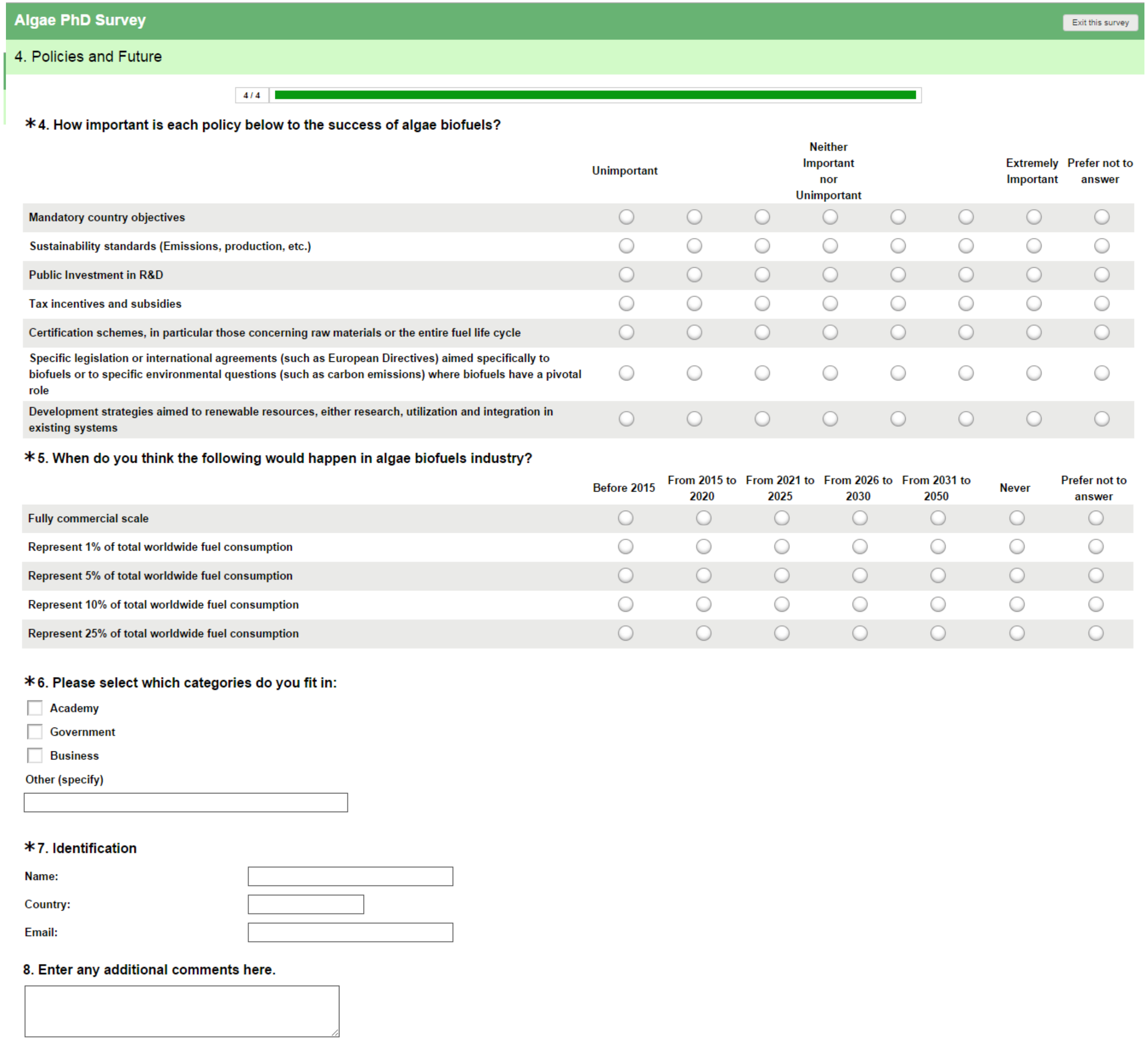


Algae PhD Survey

3. Sustainability

*3. Please rate how strongly you agree or disagree with each of the following statements by placing a check mark in the appropriate box.

	Totally Disagree	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree	Totally Agree	Prefer not to answer
The environmental sustainability of microalgal derived biofuels is a potential problem.	○	○	○	○	○	○	○	○
The utilization of genetic modified organisms may represent a potential problem in the diffusion of algal biofuels.	○	○	○	○	○	○	○	○
Open pond cultivation is more environmentally friendly than PBRs cultivation.	○	○	○	○	○	○	○	○
Closed PBRs cultivation is more environmentally friendly than open pond cultivation.	○	○	○	○	○	○	○	○
The need to reduce world's CO2 emissions is a key advantage for algae biofuels.	○	○	○	○	○	○	○	○
The production of algae biofuels in large scale could generate potential impacts on local ecosystems from new algal species.	○	○	○	○	○	○	○	○
The production of algae biofuels in large scale could generate potential impacts on water reserves.	○	○	○	○	○	○	○	○
Although microalgae can be used to capture CO2, the actual overall life cycle carbon balance is key aspect to consider.	○	○	○	○	○	○	○	○
The potential of biofuels from microalgae to be carbon neutral is a key factor concerning their sustainability.	○	○	○	○	○	○	○	○
Some potential undesired environmental aspects may arise from microalgae cultivation, as for example, increased emissions of NOx and/or methane.	○	○	○	○	○	○	○	○
The environmental impacts of energy consumption is the key factor concerning the sustainability of the microalgae cultivation.	○	○	○	○	○	○	○	○
The potential to use waste streams and/or easily available renewable nutrients is a key factor in the overall system sustainability.	○	○	○	○	○	○	○	○



Algae PhD Survey

4. Policies and Future

*4. How important is each policy below to the success of algae biofuels?

	Unimportant			Neither Important nor Unimportant			Extremely Important	Prefer not to answer
Mandatory country objectives	○	○	○	○	○	○	○	○
Sustainability standards (Emissions, production, etc.)	○	○	○	○	○	○	○	○
Public Investment in R&D	○	○	○	○	○	○	○	○
Tax incentives and subsidies	○	○	○	○	○	○	○	○
Certification schemes, in particular those concerning raw materials or the entire fuel life cycle	○	○	○	○	○	○	○	○
Specific legislation or international agreements (such as European Directives) aimed specifically to biofuels or to specific environmental questions (such as carbon emissions) where biofuels have a pivotal role	○	○	○	○	○	○	○	○
Development strategies aimed to renewable resources, either research, utilization and integration in existing systems	○	○	○	○	○	○	○	○

*5. When do you think the following would happen in algae biofuels industry?

	Before 2015	From 2015 to 2020	From 2021 to 2025	From 2026 to 2030	From 2031 to 2050	Never	Prefer not to answer
Fully commercial scale	○	○	○	○	○	○	○
Represent 1% of total worldwide fuel consumption	○	○	○	○	○	○	○
Represent 5% of total worldwide fuel consumption	○	○	○	○	○	○	○
Represent 10% of total worldwide fuel consumption	○	○	○	○	○	○	○
Represent 25% of total worldwide fuel consumption	○	○	○	○	○	○	○

*6. Please select which categories do you fit in:

☐ Academy
☐ Government
☐ Business

Other (specify)

*7. Identification

Name:
Country:
Email:

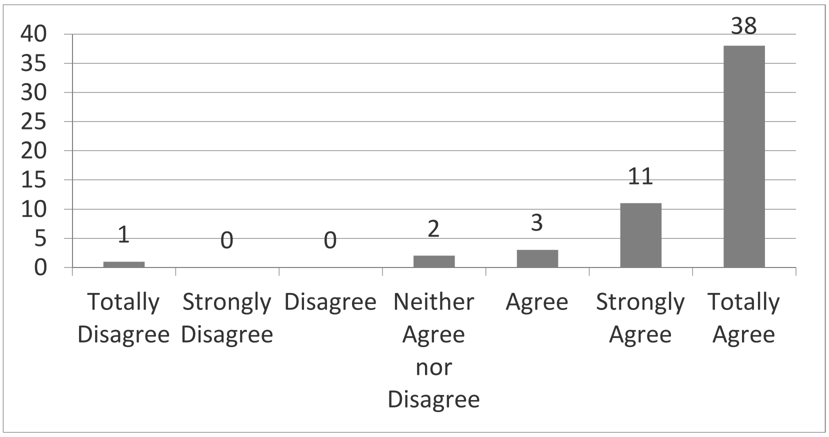
8. Enter any additional comments here.

APPENDIX C: Delphi Survey Overall Results

Theme 1:

1.1 "Achieving economic viability is considered one of the main challenges facing large-scale deployment of biofuels from microalgae."

RESPONDENTS	*55*
MEAN	6.47
MEDIAN	7
STANDARD DEVIATION	1.07
VARIANCE	1.14
Coefficient of Variation	17%

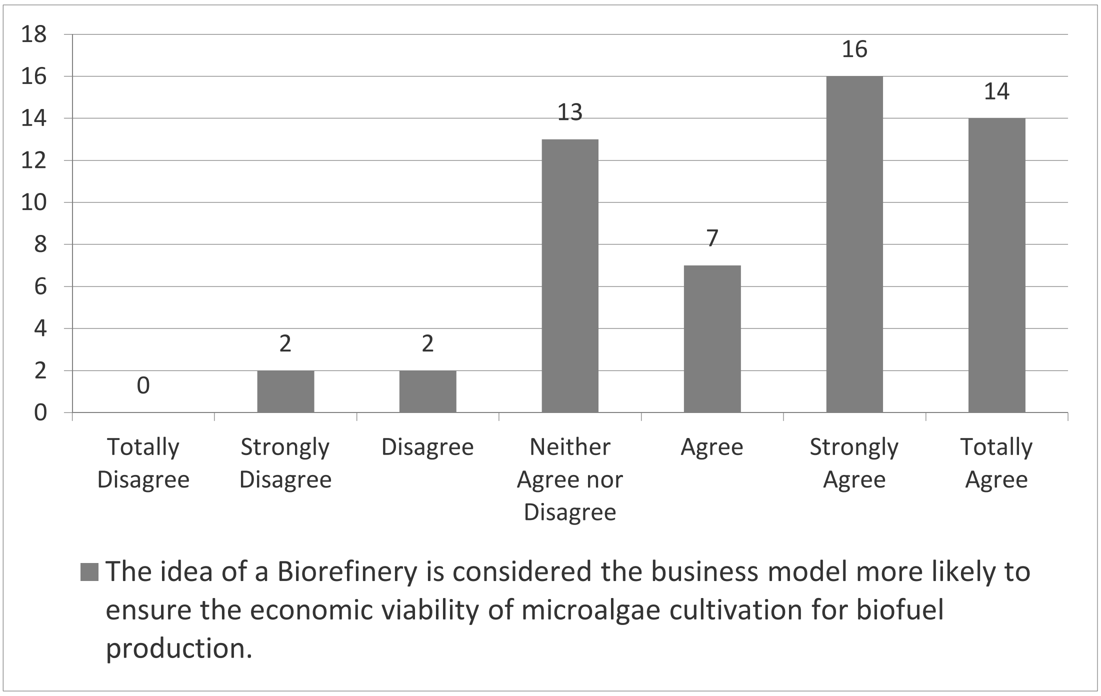


Cumulative results:

Agree	52	95%
Neither	2	4%
Disagree	1	2%
	55	

1.2 The idea of a Biorefinery is considered the business model more likely to ensure the economic viability of microalgae cultivation for biofuel production.

RESPONDENTS	*54*
MEAN	5.39
MEDIAN	6
STANDARD DEVIATION	1.39
VARIANCE	1.94
Coefficient of Variation	26%

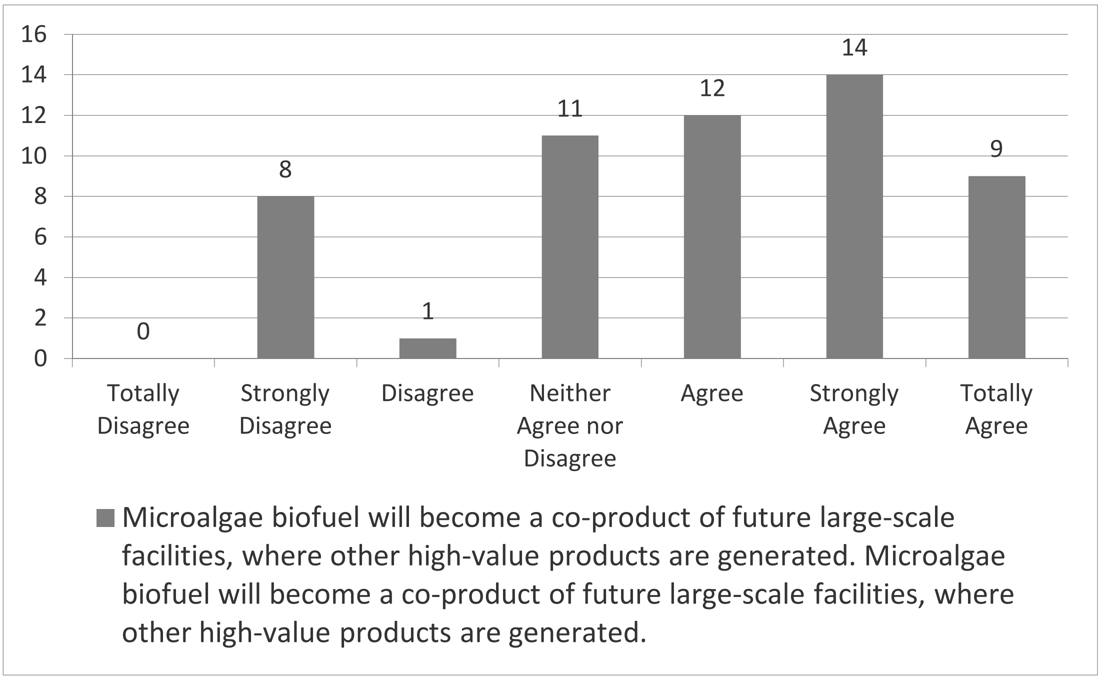


Cumulative results:

Agree	37	69%
Neither	13	24%
Disagree	4	7%
	54	

1.3 Microalgae biofuel will become a co-product of future large-scale facilities, where other high-value products are generated.

RESPONDENTS	*55*
MEAN	4.91
MEDIAN	5
STANDARD DEVIATION	1.59
VARIANCE	2.53
Coefficient of Variation	**32%**

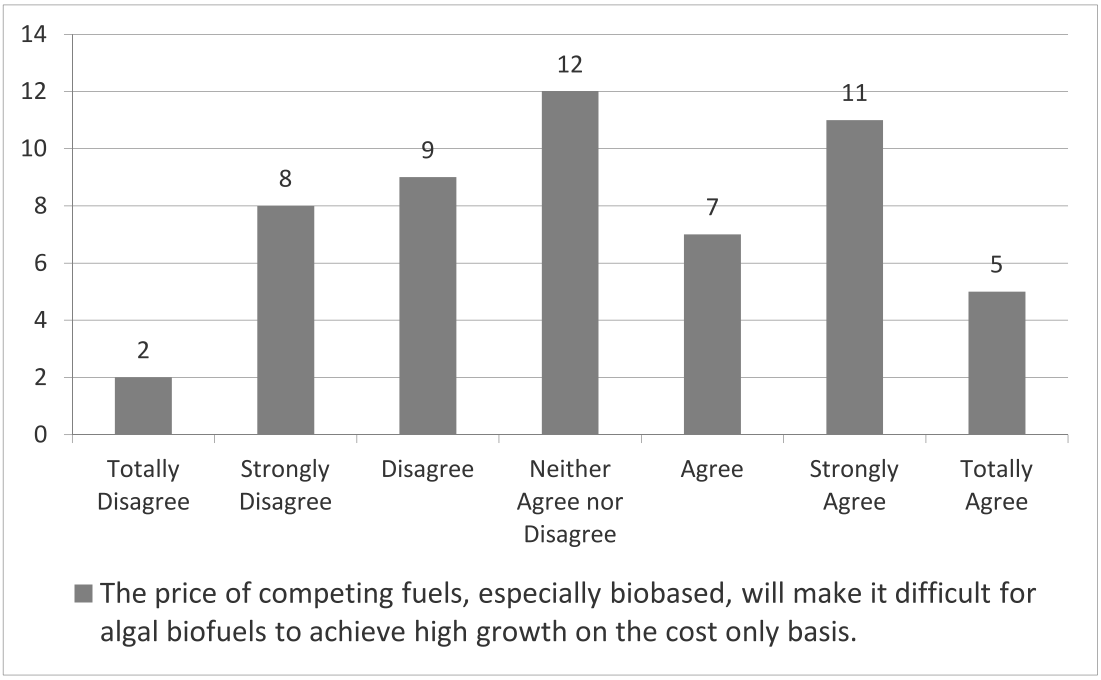


Cumulative results:

Agree	35	64%
Neither	11	20%
Disagree	9	16%
	55	

1.4 The price of competing fuels, especially biobased, will make it difficult for algal biofuels to achieve high growth on the cost only basis.

RESPONDENTS	*54*
MEAN	4.24
MEDIAN	4
STANDARD DEVIATION	1.69
VARIANCE	2.87
Coefficient of Variation	**40%**

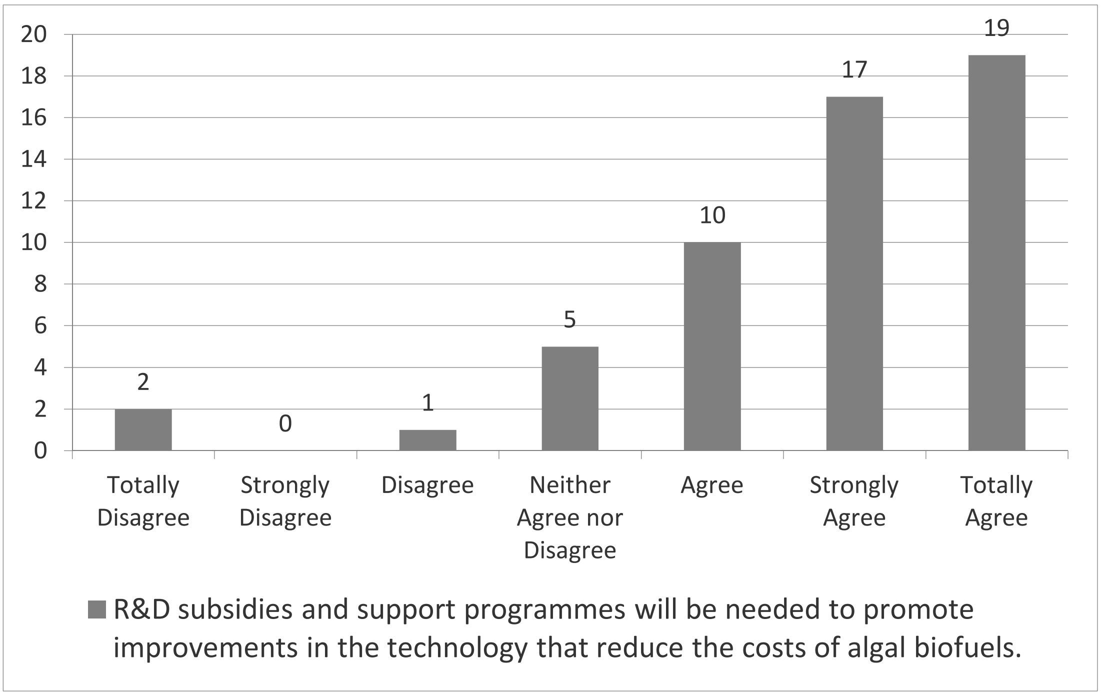


Cumulative results:

Agree	23	43%
Neither	12	22%
Disagree	19	35%
	54	

1.5 R&D subsidies and support programmes will be needed to promote improvements in the technology that reduce the costs of algal biofuels.

RESPONDENTS	*54*
MEAN	5.74
MEDIAN	6
STANDARD DEVIATION	1.40
VARIANCE	1.97
Coefficient of Variation	24%

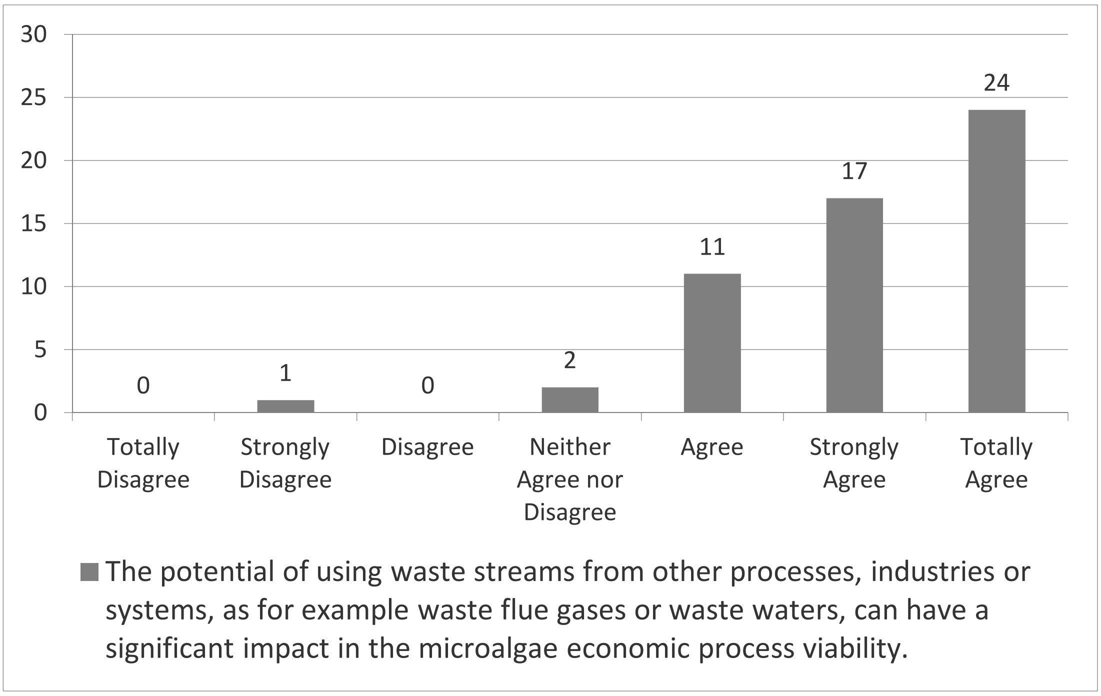


Cumulative results:

Agree	46	85%
Neither	5	9%
Disagree	3	6%
	54	

1.6 The potential of using waste streams from other processes, industries or systems, as for example waste flue gases or waste waters, can have a significant impact in the microalgae economic process viability.

RESPONDENTS	*55*
MEAN	6.09
MEDIAN	6
STANDARD DEVIATION	1.04
VARIANCE	1.08
Coefficient of Variation	17%

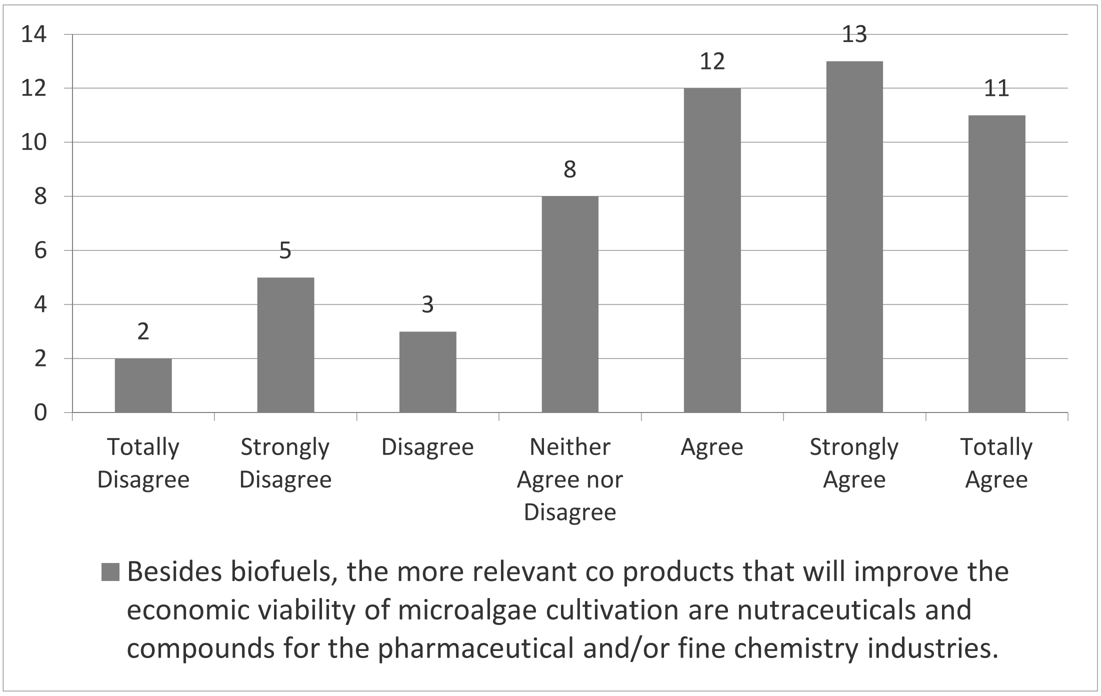


Cumulative results:

Agree	52	95%
Neither	2	4%
Disagree	1	2%
	55	

1.7 Besides biofuels, the more relevant co products that will improve the economic viability of microalgae cultivation are nutraceuticals and compounds for the pharmaceutical and/or fine chemistry industries.

RESPONDENTS	*54*
MEAN	4.96
MEDIAN	5
STANDARD DEVIATION	1.70
VARIANCE	2.90
Coefficient of Variation	**34%**

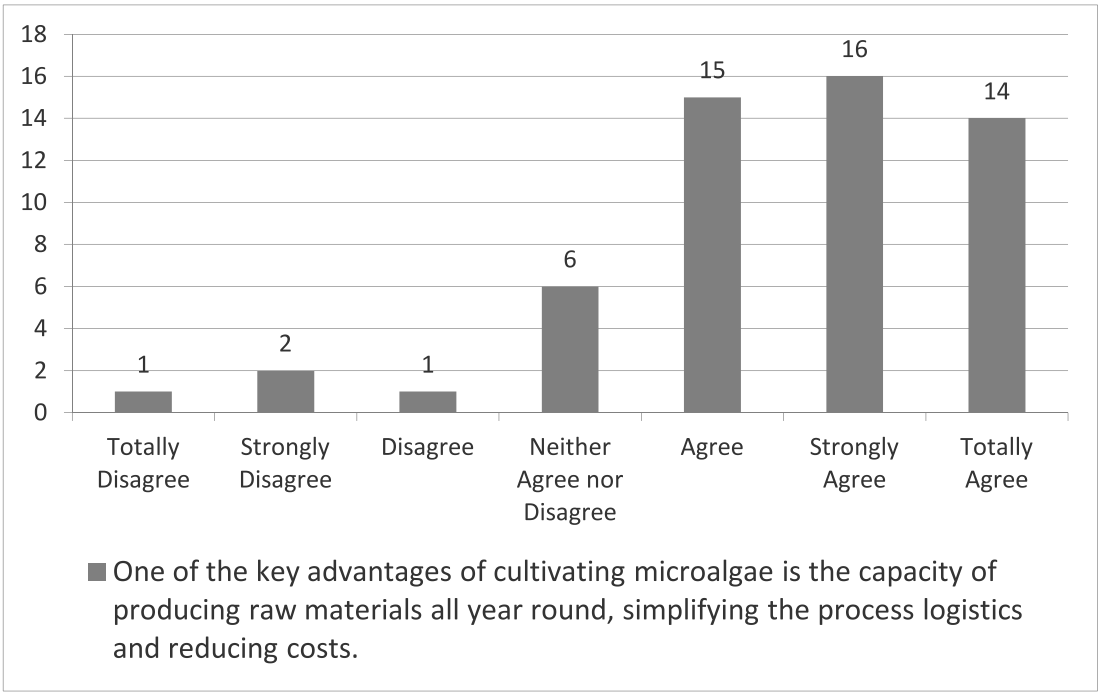


Cumulative results:

Agree	36	67%
Neither	8	15%
Disagree	10	19%
	54	

1.8 One of the key advantages of cultivating microalgae is the capacity of producing raw materials all year round, simplifying the process logistics and reducing costs.

RESPONDENTS	*55*
MEAN	5.47
MEDIAN	6
STANDARD DEVIATION	1.39
VARIANCE	1.92
Coefficient of Variation	25%

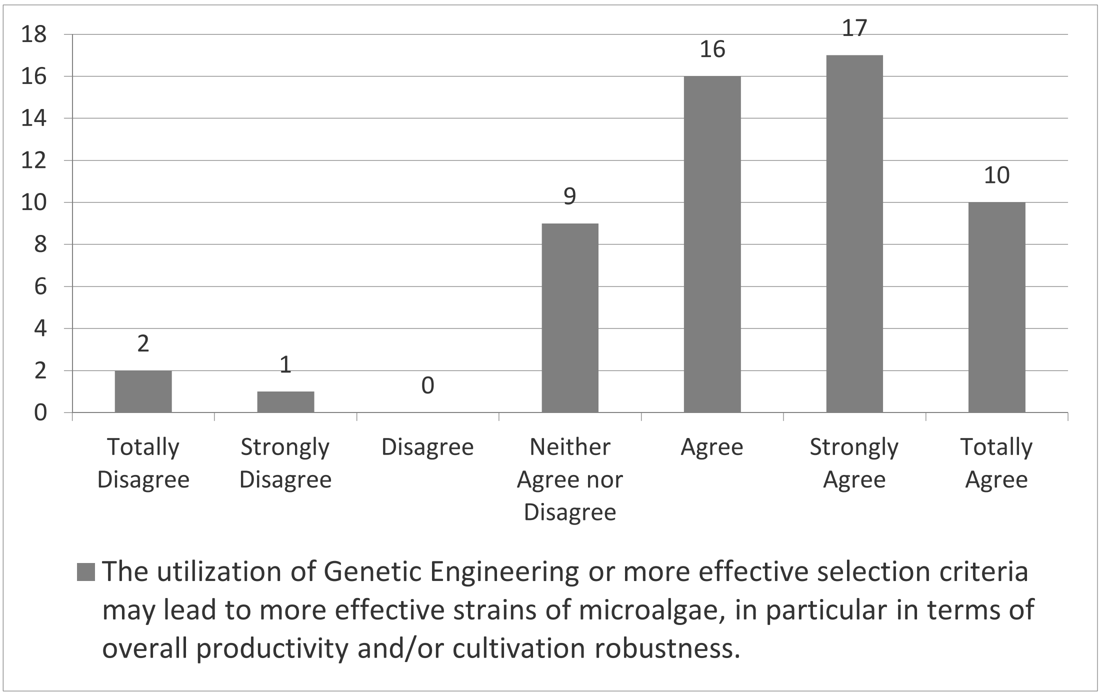


Cumulative results:

Agree	45	82%
Neither	6	11%
Disagree	4	7%
	55	

1.9 The utilization of Genetic Engineering or more effective selection criteria may lead to more effective strains of microalgae, in particular in terms of overall productivity and/or cultivation robustness.

RESPONDENTS	*55*
MEAN	5.31
MEDIAN	5
STANDARD DEVIATION	1.37
VARIANCE	1.88
Coefficient of Variation	26%

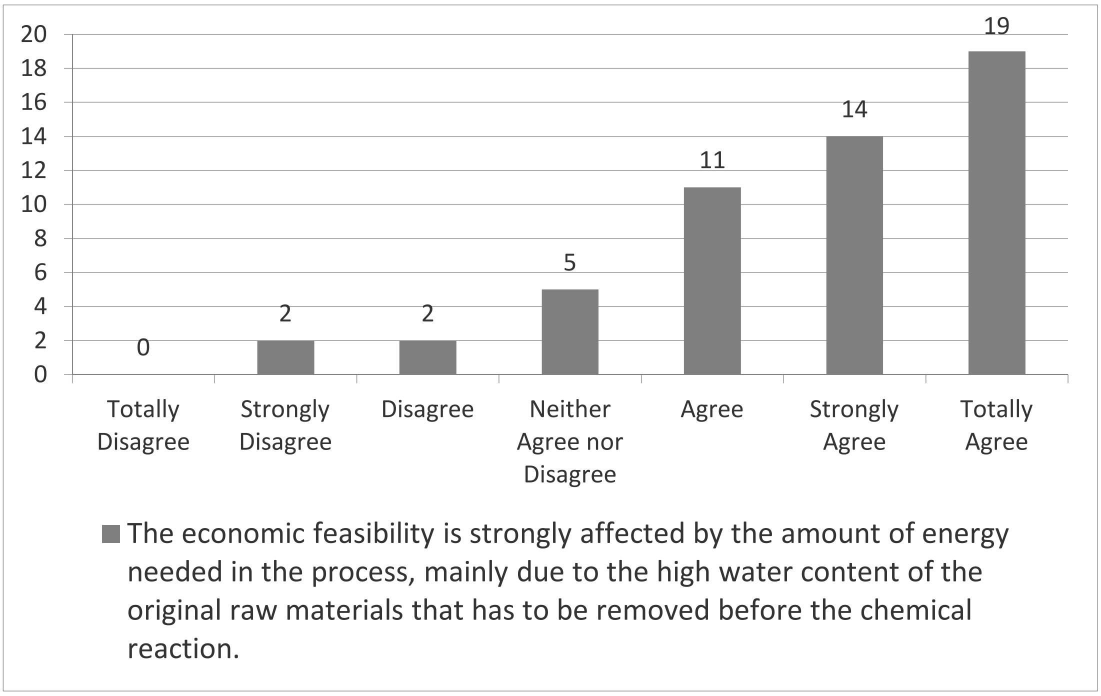


Cumulative results:

Agree	43	78%
Neither	9	16%
Disagree	3	5%
	55	

1.10 The economic feasibility is strongly affected by the amount of energy needed in the process, mainly due to the high water content of the original raw materials that has to be removed before the chemical reaction.

RESPONDENTS	*53*
MEAN	5.70
MEDIAN	6
STANDARD DEVIATION	1.35
VARIANCE	1.83
Coefficcient of Variation	24%

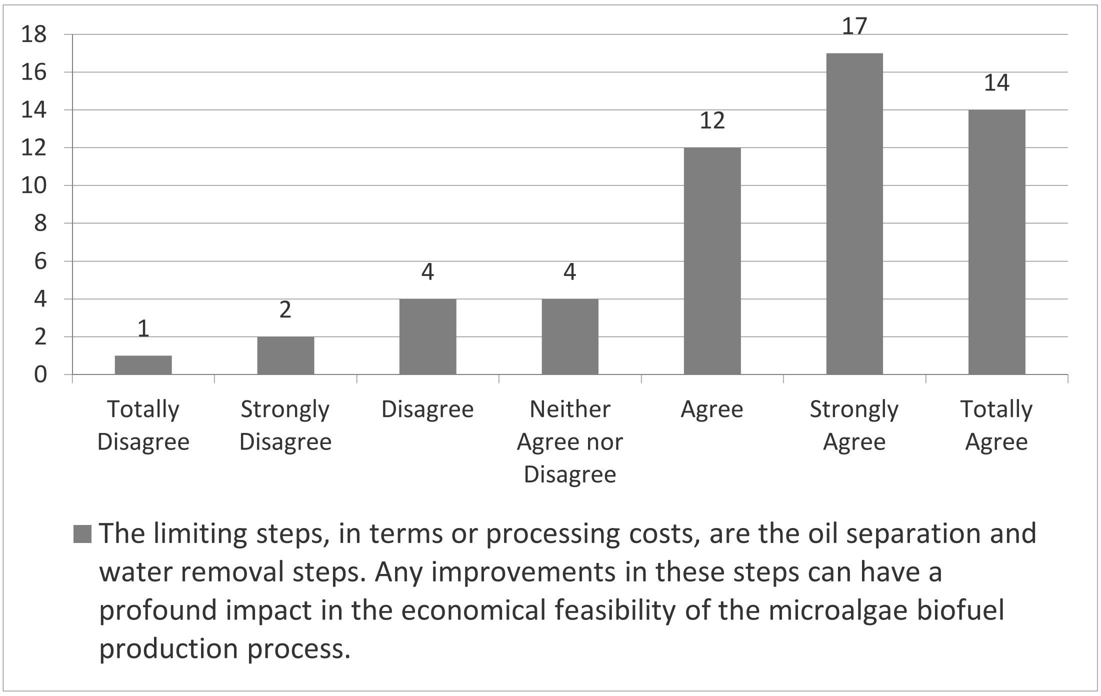


Cumulative results:

Agree	44	83%
Neither	5	9%
Disagree	4	8%
	53	

1.11 The limiting steps, in terms or processing costs, are the oil separation and water removal steps. Any improvements in these steps can have a profound impact in the economical feasibility of the microalgae biofuel production process.

RESPONDENTS	*54*
MEAN	5.43
MEDIAN	6
STANDARD DEVIATION	1.49
VARIANCE	2.21
Coefficient of Variation	27%

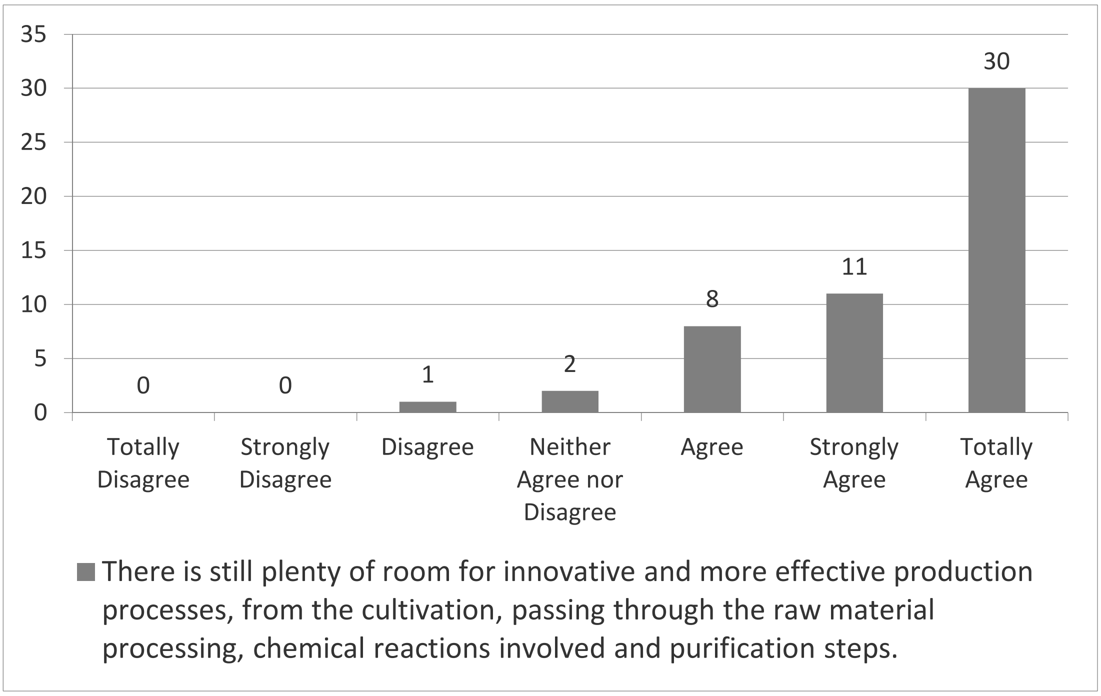


Cumulative results:

Agree	43	80%
Neither	4	7%
Disagree	7	13%
	54	

1.12 There is still plenty of room for innovative and more effective production processes, from the cultivation, passing through the raw material processing, chemical reactions involved and purification steps.

RESPONDENTS	*52*
MEAN	6.29
MEDIAN	7
STANDARD DEVIATION	1.00
VARIANCE	0.99
Coefficient of Variation	16%

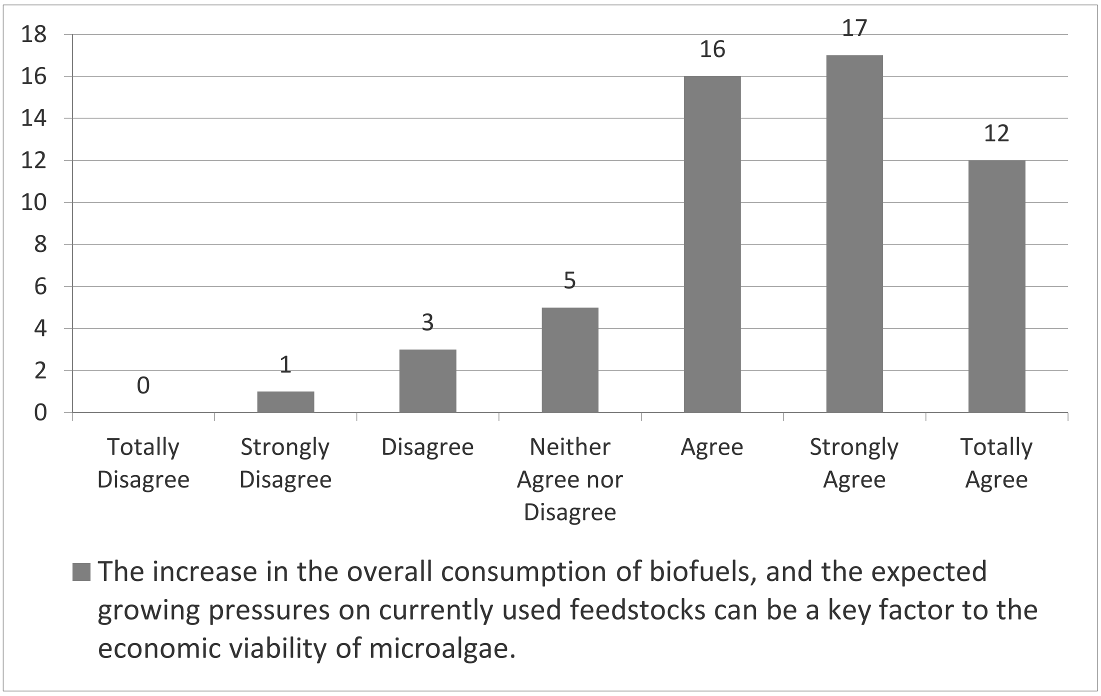


Cumulative results:

Agree	49	94%
Neither	2	4%
Disagree	1	2%
	52	

1.13 The increase in the overall consumption of biofuels, and the expected growing pressures on currently used feedstocks can be a key factor to the economic viability of microalgae.

RESPONDENTS	*54*
MEAN	5.50
MEDIAN	6
STANDARD DEVIATION	1.21
VARIANCE	1.46
Coefficient of Variation	22%

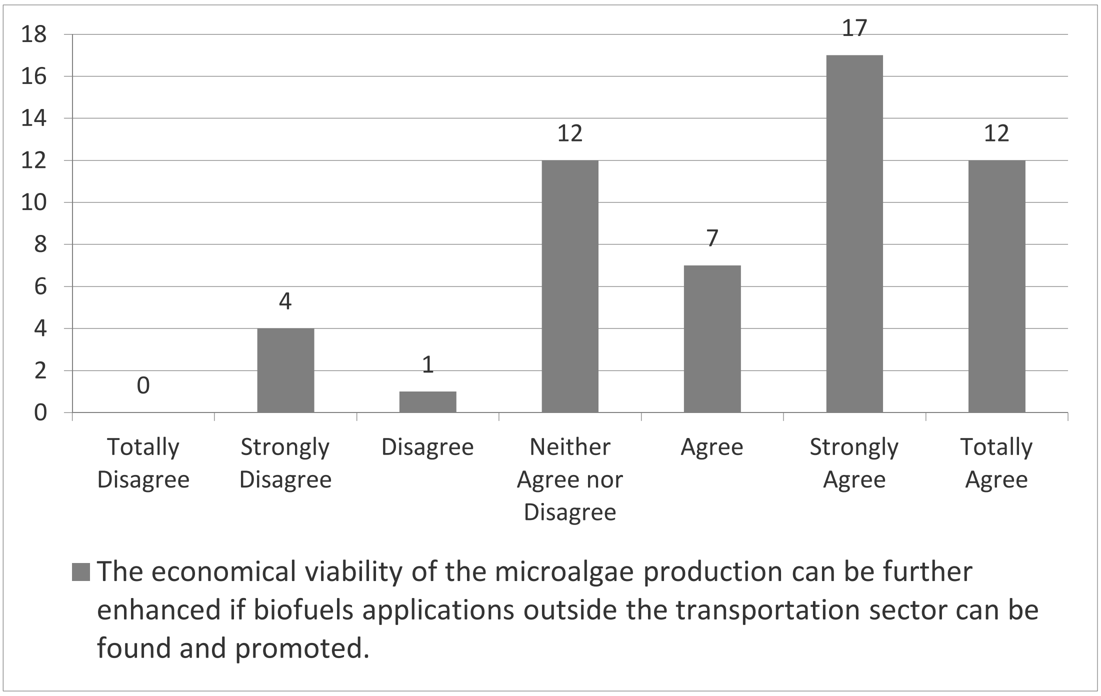


Cumulative results:

Agree	45	83%
Neither	5	9%
Disagree	4	7%
	54	

1.14 The economical viability of the microalgae production can be further enhanced if biofuels applications outside the transportation sector can be found and promoted.

RESPONDENTS	*53*
MEAN	5.28
MEDIAN	6
STANDARD DEVIATION	1.47
VARIANCE	2.17
Coefficient of Variation	28%

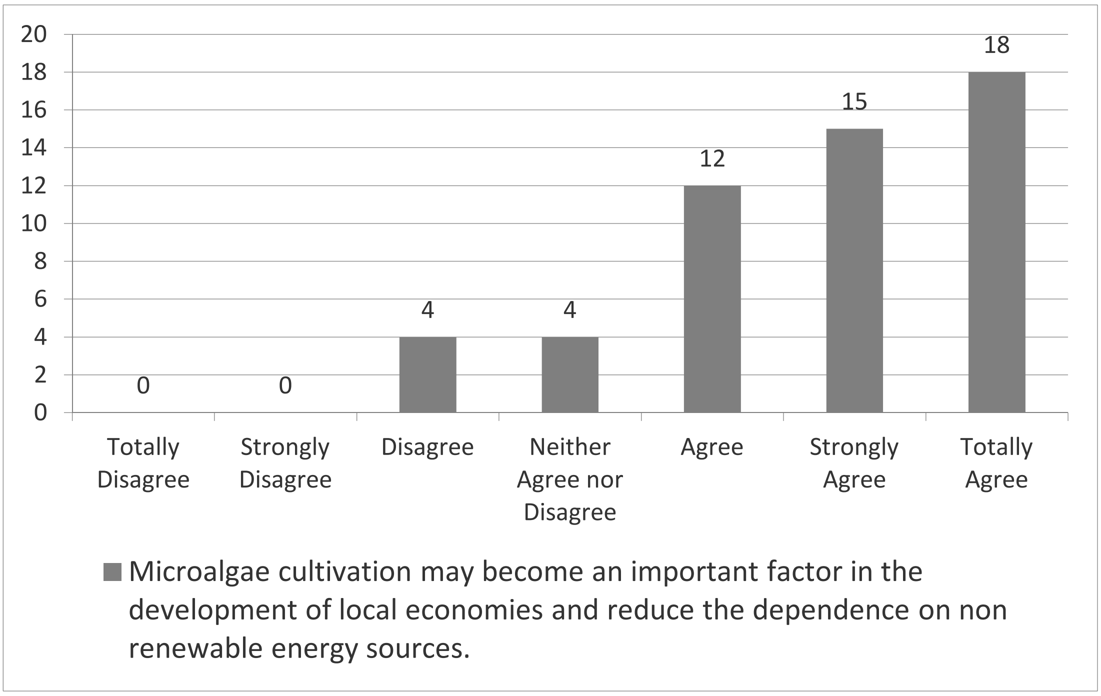


Cumulative results:

Agree	36	68%
Neither	12	23%
Disagree	5	9%
	53	

1.15 Microalgae cultivation may become an important factor in the development of local economies and reduce the dependence on non renewable energy sources.

RESPONDENTS	*53*
MEAN	5.74
MEDIAN	6
STANDARD DEVIATION	1.23
VARIANCE	1.51
Coefficient of Variation	21%



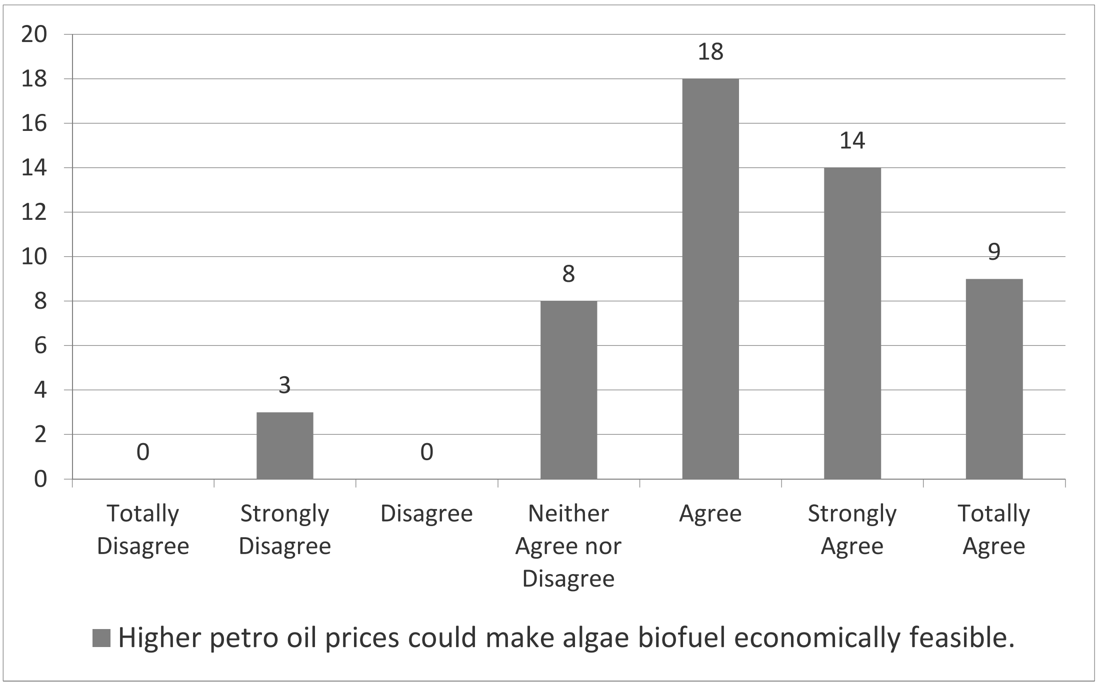
Cumulative results:

Agree	45	85%
Neither	4	8%
Disagree	4	8%
	53	

Theme 2:

2.1 Higher petro oil prices could make algae biofuel economically feasible.

RESPONDENTS	*52*
MEAN	5.29
MEDIAN	5
STANDARD DEVIATION	1.26
VARIANCE	1.58
Coefficient of Variation	24%

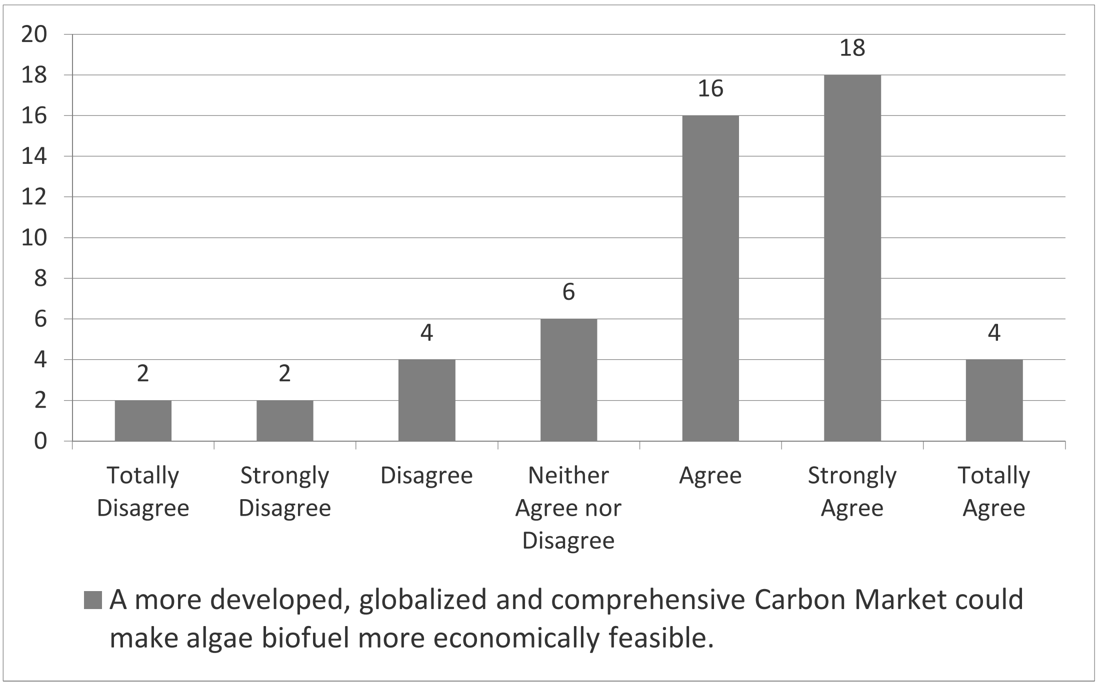


Cumulative results:

Agree	41	79%
Neither	8	15%
Disagree	3	6%
	52	

2.2 A more developed, globalized and comprehensive Carbon Market could make algae biofuel more economically feasible.

RESPONDENTS	*52*
MEAN	4.96
MEDIAN	5
STANDARD DEVIATION	1.44
VARIANCE	2.08
Coefficient of Variation	29%

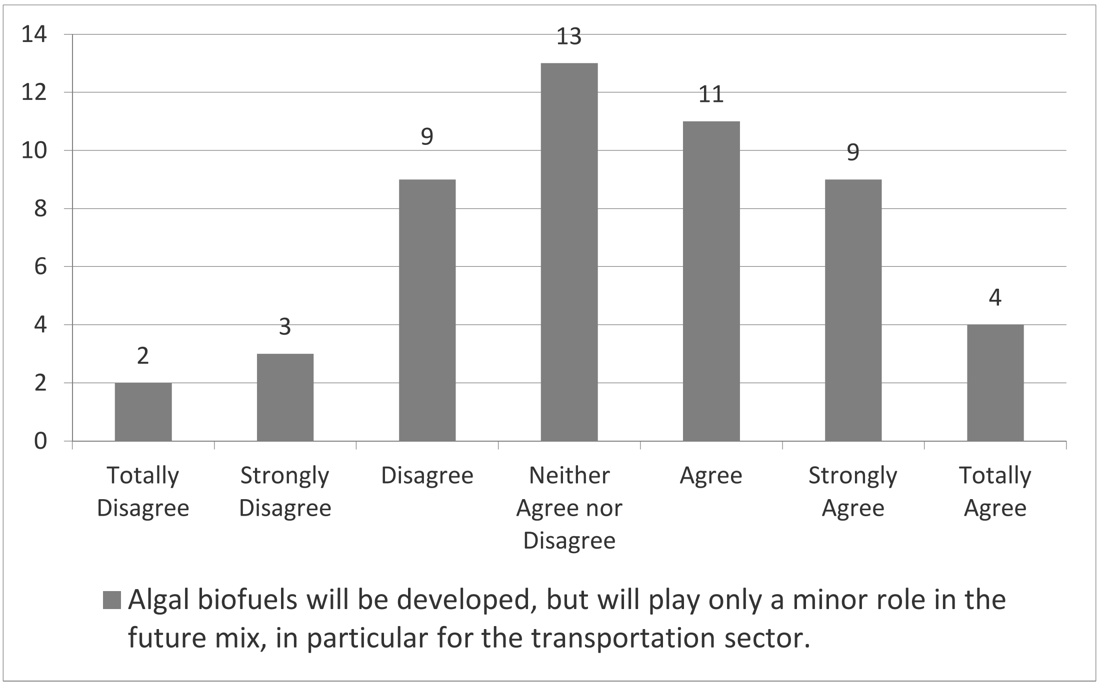


Cumulative results:

Agree	38	73%
Neither	6	12%
Disagree	8	15%
	52	

2.3 Algal biofuels will be developed, but will play only a minor role in the future mix, in particular for the transportation sector.

RESPONDENTS	*51*
MEAN	4.39
MEDIAN	4
STANDARD DEVIATION	1.51
VARIANCE	2.28
Coefficient of Variation	**34%**

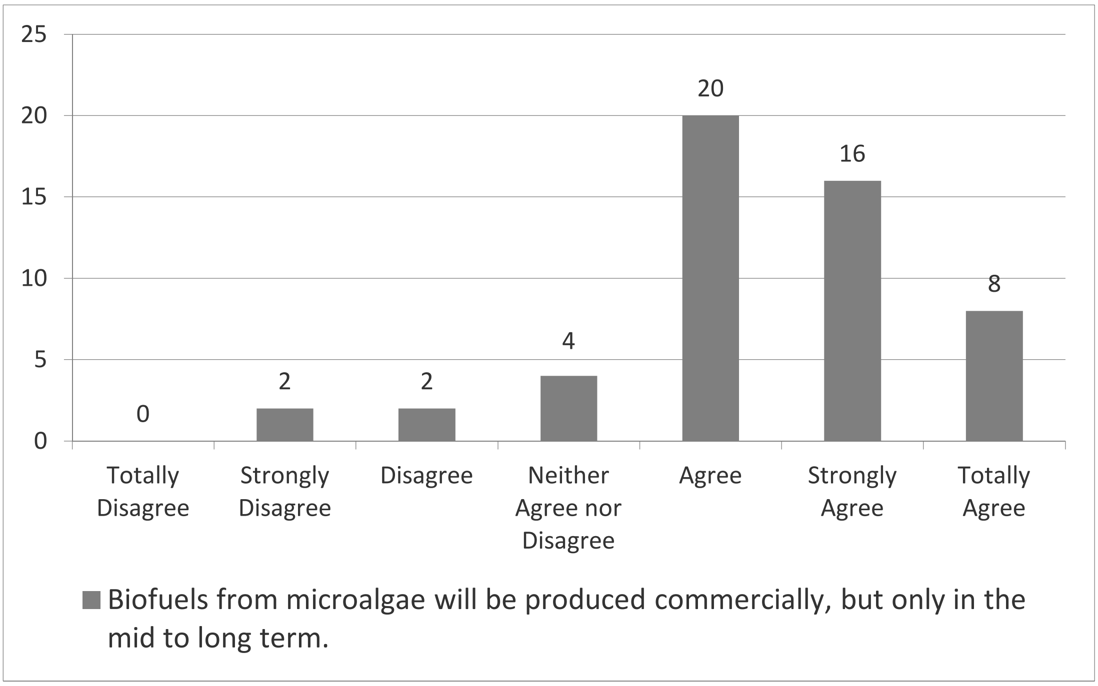


Cumulative results:

Agree	24	47%
Neither	13	25%
Disagree	14	27%
	51	

2.4 Biofuels from microalgae will be produced commercially, but only in the mid to long term.

RESPONDENTS	*52*
MEAN	5.35
MEDIAN	5
STANDARD DEVIATION	1.19
VARIANCE	1.41
Coefficient of Variation	22%

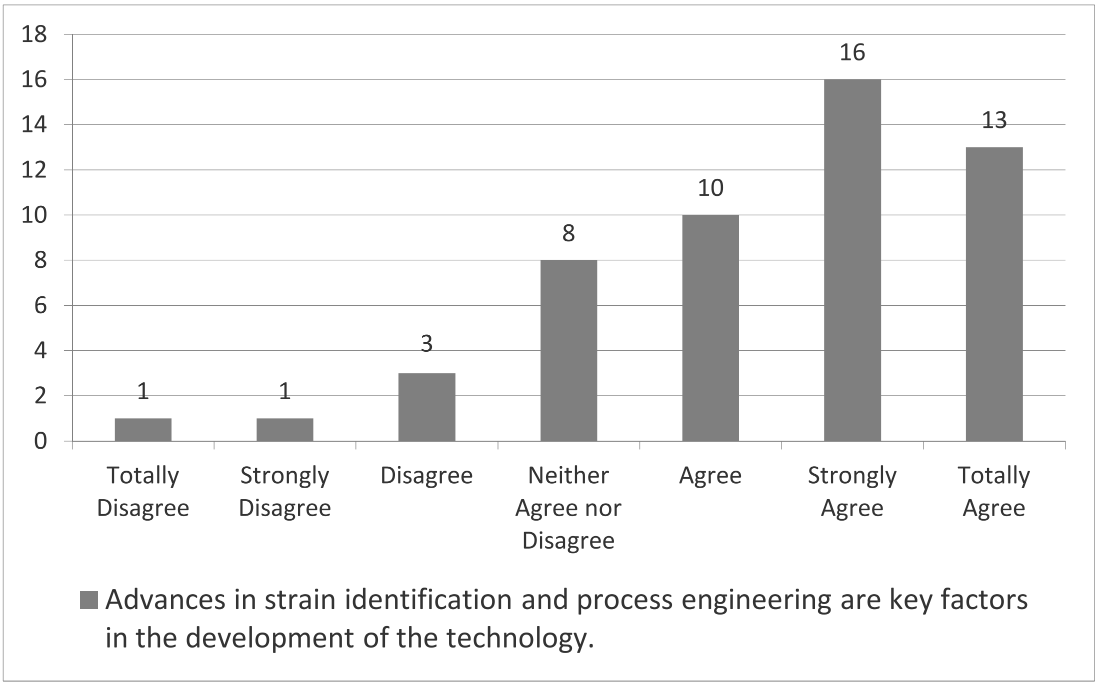


Cumulative results:

Agree	44	85%
Neither	4	8%
Disagree	4	8%
	52	

2.5 Advances in strain identification and process engineering are key factors in the development of the technology.

RESPONDENTS	*52*
MEAN	5.40
MEDIAN	6
STANDARD DEVIATION	1.43
VARIANCE	2.05
Coefficient of Variation	26%

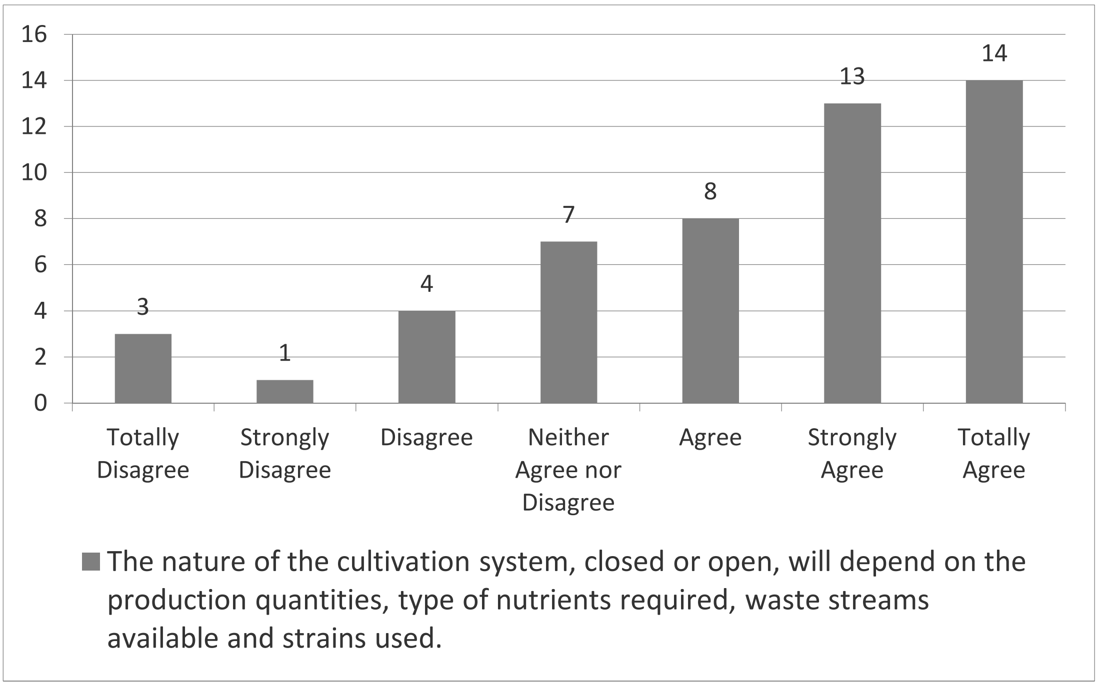


Cumulative results:

Agree	39	75%
Neither	8	15%
Disagree	5	10%
	52	

2.6 The nature of the cultivation system, closed or open, will depend on the production quantities, type of nutrients required, waste streams available and strains used.

RESPONDENTS	*50*
MEAN	5.22
MEDIAN	6
STANDARD DEVIATION	1.73
VARIANCE	2.99
Coefficient of Variation	**33%**

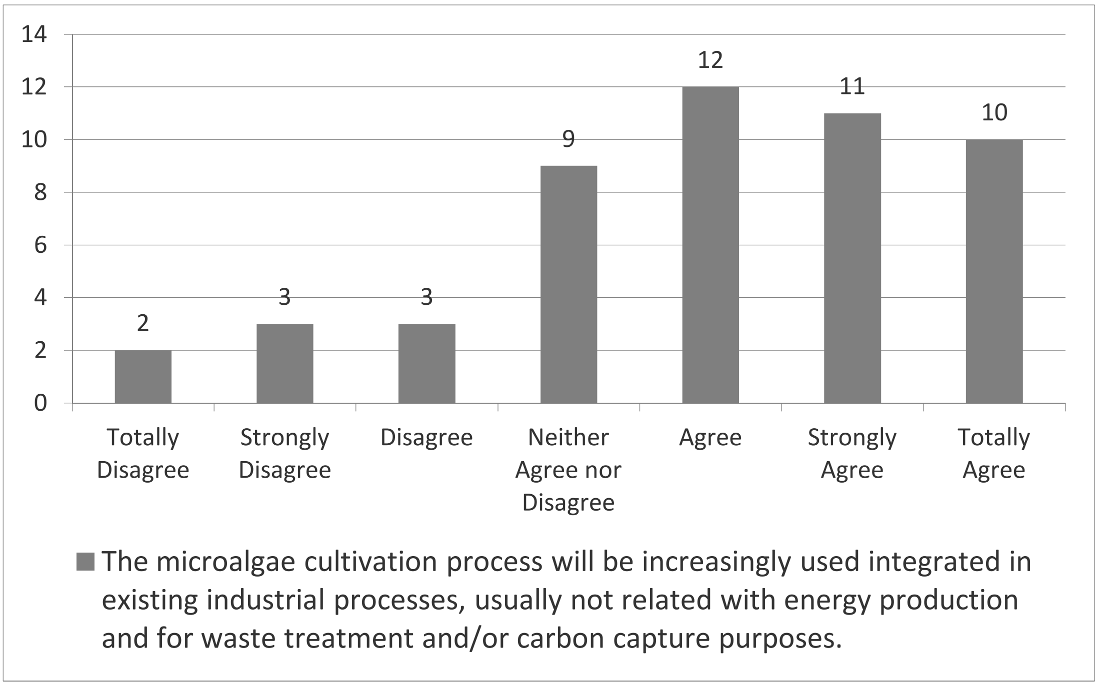


Cumulative results:

Agree	35	70%
Neither	7	14%
Disagree	8	16%
	50	

2.7 The microalgae cultivation process will be increasingly used integrated in existing industrial processes, usually not related with energy production and for waste treatment and/or carbon capture purposes.

RESPONDENTS	*50*
MEAN	4.98
MEDIAN	5
STANDARD DEVIATION	1.63
VARIANCE	2.67
Coefficient of Variation	**33%**

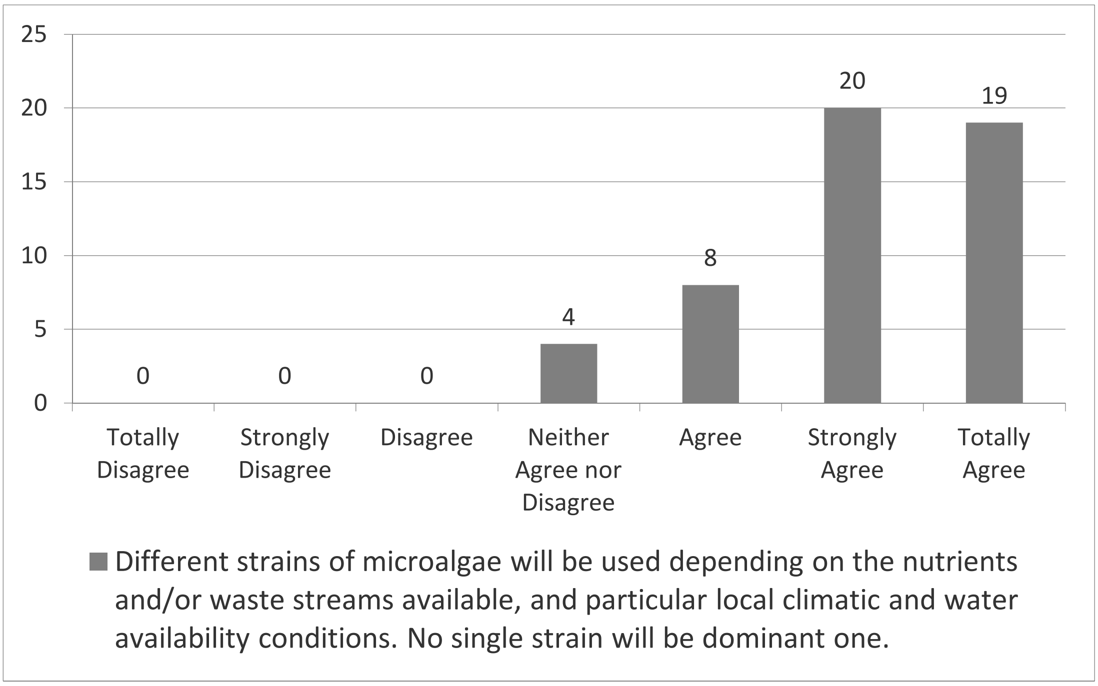


Cumulative results:

Agree	33	66%
Neither	9	18%
Disagree	8	16%
	50	

2.8 Different strains of microalgae will be used depending on the nutrients and/or waste streams available, and particular local climatic and water availability conditions. No single strain will be dominant one.

RESPONDENTS	*51*
MEAN	6.06
MEDIAN	6
STANDARD DEVIATION	0.93
VARIANCE	0.86
Coefficient of Variation	15%

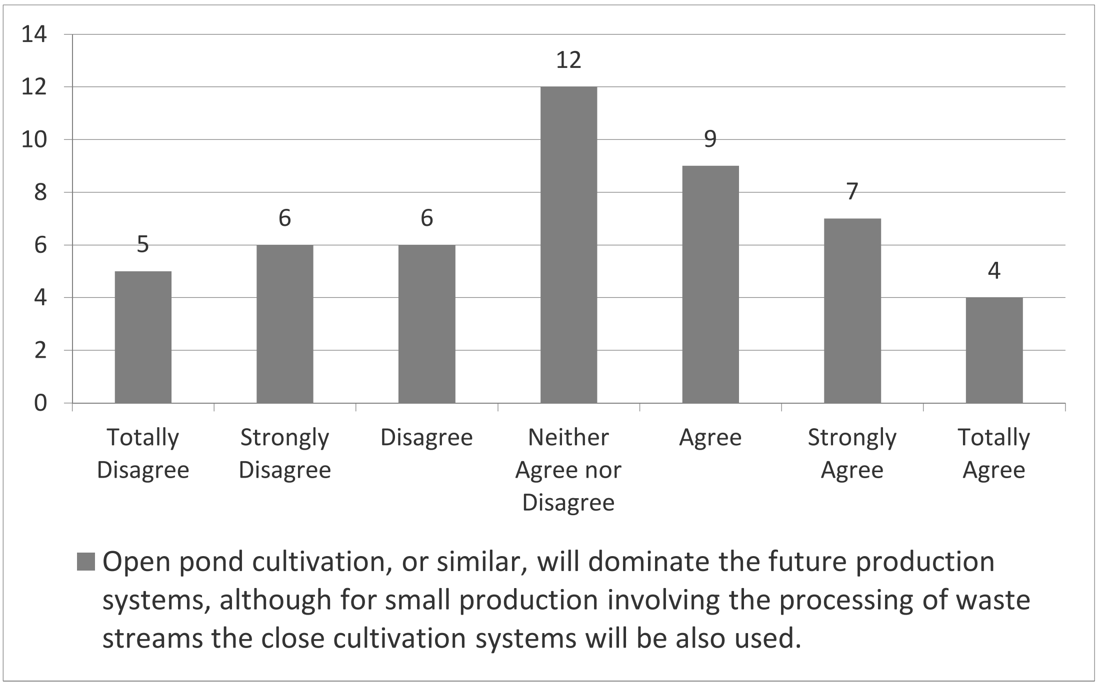


Cumulative results:

Agree	47	92%
Neither	4	8%
Disagree	0	0%
	51	

2.9 Open pond cultivation, or similar, will dominate the future production systems, although for small production involving the processing of waste streams the close cultivation systems will be also used.

RESPONDENTS	*49*
MEAN	4.04
MEDIAN	4
STANDARD DEVIATION	1.76
VARIANCE	3.08
Coefficient of Variation	**43%**

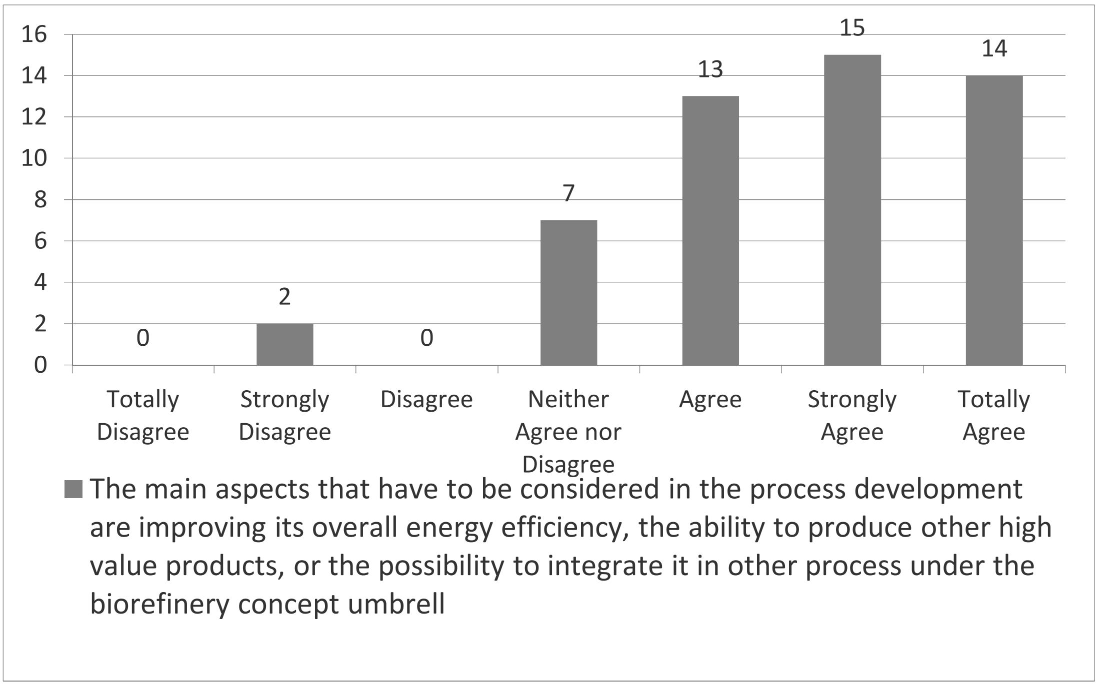


Cumulative results:

Agree	20	41%
Neither	12	24%
Disagree	17	35%
	49	

2.10 The main aspects that have to be considered in the process development are improving its overall energy efficiency, the ability to produce other high value products, or the possibility to integrate it in other process under the biorefinery concept umbrella.

RESPONDENTS	*51*
MEAN	5.59
MEDIAN	6
STANDARD DEVIATION	1.25
VARIANCE	1.57
Coefficient of Variation	22%

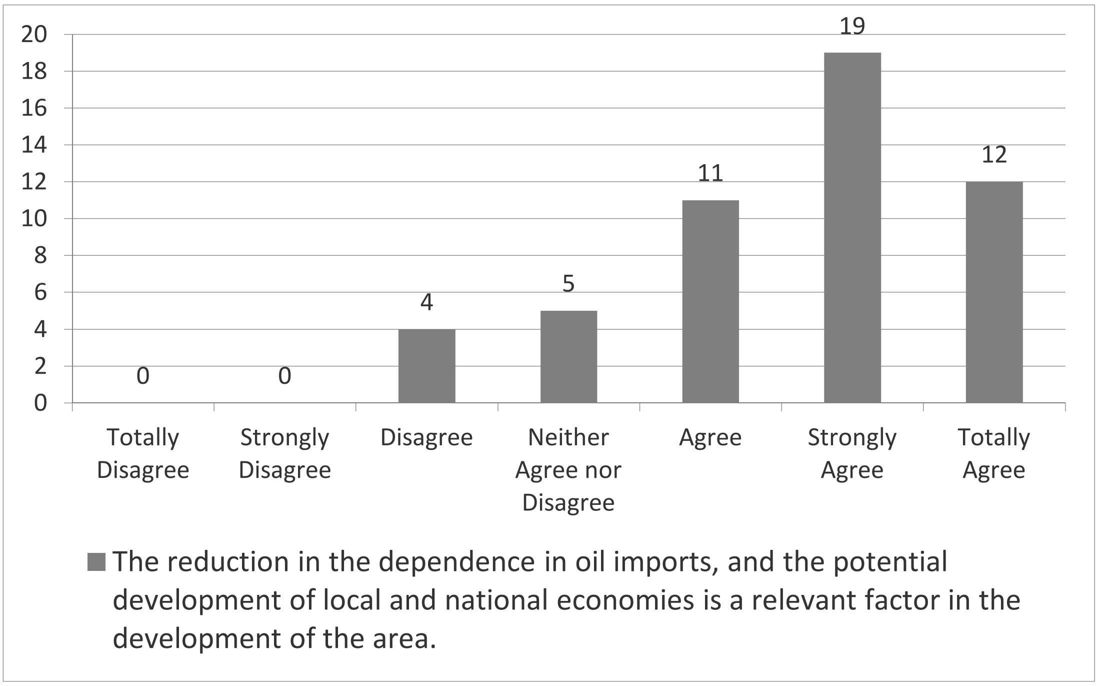


Cumulative results:

Agree	42	82%
Neither	7	14%
Disagree	2	4%
	51	

2.11 The reduction in the dependence in oil imports, and the potential development of local and national economies is a relevant factor in the development of the area.

RESPONDENTS	*51*
MEAN	5.59
MEDIAN	6
STANDARD DEVIATION	1.19
VARIANCE	1.41
Coefficient of Variation	21%



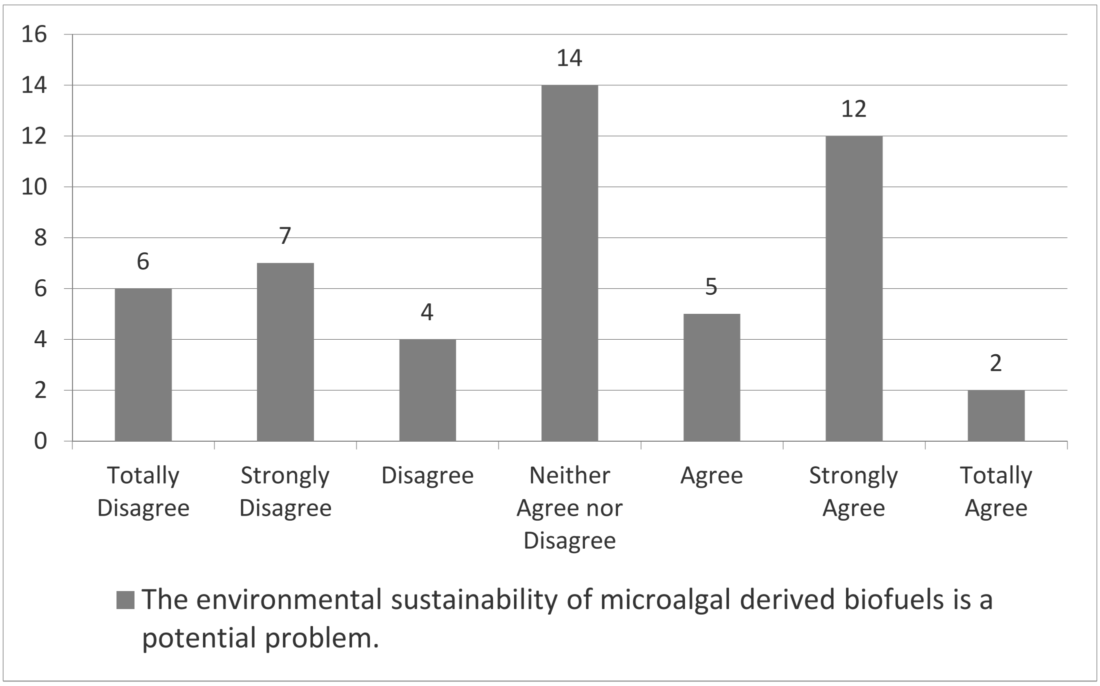
Cumulative results:

Agree	42	82%
Neither	5	10%
Disagree	4	8%
	51	

Theme 3:

3.1 The environmental sustainability of microalgal derived biofuels is a potential problem.

RESPONDENTS	*50*
MEAN	3.98
MEDIAN	4
STANDARD DEVIATION	1.79
VARIANCE	3.20
Coefficient of Variation	**45%**

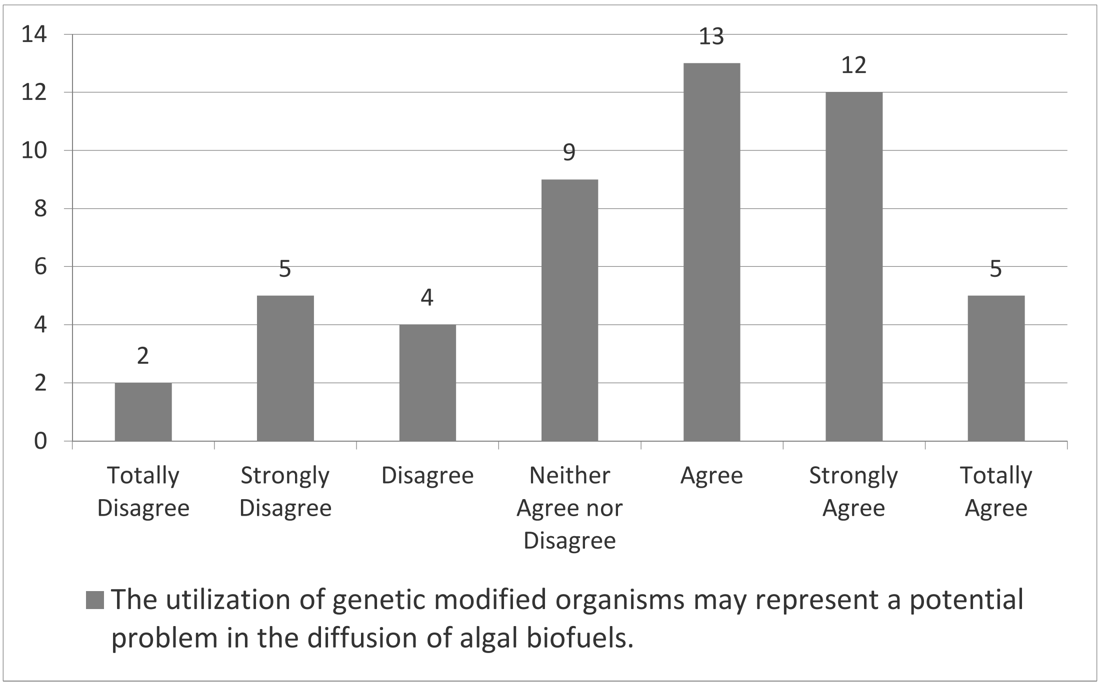


Cumulative results:

Agree	19	38%
Neither	14	28%
Disagree	17	34%
	50	

3.2 The utilization of genetic modified organisms may represent a potential problem in the diffusion of algal biofuels.

RESPONDENTS	*50*
MEAN	4.64
MEDIAN	5
STANDARD DEVIATION	1.61
VARIANCE	2.60
Coefficient of Variation	**35%**

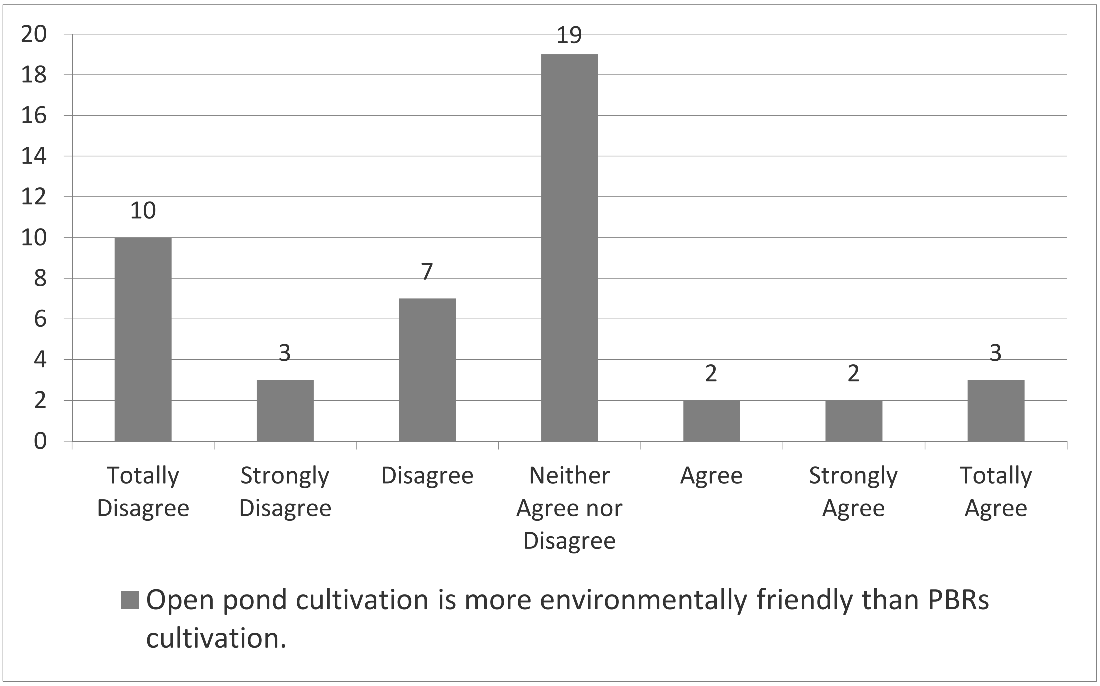


Cumulative results:

Agree	30	60%
Neither	9	18%
Disagree	11	22%
	50	

3.3 Open pond cultivation is more environmentally friendly than PBRs cultivation.

RESPONDENTS	*46*
MEAN	3.39
MEDIAN	4
STANDARD DEVIATION	1.69
VARIANCE	2.87
Coefficient of Variation	**50%**

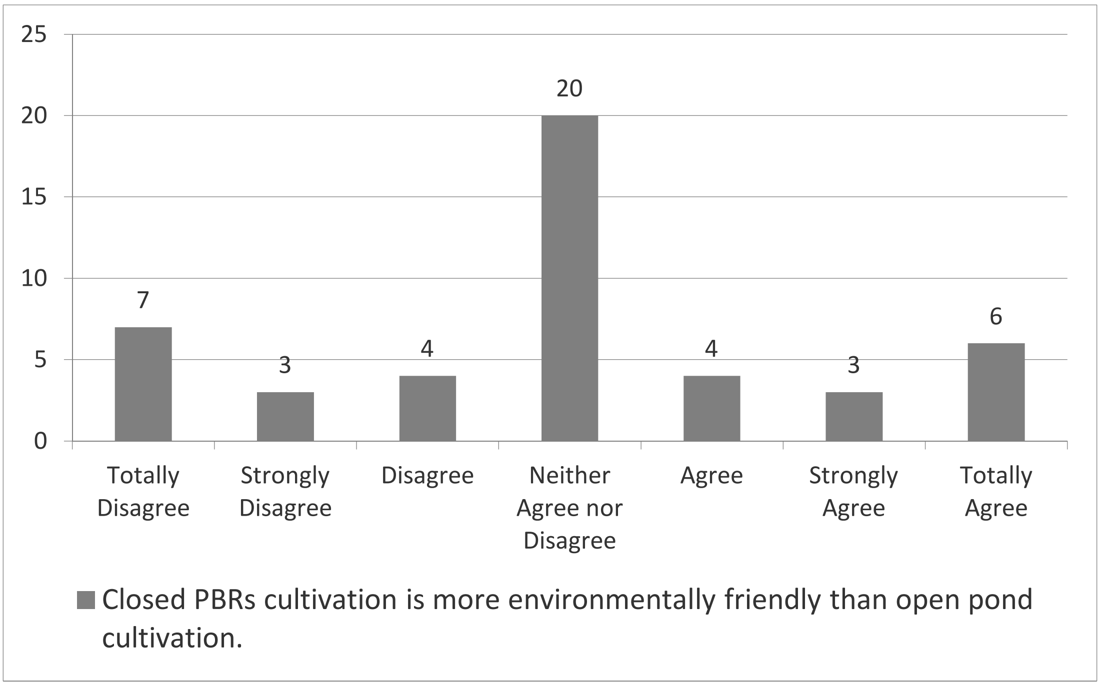


Cumulative results:

Agree	7	15%
Neither	19	41%
Disagree	20	43%
	46	

3.4 Closed PBRs cultivation is more environmentally friendly than open pond cultivation.

RESPONDENTS	*47*
MEAN	3.94
MEDIAN	4
STANDARD DEVIATION	1.80
VARIANCE	3.23
Coefficient of Variation	**46%**

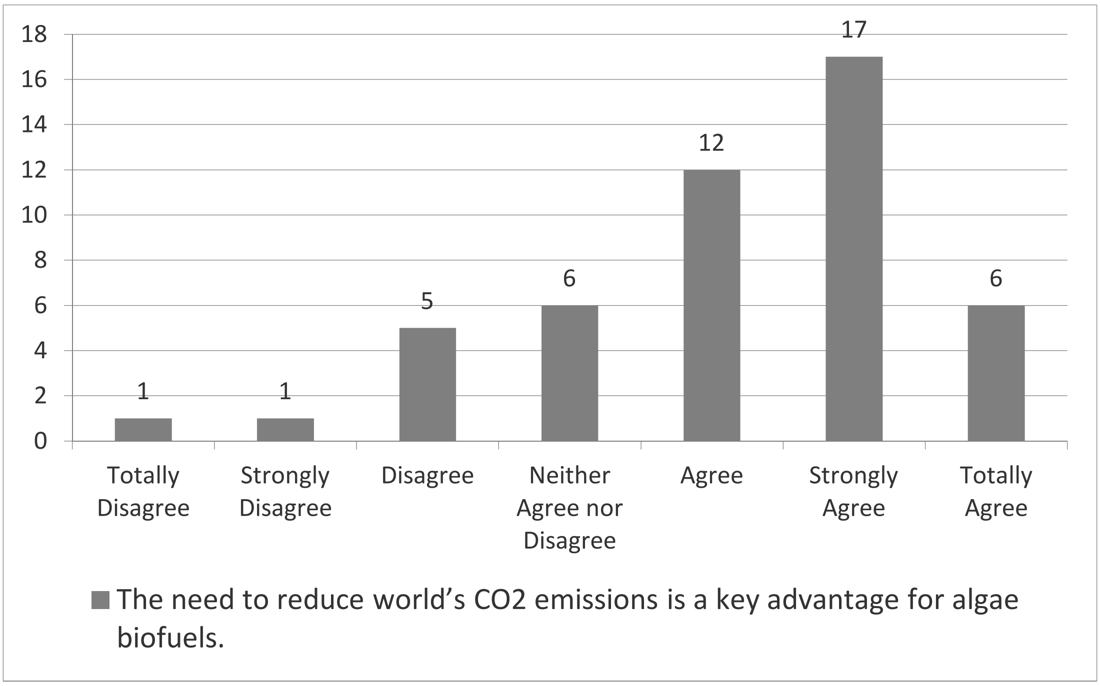


Cumulative results:

Agree	13	28%
Neither	20	43%
Disagree	14	30%
	47	

3.5 The need to reduce world's CO2 emissions is a key advantage for algae biofuels.

RESPONDENTS	*48*
MEAN	5.13
MEDIAN	5
STANDARD DEVIATION	1.39
VARIANCE	1.94
Coefficient of Variation	27%

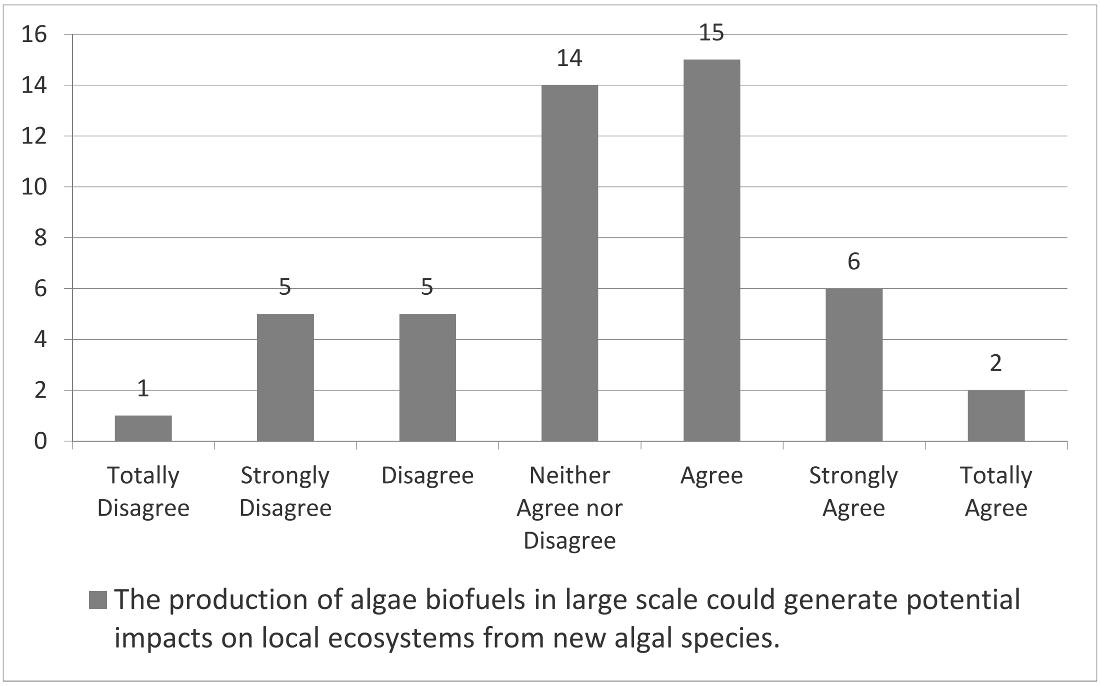


Cumulative results:

Agree	35	73%
Neither	6	13%
Disagree	7	15%
	48	

3.6 The production of algae biofuels in large scale could generate potential impacts on local ecosystems from new algal species.

RESPONDENTS	*48*
MEAN	4.31
MEDIAN	4
STANDARD DEVIATION	1.36
VARIANCE	1.84
Coefficient of Variation	**31%**

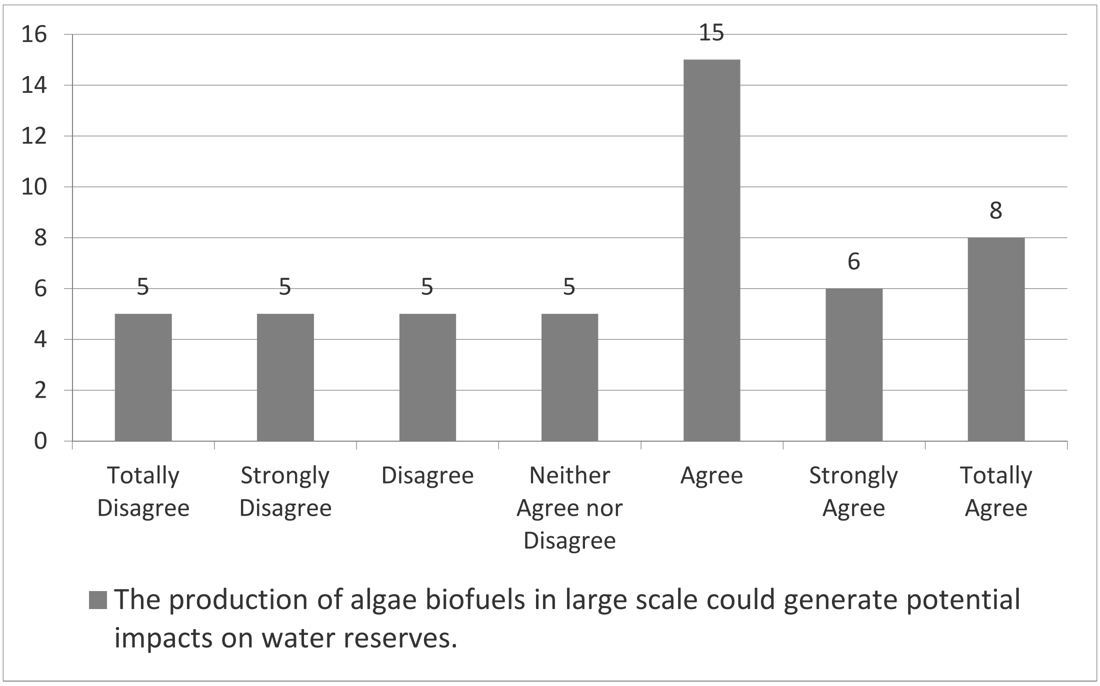


Cumulative results:

Agree	23	48%
Neither	14	29%
Disagree	11	23%
	48	

3.7 The production of algae biofuels in large scale could generate potential impacts on water reserves.

RESPONDENTS	*49*
MEAN	4.43
MEDIAN	5
STANDARD DEVIATION	1.89
VARIANCE	3.58
Coefficient of Variation	**43%**

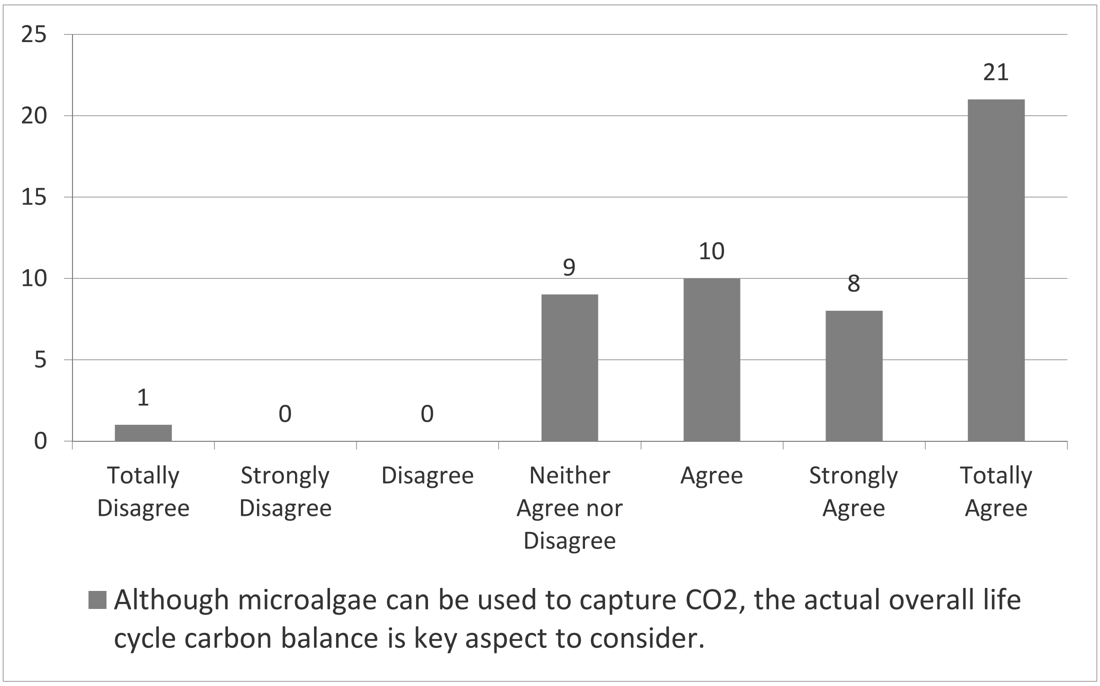


Cumulative results:

Agree	29	59%
Neither	5	10%
Disagree	15	31%
	49	

3.8 Although microalgae can be used to capture CO2, the actual overall life cycle carbon balance is key aspect to consider.

RESPONDENTS	*49*
MEAN	5.76
MEDIAN	6
STANDARD DEVIATION	1.36
VARIANCE	1.86
Coefficient of Variation	24%

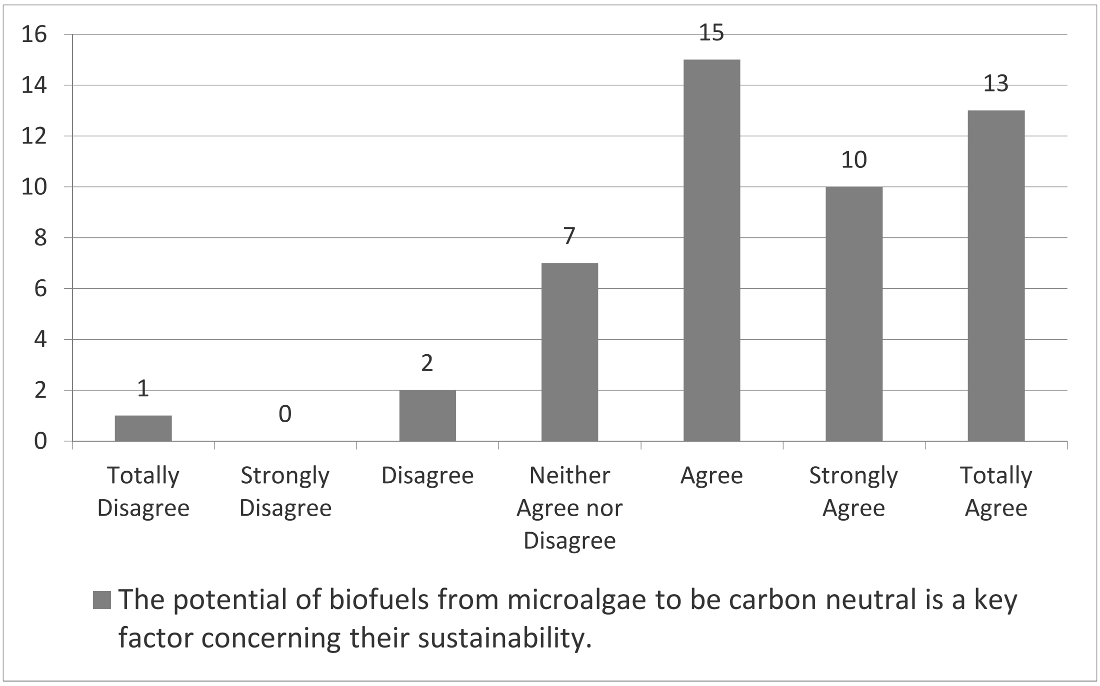


Cumulative results:

Agree	39	80%
Neither	9	18%
Disagree	1	2%
	49	

3.9 The potential of biofuels from microalgae to be carbon neutral is a key factor concerning their sustainability.

RESPONDENTS	*48*
MEAN	5.44
MEDIAN	5
STANDARD DEVIATION	1.34
VARIANCE	1.78
Coefficient of Variation	25%

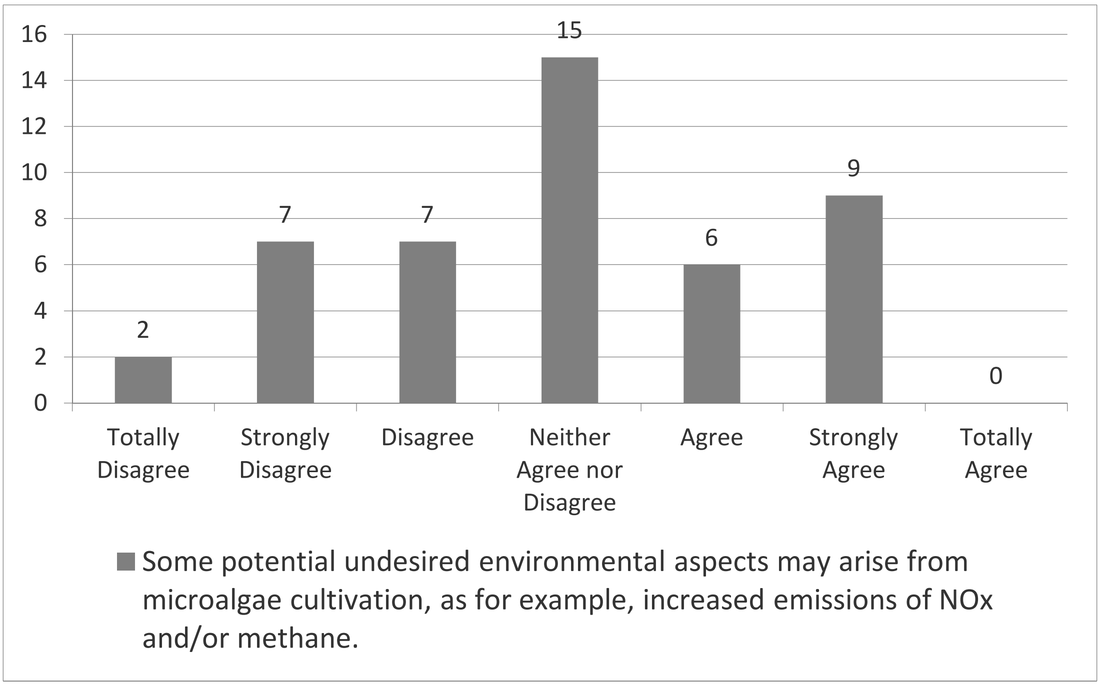


Cumulative results:

Agree	38	79%
Neither	7	15%
Disagree	3	6%
	48	

3.10 Some potential undesired environmental aspects may arise from microalgae cultivation, as for example, increased emissions of NOx and/or methane.

RESPONDENTS	*46*
MEAN	3.93
MEDIAN	4
STANDARD DEVIATION	1.45
VARIANCE	2.11
Coefficient of Variation	**37%**

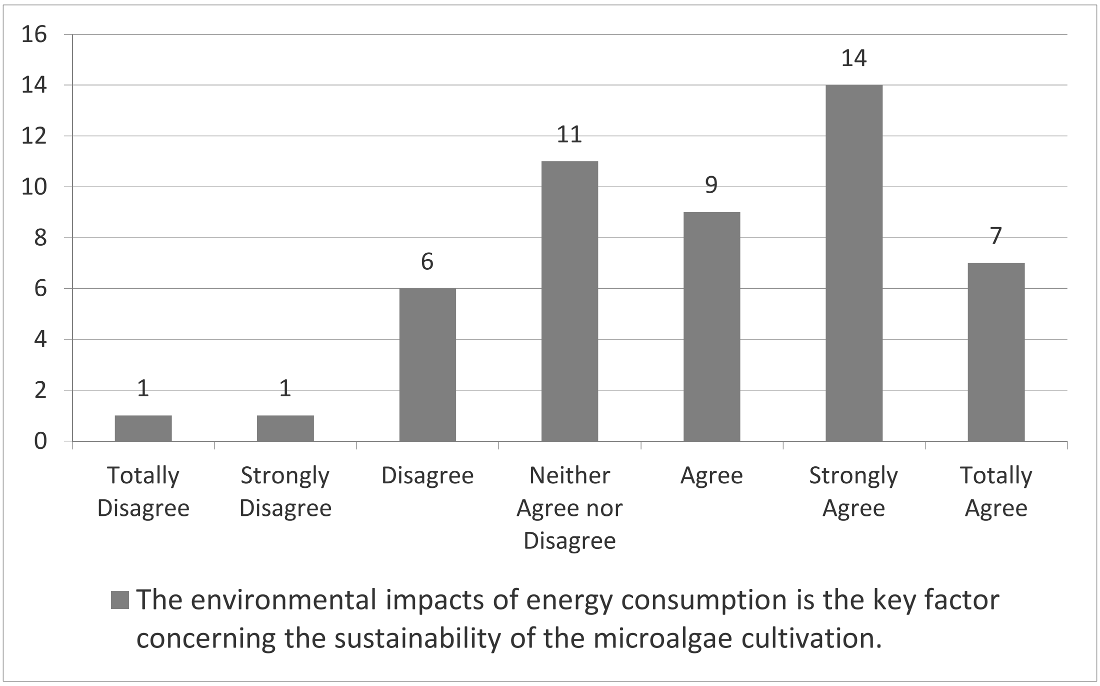


Cumulative results:

Agree	15	33%
Neither	15	33%
Disagree	16	35%
	46	

3.11 The environmental impacts of energy consumption is the key factor concerning the sustainability of the microalgae cultivation.

RESPONDENTS	*49*
MEAN	4.96
MEDIAN	5
STANDARD DEVIATION	1.46
VARIANCE	2.12
Coefficient of Variation	29%

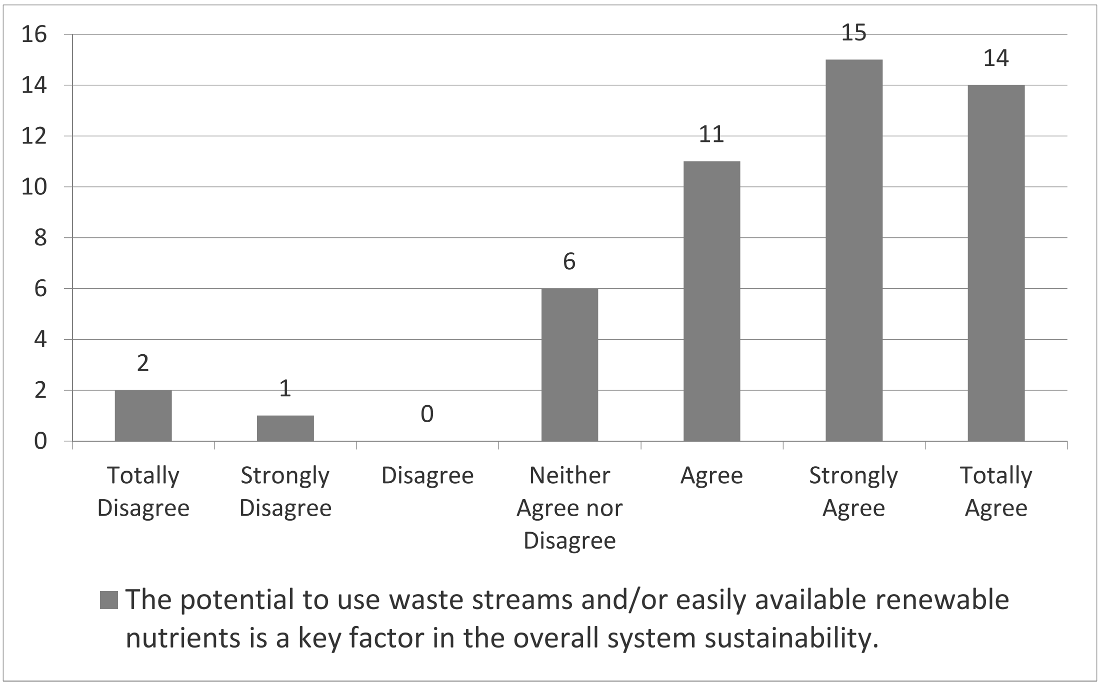


Cumulative results:

Agree	30	61%
Neither	11	22%
Disagree	8	16%
	49	

3.12 The potential to use waste streams and/or easily available renewable nutrients is a key factor in the overall system sustainability.

RESPONDENTS	*49*
MEAN	5.53
MEDIAN	6
STANDARD DEVIATION	1.47
VARIANCE	2.17
Coefficient of Variation	27%



Cumulative results:

Agree	40	82%
Neither	6	12%
Disagree	3	6%
	49	

Theme 4:

How important is each policy below to the success of algae biofuels?

Answer options	**Not at all important**	**Unimportant**	**Slightly Unimportant**	**Neutral**	**Important**	**Very Important**	**Extremely Important**	**Prefer not to answer**	**Response Count**
Mandatory country objectives;	**1**	**0**	**0**	**8**	**11**	**16**	**10**	**6**	**52**
Sustainability standards (Emissions, production, etc.);	**1**	**0**	**0**	**5**	**10**	**19**	**11**	**6**	**52**
Public Investment in R&D;	**0**	**0**	**0**	**5**	**7**	**12**	**21**	**7**	**52**
Tax incentives and subsidies;	**1**	**1**	**0**	**2**	**13**	**15**	**13**	**7**	**52**
Certification schemes, in particular those concerning raw materials or the entire fuel life cycle;	**0**	**1**	**0**	**4**	**18**	**17**	**6**	**6**	**52**
Specific legislation or international agreements (such as European Directives) aimed specifically to biofuels or to specific environmental questions (such as carbon emissions) where biofuels have a pivotal role;	**0**	**0**	**0**	**5**	**13**	**19**	**9**	**6**	**52**
Development strategies aimed to renewable resources, either research, utilization and integration in existing systems.	**0**	**0**	**0**	**4**	**12**	**14**	**16**	**6**	**52**

Delphi survey Theme 4 statements and results

	Theme 4: POLICIES	Mean
4.1	Mandatory country objectives;	**5.52**
4.2	Sustainability standards (Emissions, production, etc.);	**5.70**
4.3	Public Investment in R&D;	**6.09**
4.4	Tax incentives and subsidies;	**5.71**
4.5	Certification schemes, in particular those concerning raw materials or the entire fuel life cycle;	**5.48**
4.6	Specific legislation or international agreements (such as European Directives) aimed specifically to biofuels or to specific environmental questions (such as carbon emissions) where biofuels have a pivotal role;	**5.70**
4.7	Development strategies aimed to renewable resources, either research, utilization and integration in existing systems.	**5.91**

2nd round:

Delphi survey Theme 4 2nd round policies priorities

	Theme 4: POLICIES	1st	2nd	3rd	4th	5th
4.1	Mandatory country objectives;	27.6%	6.9%	10.3%	10.3%	10.3%
4.2	Sustainability standards (Emissions, production, etc.);	0.0%	17.2%	6.9%	24.1%	24.1%
4.3	Public Investment in R&D;	34.5%	13.8%	13.8%	13.8%	10.3%
4.4	Tax incentives and subsidies;	6.9%	20.7%	20.7%	17.2%	6.9%
4.5	Certification schemes	0.0%	6.9%	3.4%	13.8%	17.2%
4.6	Specific legislation or international agreements	10.3%	13.8%	20.7%	10.3%	20.7%
4.7	Development strategies aimed to renewable resources	20.7%	20.7%	24.1%	10.3%	10.3%

Theme 5:

When do you think the following would happen in algae biofuels industry?

Results:

Answer options	Before 2015	From 2015 to 2020	From 2021 to 2030	From 2031 to 2050	Never	Prefer not to answer	Response Count
Fully Commercial Scale	**5**	**20**	**16**	**2**	**3**	**6**	**52**
1% of worldwide fuel consumption	**0**	**7**	**32**	**1**	**1**	**11**	**52**
5% of worldwide fuel consumption	**0**	**1**	**27**	**9**	**2**	**13**	**52**
10% of worldwide fuel consumption	**0**	**0**	**10**	**21**	**6**	**15**	**52**
25% of worldwide fuel consumption	**0**	**0**	**3**	**15**	**16**	**18**	**52**

APPENDIX D: Model Template used for Generating the Scenarios

```
identifiers
//////////////  PARAMETERS

// POLICY 1: Subsidies
// Value from 0 to 1: indicates the remaining amount (after reduction /increase)  : 1 = inactive policy
Policy1_Gas = oooPolicy1_Gooo ;
Policy1_Petrol = oooPolicy1_Pooo ;
Policy1_BIO = oooPolicy1_Booo ;
Policy1_ADVBIO = oooPolicy1_Aooo ;
Policy1_ELEC = oooPolicy1_Eooo ;

//POLICY 2: Cost of Carbon Emission
// Value from 0 to 1: indicates the remaining amount (after reduction /increase)  : 1 = inactive policy
Policy2_Gas = oooPolicy2_Gooo ;
Policy2_Petrol = oooPolicy2_Pooo ;
Policy2_BIO = oooPolicy2_Booo ;
Policy2_ADVBIO = oooPolicy2_Aooo ;
Policy2_ELEC = oooPolicy2_Eooo ;

//POLICY 3: Mandate
// Value from 0 to 1 indicating the percentage of Biofuel/AdvBio in gasoline. Zero means inactive policy.
Policy3_B =  oooPolicy3_Booo;
Policy3_A =  oooPolicy3_Aooo;


// Value from 0 to 1 indicating the percentage of gasoline use within the Petrol=Gasoline+Diesel users
GasolineInPetrol = 0.75;

//COST OF RESOURCES:
costGas = ooocost_Gooo  * Policy1_Gas * Policy2_Gas;
costPetrol = ooocost_Pooo * Policy1_Petrol * Policy2_Petrol ;// gasoline + diesel
costBIO = ooocost_Booo  * Policy1_BIO * Policy2_BIO;
costADVBIO = ooocost_Aooo * Policy1_ADVBIO * Policy2_ADVBIO;
costELEC = ooocost_Eooo * Policy1_ELEC * Policy2_ELEC;

// AVAILABILITY OF RESOURCES:
// This variable denotes the availability of a resource (100 MEANS THERE IS NO LIMIT).
// If AVAIL = X then at most X% of users can use this fuel, except in the case of 0, that means that
// 0 to 1% of users may use this fuel.
// The availabilities of BIO and ADVBIO include also the amount due to mandate (Policy3).
AVAIL_P = oooAVAIL_Pooo ;
AVAIL_G = oooAVAIL_Gooo ;
AVAIL_B = oooAVAIL_Booo + (((AVAIL_P - ((st UP)*2)+1))* oooPolicy3_Booo );
AVAIL_A = oooAVAIL_Aooo + (((AVAIL_P - ((st UP)*2)+1))* oooPolicy3_Aooo );
AVAIL_E = oooAVAIL_Eooo;

///////////// END OF PAREMETERS

// Number of user levels: 51
   USER_RANGE = [0..50];

// Cost of changing fuel: Depends on cost of adapting the vehicle and fuel availability
// Value between 0 (maximum cost) and 100 (no cost)

FULL_EO = 10;
FULL_OE = 10;
```

```
PART = 20;
NONE = 100;
NONE_OB = 100 ;
NONE_OA = 100 ;

changeCostPG = PART /100;
changeCostGP = NONE /100;
changeCostPB = NONE_OB /100;
changeCostBP =  NONE  /100;
changeCostGB =  NONE_OB /100;
changeCostBG =  PART /100;
changeCostAB =  NONE /100;
changeCostBA =  NONE /100;
changeCostEB =  FULL_EO /100;
changeCostBE =  FULL_OE/100;
changeCostGA =  NONE_OA /100;
changeCostAG =  PART /100;
changeCostEA =  FULL_EO /100;
changeCostAE =  FULL_OE /100;
changeCostPE =  FULL_OE /100;
changeCostEP =  FULL_EO /100;
changeCostGE =  FULL_OE /100;
changeCostEG =  FULL_EO/100;
changeCostAP =  NONE /100;
changeCostPA =  NONE_OA /100;

// Actual Availability: Availability (percentage)
actualAVAIL_P = ( AVAIL_P / 100 ) ;
actualAVAIL_G = ( AVAIL_G / 100 ) ;
actualAVAIL_B = ( AVAIL_B / 100 ) ;
actualAVAIL_A = ( AVAIL_A / 100 ) ;
actualAVAIL_E = ( AVAIL_E / 100 ) ;

// GuardAVAIL : This is used to prevent users from going to a fuel if there is no availability.
// To disable the guard, all values can be set to 1.
// The value of this variable is zero (if the availability has reached its limit) or 1 (otherwise).

actAVAIL_P = ((AVAIL_P == 100)  * 1) +
             ((AVAIL_P != 100)  * ((((AVAIL_P - ((st UP)* 2) ) +1) / 100) ) );
actAVAIL_G = ((AVAIL_G == 100)  * 1) +
             ((AVAIL_G != 100)  * ((((AVAIL_G - ((st UG)* 2) ) +1) / 100) ) );
actAVAIL_B = ((AVAIL_B == 100)  * 1) +
         ((AVAIL_B  != 100) * ((((AVAIL_B - ((st UB)* 2) ) +1) / 100) ) );
actAVAIL_A = ((AVAIL_A == 100)  * 1) +
             ((AVAIL_A != 100)  * ((((AVAIL_A - ((st UA)* 2) ) +1) / 100) ) );
actAVAIL_E = ((AVAIL_E == 100)  * 1) +
             ((AVAIL_E != 100)  * ((((AVAIL_E - ((st UE)* 2) ) +1) / 100) ) );

 GuardAVAIL_P =  (actAVAIL_P > 0);
 GuardAVAIL_G =  (actAVAIL_G > 0);
 GuardAVAIL_B =  (actAVAIL_B > 0);
 GuardAVAIL_A =  (actAVAIL_A > 0);
 GuardAVAIL_E =  (actAVAIL_E > 0);

// Price comparisons: A number between 0 and 1.
// A unity-based normalization using as interval the distance between the minimum cost in all scenarios (10)
// and the maximum cost (50). If prices of X and Y are the same, priceDiff_XtoY is 0.5.
// To prevent zero values (that would cause division by zero later), we add 0.0001 to the result.
```

```
MAX_DIST = 40;    // 40 = 50 (MAX_PRICE)   -   10 (MIN_PRICE);

priceDiff_PtoG =  0.0001 +((costPetrol-costGas)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_GtoP =  0.0001 +((costGas-costPetrol)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_PtoE =  0.0001 +((costPetrol-costELEC)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_EtoP =  0.0001 +((costELEC-costPetrol)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_PtoA =  0.0001 +((costPetrol-costADVBIO)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_AtoP =  0.0001 +((costADVBIO-costPetrol)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_PtoB =  0.0001 +((costPetrol-costBIO)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_BtoP =  0.0001 +((costBIO-costPetrol)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_GtoB =  0.0001 +((costGas-costBIO)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_BtoG =  0.0001 +((costBIO-costGas)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_BtoA =  0.0001 +((costBIO-costADVBIO)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_AtoB =  0.0001 +((costADVBIO-costBIO)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_BtoE =  0.0001 +((costBIO-costELEC)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_EtoB =  0.0001 +((costELEC-costBIO)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_GtoA =  0.0001 +((costGas-costADVBIO)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_AtoG =  0.0001 +((costADVBIO-costGas)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_EtoA =  0.0001 +((costELEC-costADVBIO)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_AtoE =  0.0001 +((costADVBIO-costELEC)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_GtoE =  0.0001 +((costGas-costELEC)+MAX_DIST) / (2 * MAX_DIST) ;
priceDiff_EtoG =  0.0001 +((costELEC-costGas)+MAX_DIST) / (2 * MAX_DIST) ;

// Rates of conversion from one fuel to the other. These rates are numbers from 0 to 100
// representing how likely it is to make this change. This takes into account:
//           * the cost of changing from one fuel to another and
//           * the difference in the costs of fuels
//    * the availability of the fuel
// The availability of the new fuel affects the formula by preventing the change if the fuel is not available.
// We use weighted harmonic mean, price has a greater weight.

WEIGHT_CHANGE = 1;
WEIGHT_PRICE = 3;
WEIGHT_AVAIL = 2;
SUM_WEIGHT = WEIGHT_CHANGE + WEIGHT_PRICE + WEIGHT_AVAIL ;
  rateGP =  GuardAVAIL_P  *
          ( SUM_WEIGHT / ( (WEIGHT_CHANGE /  changeCostGP ) +
                                        (WEIGHT_AVAIL  /  actualAVAIL_P) +
                     (WEIGHT_PRICE  / priceDiff_GtoP   ) )  ) ;
  ratePG =  GuardAVAIL_G *
                    ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostPG ) +
                                        (WEIGHT_AVAIL  / actualAVAIL_G ) +
                     (WEIGHT_PRICE  / priceDiff_PtoG  ) )  ) ;
  rateBP =  GuardAVAIL_P   *
                    ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostBP ) +
                                        (WEIGHT_AVAIL  / actualAVAIL_P )+
                     (WEIGHT_PRICE  / priceDiff_BtoP  ) )  ) ;
  ratePB =  GuardAVAIL_B *
                    ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostPB ) +
                                        (WEIGHT_AVAIL  / actualAVAIL_B) +
                     (WEIGHT_PRICE/ priceDiff_PtoB  ) )  ) ;
  rateAP =  GuardAVAIL_P   *
                    ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostAP ) +
                                        (WEIGHT_AVAIL  / actualAVAIL_P) +
                     (WEIGHT_PRICE/ priceDiff_AtoP  ) )  ) ;
  ratePA =  GuardAVAIL_A  *
                    ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostPA ) +
```

```
                              (WEIGHT_AVAIL  / actualAVAIL_A) +
                   (WEIGHT_PRICE/ priceDiff_PtoA  ) )  ) ;
rateEP =  GuardAVAIL_P  *
                  ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostEP ) +
                              (WEIGHT_AVAIL  / actualAVAIL_P) +
                   (WEIGHT_PRICE/ priceDiff_EtoP  ) )  ) ;
ratePE =  GuardAVAIL_E  *
                  ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostPE ) +
                              (WEIGHT_AVAIL  / actualAVAIL_E) +
                   (WEIGHT_PRICE/ priceDiff_PtoE  ) )  ) ;
rateAB =  GuardAVAIL_B  *
                  ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostAB ) +
                              (WEIGHT_AVAIL  / actualAVAIL_B) +
                   (WEIGHT_PRICE/ priceDiff_AtoB  ) )  ) ;
rateBA =  GuardAVAIL_A  *
                  ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostBA ) +
                              (WEIGHT_AVAIL  / actualAVAIL_A)  +
                   (WEIGHT_PRICE/ priceDiff_BtoA  ) )  ) ;
 rateEB =  GuardAVAIL_B  *
                  ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostEB ) +
                              (WEIGHT_AVAIL  / actualAVAIL_B) +
                   (WEIGHT_PRICE/ priceDiff_EtoB  ) )  ) ;
rateBE =  GuardAVAIL_E   *
                  ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostBE ) +
                              (WEIGHT_AVAIL  / actualAVAIL_E) +
                   (WEIGHT_PRICE/ priceDiff_BtoE  ) )  ) ;
rateGB =  GuardAVAIL_B  *
                  ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostGB ) +
                              (WEIGHT_AVAIL  / actualAVAIL_B) +
                   (WEIGHT_PRICE/ priceDiff_GtoB  ) )  ) ;
rateBG =  GuardAVAIL_G   *
                  ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostBG ) +
                              (WEIGHT_AVAIL  / actualAVAIL_G) +
                   (WEIGHT_PRICE/ priceDiff_BtoG  ) )  ) ;
rateAG =  GuardAVAIL_G  *
                  ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostAG ) +
                              (WEIGHT_AVAIL  / actualAVAIL_G) +
                   (WEIGHT_PRICE/ priceDiff_AtoG  ) )  ) ;
rateGA =  GuardAVAIL_A  *
                  ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostGA ) +
                              (WEIGHT_AVAIL  / actualAVAIL_A )+
                   (WEIGHT_PRICE/ priceDiff_GtoA  ) )  ) ;
rateAE =  GuardAVAIL_E  *
                  ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostAE ) +
                              (WEIGHT_AVAIL  / actualAVAIL_E) +
                   (WEIGHT_PRICE/ priceDiff_AtoE  ) )  ) ;
rateEA =  GuardAVAIL_A  *
                  ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostEA ) +
                              (WEIGHT_AVAIL  / actualAVAIL_A )+
                   (WEIGHT_PRICE/ priceDiff_EtoA  ) )  ) ;
rateGE =  GuardAVAIL_E   *
                  ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostGE ) +
                              (WEIGHT_AVAIL  / actualAVAIL_E) +
                   (WEIGHT_PRICE/ priceDiff_GtoE  ) )  ) ;
rateEG =  GuardAVAIL_G  *
                  ( SUM_WEIGHT /((WEIGHT_CHANGE /  changeCostEG ) +
                              (WEIGHT_AVAIL  / actualAVAIL_G) +
                   (WEIGHT_PRICE/ priceDiff_EtoG  ) )  ) ;
```

```
events
  syn PtoG ratePG
  syn PtoB ratePB
  syn PtoA ratePA
  syn PtoE ratePE
  syn GtoB rateGB
  syn GtoP rateGP
  syn GtoA rateGA
  syn GtoE rateGE
  syn BtoG rateBG
  syn BtoP rateBP
  syn BtoA rateBA
  syn BtoE rateBE
  syn AtoG rateAG
  syn AtoP rateAP
  syn AtoB rateAB
  syn AtoE rateAE
  syn EtoG rateEG
  syn EtoP rateEP
  syn EtoA rateEA
  syn EtoB rateEB


//////   INITIAL STATE
reachability = ( (st UP==range48) && (st UB==range0) && (st UG==range2)  && (st UA==range0) && (st
UE==range0) );
/////

//////// AUTOMATA
network Fuel (continuous)
  aut UG // represents the percentage of Users of Gas, each state represents a range of 2%
    stt  range[USER_RANGE]
         to  (++ )
                                  BtoG
                                  PtoG
                                  AtoG
                                  EtoG
         to (--)
                                  GtoB
                                  GtoP
                                  GtoA
                                  GtoE

 aut UP // represents the percentage of Users of Gasoline,each state represents a range of 2%
    stt  range[USER_RANGE]
         to  (++)
                                  BtoP
                                  GtoP
                                  AtoP
                                  EtoP
         to (--)
                      PtoB
                                  PtoG
                                  PtoA
                                  PtoE
```

```
 aut UB // represents the percentage of Users of BIO, each state represents a range of 2%
   stt  range[USER_RANGE]
      to  (++)
                        GtoB
                        PtoB
                        EtoB
                        AtoB
      to  (--)
                        BtoG
                        BtoP
                        BtoA
                        BtoE

 aut UA // represents the percentage of Users of ADVBIO, each state represents a range of 2%
   stt  range[USER_RANGE]
      to  (++)
                        GtoA
                        PtoA
                        EtoA
                        BtoA
      to  (--)
                        AtoG
                        AtoP
                        AtoB
                        AtoE

 aut UE // represents the percentage of Users of ELECTRICITY, each state represents a range of 2%
   stt  range[USER_RANGE]
      to  (++)
                        GtoE
                        PtoE
                        AtoE
                        BtoE
      to  (--)
                        EtoG
                        EtoP
                        EtoB
                        EtoA

results
      PETROL_BIO_ADVBIO_use = (st UP)*2 ;
      PETROL_ONLY_use = (st UP)*2 - ((((st UP)*2)  * Policy3_B * GasolineInPetrol) +  (((st UP)*2)  *
Policy3_A));
      GAS_use = (st UG)*2;
      BIO_ONLY_use = (st UB)*2  ;
      BIO_use = (st UB)*2  + (((st UP)*2)  * Policy3_B * GasolineInPetrol);
      ADVBIO_ONLY_use = (st UA)*2  ;
      ADVBIO_use = (st UA)*2 + (((st UP)*2)  * Policy3_A);
      ELEC_use = (st UE)*2;
```

APPENDIX E: Results of all scenarios modeled

Tabela REF in 2040

	Low	Low	Low	Low	Low	Med	Med	Med	Med	Med	High	High	High	High	High
	UP	UG	UB	UA	UE	UP	UG	UB	UA	UE	UP	UG	UB	UA	UE
Reference	84.9%	4.5%	8.1%	1.6%	1.0%	84.2%	4.5%	8.0%	2.3%	1.0%	82.2%	4.6%	7.9%	4.3%	1.0%
Price subsidy 10%	84.6%	4.5%	8.1%	1.9%	1.0%	83.7%	4.5%	8.0%	2.7%	1.0%	80.8%	4.6%	7.8%	5.7%	1.0%
Price subsidy 25%	84.0%	4.6%	8.1%	2.3%	1.0%	82.7%	4.7%	8.0%	3.6%	1.0%	77.4%	4.8%	7.7%	9.1%	1.0%
Price subsidy 50%	82.2%	5.1%	8.0%	3.6%	3.6%	79.4%	5.2%	7.9%	6.4%	1.1%	67.3%	5.4%	7.2%	19.0%	1.1%
With 10% Petrol Tax															
Price subsidy 10%	82.0%	6.5%	8.2%	2.3%	1.1%	80.8%	6.5%	8.1%	3.5%	1.1%	75.9%	6.7%	7.8%	8.5%	1.2%
Price subsidy 25%	81.0%	6.8%	8.2%	2.9%	1.1%	79.1%	6.8%	8.1%	4.9%	1.1%	70.4%	7.0%	7.6%	13.8%	1.2%
Price subsidy 50%	78.0%	7.8%	8.1%	4.9%	1.2%	73.9%	7.9%	7.9%	9.0%	1.2%	59.9%	8.2%	7.2%	23.4%	1.3%
With 25% Petrol Tax															
Price subsidy 10%	74.1%	12.6%	8.4%	3.4%	1.5%	71.8%	12.6%	8.3%	5.8%	1.5%	61.3%	12.9%	8.0%	16.3%	1.5%
Price subsidy 25%	72.0%	13.4%	8.5%	4.7%	1.5%	68.3%	13.4%	8.3%	8.3%	1.5%	54.6%	13.8%	7.9%	22.1%	1.6%
Price subsidy 50%	65.9%	15.6%	8.6%	8.2%	1.7%	59.9%	15.8%	8.5%	14.1%	1.7%	46.9%	16.1%	8.3%	27.0%	1.8%
With 50% Petrol Tax															
Price subsidy 10%	50.3%	23.7%	12.9%	9.6%	3.4%	44.3%	23.7%	13.2%	15.2%	3.5%	30.7%	23.9%	14.3%	27.5%	3.7%
Price subsidy 25%	46.2%	24.1%	13.9%	12.1%	3.7%	40.7%	24.1%	14.1%	17.3%	3.8%	28.2%	24.2%	15.2%	28.5%	3.9%
Price subsidy 50%	40.5%	24.7%	15.7%	14.7%	4.4%	36.2%	24.7%	15.5%	19.1%	4.5%	24.5%	24.7%	16.8%	29.4%	4.6%

Tabela REF Price 42.00 (Advanced Biofuels) in 2040

	Low	Low	Low	Low	Low	Med	Med	Med	Med	Med	High	High	High	High	High
	UP	UG	UB	UA	UE	UP	UG	UB	UA	UE	UP	UG	UB	UA	UE
Reference	85.2%	4.5%	8.1%	1.3%	1.0%	84.8%	4.5%	8.1%	1.7%	1.0%	83.7%	4.6%	8.0%	2.6%	1.0%
Price subsidy 10%	85.0%	4.4%	8.1%	1.5%	1.0%	84.5%	4.5%	8.1%	2.0%	1.0%	83.0%	4.6%	8.0%	3.5%	1.0%
Price subsidy 25%	84.6%	4.5%	8.1%	1.9%	1.0%	83.7%	4.5%	8.0%	2.7%	1.0%	80.8%	4.6%	7.8%	5.7%	1.0%
Price subsidy 50%	83.1%	4.9%	8.1%	3.0%	1.0%	81.1%	4.9%	7.9%	5.0%	1.0%	71.7%	5.1%	7.4%	14.8%	1.1%
With 10% Petrol Tax															
Price subsidy 10%	82.6%	6.4%	8.2%	1.8%	1.1%	81.9%	6.4%	8.1%	2.5%	1.1%	79.5%	6.6%	8.0%	4.8%	1.2%
Price subsidy 25%	81.9%	6.5%	8.2%	2.3%	1.1%	80.7%	6.5%	8.1%	3.5%	1.1%	75.9%	6.7%	7.8%	8.5%	1.2%
Price subsidy 50%	79.5%	7.3%	8.1%	3.9%	1.2%	76.4%	7.4%	8.0%	7.0%	1.2%	63.7%	7.6%	7.3%	20.1%	1.3%
With 25% Petrol Tax															
Price subsidy 10%	75.4%	12.2%	8.4%	2.5%	1.4%	74.1%	12.3%	8.3%	3.8%	1.5%	68.7%	12.5%	8.1%	9.1%	1.5%
Price subsidy 25%	74.0%	12.6%	8.4%	3.4%	1.5%	71.8%	12.6%	8.3%	5.8%	1.5%	61.3%	12.9%	8.0%	16.3%	1.5%
Price subsidy 50%	68.8%	14.6%	8.5%	6.5%	1.6%	63.5%	14.7%	8.4%	11.7%	1.6%	49.5%	15.1%	8.1%	25.7%	1.7%
With 50% Petrol Tax															
Price subsidy 10%	54.5%	23.5%	12.1%	6.7%	3.3%	49.5%	23.4%	12.3%	11.4%	3.3%	34.6%	23.5%	13.3%	25.1%	3.5%
Price subsidy 25%	50.3%	23.7%	12.9%	9.6%	3.4%	44.3%	23.7%	13.2%	15.3%	3.5%	30.7%	23.9%	14.3%	27.5%	3.7%
Price subsidy 50%	42.5%	24.4%	15.0%	13.9%	4.1%	37.8%	24.5%	15.0%	18.5%	4.2%	25.9%	24.5%	16.2%	29.1%	4.3%