IIIEE Theses 2012:27

Microalgal biofuels

Some potential - many reservations

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Thesis for the fulfillment of the
Master of Science in Environmental Management and Policy
Lund, Sweden, September 2012

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ISSN 1401-9191

Acknowledgements

Once upon a time, in a far away land, where Nils flew on geese, forest trolls were scaring children and lush nature with berries and mushrooms was ruling, a magnificent building in the oldest town was erected with the monastic dedication without a single clue that, after an insurance company little refurbishment touch, it would become the center of the most marvelous human value creation.

To start with, I am thankful to myself for having created the necessary circumstances that brought me here, in Lund, in the right EMP batch, so that I could live this incredible experience, from LUVIT's portal first login to graduation. Apart from gaining some knowledge on sausage factories, non-recyclable porcelain beer bottles stoppers, T-shirt counter washing, LCA and eco-designed unable-to-pass-a-crash-test homemade cars, the best is the memories that were the funniest ever for which I would like to thank: my Kullen's cliff climbing green Viking teammates, the Korean teeth that learned the danger of Heineken bottles, Canadian's pragmatic methods for basic human needs, the Don Huisingh trophy which might be the best accomplishment of his designer (besides catching northern lights at the perfect moment), moustache growing diversity for prostate cancer awareness raising, my absolutely fantastic two roommates for the "family dinners", the open eyebrow, the incredible home biking attempts, the "illegal laundry", the note in our mailbox, "Nurzat's bed"…, my awesome, slightly rusty, faithful and incredibly good looking Mats that I loved so much for having the merit to have carried me all through the year on Lund's bike paths, Broci Balboa the kinky behavior of which changed my perception of broccoli, the tables which are as useful to share meals as to dance on, the coffee machines for survival remedy, the amazing road trip partners, the leprechaun, Nurzat's skype messages popping up during ppt presentation, Lars' movie nights, Bulgarian temper in reaction to Nation's party exclusion, all what temporary memory losses took away from me and many other things.

The IIIEE staff, professors, guest lecturers, "Mespomers", cleaning lady, the institute's dwarf and especially the 10:00 pm touring security guys are to be remembered! I would especially thank two people: Professor Philip Peck, my supervisor, to have had the patience to read my drafts, to always have provided me with valuable feedback and inspiring me with his endless enthusiasm and energy, and Vincent Toepoel for his useful insight, guidance and support all the way. This thesis, written in multiple places, blurred my perception of diurnal/nocturnal alternation while tremendously increased my specific knowledge, therefore I am very grateful to everyone that was involved in this process, from interviewees to privileged contacts and supportive people, along with my computer and Wi-Fi connections as both were the center of my world and the most precious thing during those months.

You guys, B17ers, are the best. You know it!

I have to apologize, but the narrative fun stops here, the rest of this paper was written in an attempt to be serious… for once, at least.

Abstract

Achieving climate policy goals and addressing the challenges of energy security requires very significant efforts from many private and public actors to bring immature technologies to competitiveness. Algae-based biofuel production is an emerging industrial sector that has great promise with regards to many sustainability aspects but faces many challenges in order to attain any meaningful market potential. This thesis seeks to provide deeper understanding of various aspects, such as technico-economical, political and social elements, that constrain the progression of algal biofuels based on a realistic view of this industry. The approach taken uses a theoretical framework for mapping industrial emergence that focuses on the early development phases of the industrial lifecycle and provides a market-based structure to the work.

The analysis discusses the policy framework structure and concerns as well as the obstacles related to issues of standardization obstacles. The attitude of incumbent industrial systems in the biofuel sector is investigated as there are both limiting forces and positive externalities emanating from competitors. The analysis examines the technological advancements that act as market push but are limited by many challenges that R&D still seeks to overcome, and further explores the deep need for public/private investment money and for new investors. Findings also underline the problematic issue of communication challenges that face the industry as it seeks to strategically build legitimacy and acceptance for both the investing world and the public. While the work highlights the nature of the economic predicament that algae biofuel currently faces, it also examines the role the already viable options, such as production regimes that focus on high-value products, which can be harnessed to offer learning opportunities and industrial experience for the algae sector. The concluding portions of the work reflect on those findings and on multiple possibilities that algae offer in terms of energy carriers for the transport sector.

Keywords: Biofuels, Microalgae, new technologies, industrial emergence, constraints, transport.

Executive Summary

Since the Industrial Revolution, transport has been a major driver for economic growth and wellbeing worldwide and demand for transportation fuel is expected to continue to grow as the sector continues to expand. As this sector mainly relies on fossil fuels, there are growing concerns over the environmental impacts along with energy security issues caused by oil dependence, namely exposure to high and volatile prices, vulnerability to supply, monopolistic abuse and serious health hazards.

The European Renewable Energy Directive on the promotion of the use of energy from renewable sources sets a target for 2020 of 10% fuel from any renewable sources. Increased concerns over first generation biofuels at the European Union level lead to a review of the biofuels strategy. While doubts have grown regarding the first generation, there is a much more favorable belief in second generation biofuels, also referred to as advanced biofuels. This is based on both their potential to mitigate GHG emissions and reduce competition for land-use between food vs fuel. Algae-based biofuels refer to those produced from microalgae biomass. Microalgae –those focused upon in this review- are the oldest living micro-organisms on earth. The real value of microalgae lies in their oil content and the possibility to convert it into biodiesel.

However, for now there is no truly commercial application of algae production that aims at biofuel production in Europe. A low level of maturity of algal biofuels production processes, very high capital, operational and maintenance costs make the revenues uncertain, investment unattractive, the scaling-up doubtful, and the time to market very long.

Although many very promising claims have been made over the past years, these have been grossly over-stated and have contributed to portray an unrealistic picture of this industry sector. Pursuant to issues of "confusion" arising from such, the first objective of this thesis is to deliver a more realistic image of what this industry sector. There are specific obstacles that are faced by algae-to-biofuels developers which are necessary to be first identified and understood in a more comprehensive manner. Thus the second objective of this thesis is to help understand the interaction between all factors in order to better reflect on the potential of overcoming the specific development constraints. For that purpose, the analysis seeks to be deepened to a reasonable level so that relevant conclusions and/or remarks can be made.

The overall aim of this work is to provide a much deeper understanding of various technico-economical, political and social elements that constrain the progression of algal biofuels in the European Union, based on an objective and realistic assessment. A literature review and semi-structured interviews with a wide range of informants (experts from governmental and intergovernmental bodies, independent consultants, researchers, scientists, industrial professionals, etc.) constituted the basis for data collection. From the literature review, a theoretical framework for mapping industrial emergence that focuses on the early development phases of the industrial lifecycle while having a market-based approach was identified. This was utilized as a structure for the work, situated the industry within the industrial emergence lifecycle and organized the collected data, findings and analysis. The findings are categorized as follows: (1) technico-economical constraints, (2) political constraints and (3) social constraints.

(1) Technico-economical constraints

There are many scientific and technical challenges to be addressed, at both research and scale up levels, in order to reach economic viability. Examples include the need to study the tens of thousands of algae species as well as their fatty acid profiles, and the need to develop standardized methodologies for profiling and testing. The possibility to use nutrient-rich waste

water effluents and CO_2-rich flue gases is very promising but adds to the challenges to reach consistency for a good outcome. Algae growing and harvesting is a new process, the complexity of which remains a challenge for the sector.

The sector also has a funding problem as there is a need for investment money with a long term perspective and a need to account for the sustainability gain from such a technology. However, this logic isn't shared by the investing world. In addition, visibility on the real costs of technologies is hindered by the fact that negative and positive externalities are properly not accounted for.

Importantly as one looks to the future, this study indicates that cost reduction can be achieved for the industry. Such can be achieved through learning opportunities providing experience as dictated by the learning curve theory. After a certain cost reduction, niche markets can help serve as "bridging markets" toward mass markets. While high-value products already break even, coordinated developments such as biorefineries and industrial integration carry economic viability potential, and all of those models represent learning opportunities and hence potential for cost reduction. Learning opportunities and cost reduction, reinforced by a strategic positioning, can also be attained by a deployment phase characterized by smaller plants, closer-to-the-market with flexible design.

Reaching economic viability can also be achieved through revenue diversification, which also faces challenges. With the price per carbon ton still being too low, carbon credits from using CO_2-rich flue gases are an avenue for increasing the profitability of the system although it cannot sustain a business model. As the glycerol – the diesel production by-product- market reached saturation, revenue diversification from it will be the case only once new applications will be found.

(2) Political constraints

There is a strong policy framework at the EU level that one can perceive as the major driver for ensuring a market and bring certainties for investors. Nevertheless, the indirect land use issue has come along with ambiguity and hence uncertainties. In addition, there is still no GHG default value for growing algae for fuel making. The GHG default value allows to account for GHG emission savings and to comply the European Renewable Energy Directive.

There is a European standard for biofuels that all biofuels need to comply with and there is a European diesel standard (EN 590) that allows the blending of up to 7% biodiesel. As the technical limit is much higher that 7%, the blending percentage limit needs to be revised and opposition needs to be tackled in order to gain consistency in reaching the 10% biofuels target. Ultimately any constraint on access to the market for biofuels has consequences on algal biofuels as there is no distinction of the fuel source within the pump station blending.

At the Member State level, biofuels may suffer from a lack of priority. Indeed, MS' behavior has been a bit disappointing so far in the eyes on the European Commission, highlighting a lack of awareness and generating red tape issues for the algae industry. In addition, Member States support schemes for biofuels are a mixture of tax exemptions and mandates, the economic assessment of which would certainly benefit the policy enforcement process.

(3) Social constraints

Aggressive claims that overstated the current potential and development of the algal sector contributed to depict an unrealistic picture of this industry, and also contributed to the unsuccessful experience of many start-ups. Those claims in addition to imprecise and unreliable scientific data based on extrapolation from laboratory results, have affected the credibility and trust of the industry.

The fierce opposition to crop-based biofuels (food crops), the weak communication around advanced biofuels, the terminology analogy and the low level of knowledge and understanding on all those issues are a set of communication constraints that raise the question of how to gain legitimacy and acceptance. This work proposes a communication strategy based on the sustainable criteria promotion as a leverage mean for first generation biofuels to become a bridging technology towards more sustainable advanced technologies.

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Abbreviations

AEBIOM	European Biomass Association
BtL	Biomass-to-liquid
CFPP	Cold-filter plugging point
CN	Cetane number
CO_2	Carbon dioxide
CP	Cloud point
CtL	Coal-to-liquid
EABA	European Algae Biomass Association
EBB	European Biodiesel Board
EU	European Union
ETS	Emissions Trading System
FAME	Fatty acid methyl esters
FFA	Free fatty acid
FP7	Seventh Framework Programme
GHG	Greenhouse gas
GtL	Gas-to-liquid
HEPA	Hydro-processed esters and fatty acid
IEA	International Energy Agency
ILUC	Indirect land use change
IPPC	Intergovernmental Panel on Climate Change
LCA	Life cycle analysis
LPG	Liquefied petroleum gas
M&O	Maintenance&Operations
Mtoe	Million tones oil equivalent
MS	Member States
NER	Net energy ratio
PBR	Photobioreactors
PR	Public relation
R&D	Research and Development
RD&D	Research, Development and Deployment
REAP	Renewable energy action plan
RED	Renewable Energy Directive
RET	Renewable energy technology
TIS	Technology innovation system
TG	Triglyceride
TAG	Triacylglycerol
U.S.	United States
WtL	Waste-to-liquid
WTO	World Trade Organization

1. Introduction

1.1 Background and problem definition

Since the Industrial Revolution, transport has been a major driver for economic growth and wellbeing worldwide. Demand for transportation fuel is expected to grow modestly in developed countries but dramatically in developing countries (European Expert Group on Future Transport Fuel, 2011).

Today's transportation fuel supply is dominated by oil and oil products i.e. about 60% of the petroleum products are used as transportation fuels (IEA, 2009). Transport accounts for 19% global energy use representing 23% of energy-related carbon dioxide (CO_2) emissions and the growth projections estimate a nearly 50% increase in transport energy use and CO_2 emissions by 2030 and more than 80% by 2050 (IEA, 2009).

According to the Intergovernmental Panel on Climate Change (IPCC), "carbon dioxide is the most important anthropogenic greenhouse gas" and the observed climate change is "very likely due to the observed increase in anthropogenic greenhouse gas concentrations" (IPCC, 2007). The 2009 United Nations Climate Change Conference in Copenhagen recognized the need of "deep cuts in global emissions" in order to "stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 2010).

Together with climate change, the environmental impacts of transport are raising some concerns (Steenberghen & López, 2008), along with energy security issues caused by oil dependence, namely exposure to high prices, vulnerability to supply, monopolistic abuse and serious health hazards (Rosillo-Calle & Walter, 2006). Such issues support the argument that an energy transition within the transportation sector is necessary.

There is a shift in government's energy planning strategies of many countries towards a better integration of energy-related environmental issues into sustainable development promotion (IEA, 2011b). In that regard, the European Union (EU) implemented a political commitment of 20% reduction of its greenhouse-gas emissions by 2020 compared to the 1990 levels, together with a target of 20% renewables of final energy demand for the same year. The Kyoto Protocol made it possible for carbon to be a tradable commodity, the EU has implemented the largest emissions trading scheme (ETS) in operation in order to achieve the GHG emissions reduction target. The EU ETS covers emitters from the energy and the industrial sector, representing around 45% of the energy-related CO_2 emissions for the region.

There are three major challenges that require an energy-innovation system to be fully explored. The first challenge is to reduce economic vulnerability arising from oil dependence, as well as balance of payments[1] and the foreign-policy liabilities that go with oil imports. The second challenge is the lack of modern energy services for two billion poor people worldwide who rely on unsafe, inefficient and dirty energy sources. The last challenge refers to the need to provide energy for humankind without disrupting the global climate (K. S. Gallagher, Holdren, & Sagar, 2006).

[1] The balance of payment compares the dollar difference of the amount of imports and exports made between one country and all other countries

The transportation sector has been the most difficult sector to reduce its CO_2 emission due to its steady growth and the technical and economic difficulties to switching from fossil fuels to alternatives. The increase in number has offset efficiency gains per vehicle that were made in the recent year and the European Expert group on transportation fuels advocates that "increased energy efficiency is not an alternative to oil substitution but a bridge to alternative fuels". (European Expert Group on Future Transport Fuel, 2011).

Alternatives to petroleum-based transportation fuels have been searched (Rosillo-Calle & Walter, 2006) and the current options are electricity/hydrogen, biofuels, synthetic fuels, methane/LPG. Compatibility with existing fuels and vehicle technologies offers a smoother market transition possibility, together with cost optimization and public acceptance. (European Expert Group on Future Transport Fuel, 2011).

Biofuels, are non-toxic, biodegradable and have lower GHG emissions when burned in combustion engines than incumbent fossil fuels (Lam & Lee, 2012). According to The Renewable Energy Directive "Biofuel means liquid or gaseous fuel for transport produced from biomass" (EC, 2009). Biofuels are essentially bioethanol and biodiesel. On the one hand, bioethanol is an alcohol-based fuel made by fermenting and distilling starch-, sugar- and lignocellulose-based materials, and, on the other hand, biodiesel is most typically a mixture of fatty acid alkyl monoesters produced through the chemical transesterification of triglycerides from vegetable oils and fats that have similar structures to petrodiesel (Cheng & Timilsina, 2011).

The European Renewable Energy Directive (RED), Directive 2009/28/EC of 23 April 2009 on the promotion of the use of energy from renewable sources[2], sets a target for 2020 of 10% fuel from renewable sources, which means any source provided that the biofuels comply with the sustainable criteria given in the Directive. The sustainable criteria mainly seeks to achieve a percentage of GHG emission reduction and forbids the use of certain types of land for cultivation. (EC, 2009).

First generation biofuels[3] are of three types namely ethanol, fatty acid methyl ester (FAME or biodiesel) and pure plant oil. Ethanol is mainly produced in Brazil from sugarcane and in the U.S. from corn. European production of bioethanol (mainly from potato, wheat and sugar beet) is marginal in comparison to biodiesel production, 70% of which comes from rapeseed oil and 30% from soybean oil, sunflower and palm oil (Havlík et al., 2011). Cultivation of oilseed for biofuel production is more profitable than for food production which diverts land use dynamics, may increases deforestation and land value while introducing price volatility for primary agricultural production (food vs fuel is not the only reason for food price increase), the demand of which is inelastic[4] (Rathmann, Szklo, & Schaeffer, 2010). Having diversification opportunities for final uses of crops grown increases the opportunity costs of tillable lands (Rathmann et al., 2010). It is claimed that there are heavy sustainability concerns for those biofuels from the first generation that arose in relation to competition with food and water consumption on the one hand, and economic concerns mainly due to reliance on feedstock prices and incentives on the other hand (Balat, 2009). However there is no consensus among scientists and politicians on the "food vs fuel" controversy, especially since there are many other factors involved in food price increase (WEC, 2010).

[2] The RED amends and subsequently repeals the Directives 2001/77/EC and 2003/30/EC,

[3] Because the literature isn't always consistent with the distinction between the different biofuel generations and the Renewable Energy Directive 2009/28/EC doesn't explicitly provide any definition, the terminology used in this paper is consistent with the one sued at the European level i.e. within the regulations and materials issued by the European Commissions.

[4] When a price change has no effect on the supply and demand of a good or service, it is considered inelastic

Increased concerns over first generation biofuels at the European Union level lead to a public consultation carried out by the Commission in 2006 and a review of the biofuels strategy by the end of that year. The consultation showed a much more favorable belief in second generation biofuels, also referred to as advanced biofuels, in their potential to mitigate GHG emissions, to widen the range of feedstock to be used, to enhance the quality of biofuels produced and to avoid the loopholes of first generation biofuels (EurActiv, 2006). In addition, the concern over indirect land-use change, lead to a public consultation[5] from the European Commission during autumn 2010 after which a report was issued (EC, 2012a). Indirect land use can reduce the GHG-benefits from using biofuels up to 70%; those benefits being one of the major goals of the European sustainability criteria (Vessia, 2012). For MS to account for the biofuel produced in respect to their national production targets those sustainability criteria are mandatory and impose a certain CO_2 emission reduction target as well as prohibit the use of certain types of land for feedstock cultivation

Second generation biofuels are bioethanol from lignocellulosic materials and biodiesel using various oils (Cheng & Timilsina, 2011). Feedstock for bioethanol includes agricultural residues (corn stover and straw from wheat and rice), grasses (switchgrass, Bermudagrass and Miscanthus), forestry and wood residues. Feedstock for biodiesel includes vegetable oil (e.g. from jatropha and algae), animal fat, and waste oils from restaurants and kitchens (Cheng & Timilsina, 2011). The generation of alcohol-based biofuels in this category results from the transformation of lignocelluloses (IFPénergiesnouvelles) but isn't fully developed yet (Havlík et al., 2011). It has to be noted that there isn't any official classification for biofuels that anyone could relate to and that there is no consensus among the literature. Second generation biofuels refers, in principle, to a new technological conversion pathway for lignocellulosic material, which then excludes transesterified oils from this category as transesterification is also the process used to produce biodiesel from the oil extracted from first generation feedstocks. However, the literature almost always classifies the oil mentioned above as second generation because they do not come from feedstocks that have the same land use concern as first generation biofuels. For this paper, in line with the literature, second generation biofuels for biodiesel production include those transesterified oils from non-food crop feedstocks, although it perpetuates a scientific inaccuracy.

Those second generation biofuels are supposed to reduce competition for land-use between food vs fuel. However, taking a life cycle analysis approach, there are some doubts that second generation biofuels perform better than first generation ones, as this very much depends on agricultural practices (Havlík et al., 2011). Additionally, although crops to make second generation biofuels can often be grown on marginal land unsuitable to conventional agriculture, the highest yields of non-food crops have been realized on fertile land better suited for food production and using water for irrigation and heavy fertilization, which makes them disappointing (Anonymous, 2009) (Lam & Lee, 2012). The main pathway for second generation bioenergy production is gasification, also referred to as biomass-to-liquid (BtL), which uses high temperatures, controlled levels of oxygen, chemical catalysts, etc. and requires large-sized facilities, big capital investments and, in the EU, support from the European Commission for its development (EurActiv, 2006). Additionally, even though major progresses have been achieved in developing lignocellulosic ethanol generation, the costs need to be further reduced for the commercial application of second generation ethanol technologies and for being economically competitive (Cheng & Timilsina, 2011).

[5] Public consultation target public authorities, Member States authorities, private organizations, industry associations, SMEs, citizens, consumer organizations and environmental organizations (EC, 2012a)

Algae-based biofuels[6] refer to those produced from heterotrophic (photosynthetic organisms) and autotrophic (which need carbon from sugar to grow) microalgae biomass (IFPénergiesnouvelles), yeast and fungus. Microalgae, the oldest living micro-organisms on earth, are very small aquatic plants that grow at an exponential rate (they can double their biomass in less than one day (Lam & Lee, 2012) .They are a versatile energy source as they can be used as biomass feedstock in biochemical[7] (fermentation) and thermochemical (pyrolysis, gasification and liquefaction) conversion pathways or be used specifically for their high oil content that can be extracted and upgraded into infrastructure compatible fuels (Davis, Aden, & Pienkos, 2011). Appendix A synthesizes in a graph most common energy sources that are possible to produce from algal biomass. However, in this paper 'algal biofuel' refers mainly to biodiesel obtained from the extracted oil conversion. It has to be noted that bioethanol production from the remaining starch and sugar, as well as biogas from the biomass left, can be further valorized to help improve the economics. The main reason is that for bioethanol production and even biogas production, macroalgae are more suitable as they usually have much higher starch, sugar, proteins and carbohydrate contents and barely any oil. The real value of microalgae lies in the oil content and the possibility to convert it into biodiesel.

Some microalgae strains can store CO_2 from photosynthesis as lipids[8] that can reach up to 30% of the dry matter content (IFPénergiesnouvelles) and have the potential for yields per unit of land used that are claimed to be hundreds or thousands of times higher than most oil plants[9] (Cheng & Timilsina, 2011). The process of making biofuel comprise several steps i.e. growth, harvest, extraction and conversion into the final product (B. J. Gallagher, 2011) as depicted in Figure 1 and simply require sunlight, CO_2, nutrients and water (according to the algae strain it can be salt water, brackish water or waste water). The CO_2 released during the biofuel combustion has previously been fixed from the CO_2 during the photosynthetic process; thus, this fuel is considered neutral (Gao, Gregor, Liang, Tang, & Tweed, 2012).

According to Person, the algae sector is about to expand rapidly but for high value products in low volumes (pharmaceuticals, chemicals, food & feed) rather than low value and high volume such as fuels because the current production cost levels for algal fuels remain far too high for the process to be profitable if fuel production is the key focus (Person, 2011).

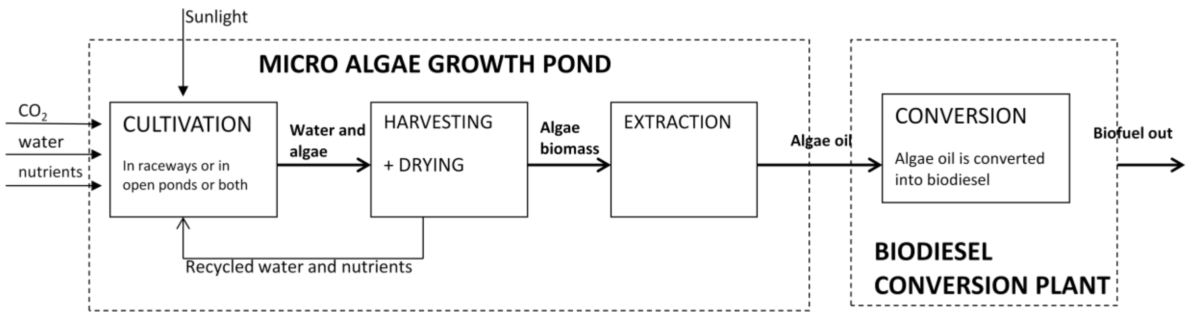


Figure 1: simplified algae oil production process

Source: (B. J. Gallagher, 2011)

[6] Algal biofuels are sometimes referred to as a third generation biofuels and although the distinction between first and second generations is consensual, any distinction between a second and third generation isn't clear.
[7] Microalgae do not content only oil but also carbohydrates (usually not cellulose) that can be used as substrate for fermentation (Lam & Lee, 2012).
[8] Microalgae are capable of fixing CO_2 from the atmosphere, flue gases or soluble carbonate and capture solar energy with an efficiency 10-50 times greater than terrestrial plants (Lam & Lee, 2012).
[9] The relevance of such claims is discussed later.

However, for now there is no truly commercial application of algae production that aims at biofuel production in Europe. Indeed, there are research projects mainly and also some demonstration and pilot projects running, with the objective of obtaining results within the next 4 to 6 years (personal communication with the Principal administrator of the DG Energy, European Commission). In terms of knowledge gaps, there is research conducted on the technology aspect as well as on feedstock i.e. the algae strains (strains with high oil yield and suitable for cultivation).

A low level of maturity of algal biofuels production processes, very high capital and O&M (Operations&Maintenance) costs (there are energy intensive processes such as extraction and dewatering (Bernard, 2008) make the revenues uncertain, investment unattractive, the scaling-up doubtful and the time to market very long (Person, 2011).

As such the economic viability has not been proved yet and there is a lot to do before reaching any further development stage. Although many very promising claims have been made over the past years, these have been grossly over-stated and have contributed to portray an unrealistic picture of this industry sector. A lot of confusion regarding "what the status really is" and "what the promise really may be" has arisen from this lack of clarity. Pursuant to the issues of "confusion", the first objective of this thesis is to deliver a more realistic image of what this industry sector is comprised of, what the status of the technological progress is, and what are the challenges to be overcome. A prime information source is to be from what experts state about it. This shall also encompass reflection on the consequences that over-optimistic claims, or misleading claims have on the industry.

As this industry seeks opportunities for its further deployment and commercialization, there are specific obstacles of various aspects that are faced by algae-to-biofuels developers which are necessary to be first identified and understood in a more comprehensive manner. The literature is rather limited to the techno-economical barriers that the fuel making technologies encounter and on the potential prospects for the future. Some research has been conducted on other aspects such as the thermodynamic feasibility and the legal incentives provided by the current policy framework but there is not much material to be found on social considerations, as well as literature on the interaction between all these aspects. Therefore, there is a lack of understanding on how all these aspects (techno-economical, political and social) interact at this early stage and hinder market development potential. Pursuant to this there appears to be value in investigating what paralyzes the algal biofuels sectors on various aspects and reflecting on their interaction, which is the approach taken in this paper.

Other clean energy technologies that have reached the wide diffusion stage e.g. wind energy, show that the deployment strategies that were developed encompass a wide range of cross-disciplinary measures that help overcome developmental barriers i.e. removing market barriers (securing investments through tools that develop assumptions on future markets), securing revenues, promoting positive externalities, adapting the grid infrastructure and removing policy and administrative barriers (see: http://www.wind-energy-the-facts.org/fr/part-i-technology/chapter-7-research-and-development/market-deployment-strategy-.html). This advocates for taking a broader approach than just focusing on the costs, which is always too high for new technologies that have just been researched. Thus the second objective of this thesis is to help understand the interaction between all factors in order to better reflect on the potential of overcoming the specific development constraints. For that purpose, the analysis seeks to be deepened to a reasonable level so that relevant conclusions and/or remarks can be made.

1.2. Aim

This thesis seeks to provide a comprehensive understanding of technico-economical, political and social elements that constrain the progression of algal biofuels in the European Union, based on an objective and realistic assessment of this industry.

For this thesis, the definition of constraints is based on the one from Verbruggen et al. i.e. as anything that prevents or hinders action, impedes progress or achievement in realizing potentials (Verbruggen et al., 2010) and is further enlarged to anything that is not existing yet and the presence of which would benefit the industrial emergence. In this thesis the progression of the sector aims at achieving the market potential.

Potential necessarily refers to something that hasn't been achieved yet, can develop and become actual. There are two elements that follow from that assertion: a time perspective -attributed by the gap between the present state and the future (potential) state- and a dynamic structure (Verbruggen et al., 2010). The former, according to Verbruggen et al., implies that every condition and action affects realization. Constraints are then necessarily sitting between the actual state and the potential state in an intentional or unintentional fashion.

Therefore it is reasonable to assume that the market potential could be achieved if the conditions are conducive for a full realization, which necessitates the identification of, and work to overcome the constraints. The market potential is defined as "the amount of renewable energy output expected to occur under forecast market conditions that are shaped by private economic agents and are regulated by public authorities" and is very dynamic as it depends on many factors such as what is available on the market, the policy measures, the technical progresses, etc. (Verbruggen et al., 2010). It has to be noted that the market potential is very restricted in comparison to the technical potential and even more restricted than the theoretical potential. The technical potential and the theoretical potential are respectively defined as the global bioenergy potential i.e. the total amount of energy produced by photosynthesis and as the potential that can be harnessed in practice (Schmidhuber, 2007).

1.3 Research question

In order to address the previously defined objectives, this thesis will attempt to answer the fundamental following question:

<u>How is the emergence of the algal biofuels industry currently constrained?</u>

In order to work with this high level question, the following tasks will be addressed:

- Review the algae based biofuels sector and its development, together with the policy background and the market infrastructure;
- Identify and delineate a theoretical framework to assess the emergence of this new industrial sector in order to provide a consistent structure for the work;
- Identify a set of key "aspects" that constraint the sector;
- Acquire information and primary data in order to perform the subsequent analysis;
- Describe and analyze this set of key constraints to progression towards deployment.

1.4 Methodology

1.4.1 Defining a topic to research

Following the fuel debate and the sustainability issues that alternatives try to address, biofuels are a very stimulating domain that I intended to research in order to both gain further specialized knowledge and contribute, to some extent, in its development. Having read some very promising articles on algae-based biofuels claiming that they were the "petroleum of the future", a natural interest grew from it. New technologies are fascinating in their potential to generate interest; especially in this quest for alternative to conventional fuels one become certainly more inclined to believe and have people believing in them. After a bit more research it became clear that this very nascent industry was given a lot of credit even though no industrial application was existing to date. The discrepancy between all published information and what seemed to be the reality, and the fact that this topic has not been widely researched made it interesting and a starting point to define a researchable focus area for this paper.

1.4.2 Literature review - building knowledge

The conduct of this work started with a review of online articles, dedicated websites and some quick research under "algae" and "biofuel" within online databases. In order to help understand the state-of-the-art of algae fuels a literature review was conducted in parallel to personal communications with a wide range of actors: essentially consultancy firms, private entities and research centers. A lot of material on algae, all things being relative, is now available, albeit there is a discrepancy between what is claimed about it and what really exists. This consisted in the first stumbling block of the process. An adapted focus area was found, taking this into account.

Next a more thorough and precise literature review also included the research for informants from a diverse panel of competencies (experts from governmental and intergovernmental bodies, industrial professionals, independent consultants, researchers, scientists, etc.) who could be interviewed and could deliver consistent primary data. The interviews helped understanding the reality of the industry and the most up-to-date trends, along with the contribution of the policy framework, the latest scientific research tendencies and the major constraints as the framework suggested them. In that regard personal communication with people, essentially over the phone and sometimes also combined with e-mail exchanges, was the most valuable source of information. Some document and reports were in some cases sent to me as interview follow-ups. The literature analysis can be broken down into three categories: (1) the policy context and statistics, (2) the general information describing the state-of-the-art, the technology and the progresses done, and (3) the critique of the algae based sector, the offering.

(1) The policy context and statistics category comprised:

- Documents from regulatory and governmental bodies, essentially reports from the IEA, European Directives and the U.S. Department of Energy, that provided the policy context, some energy policy analysis and useful statistics;
- Documents from public organizations such as AEBIOM and the EABA. Those documents, as well as the one from the previous bullet point (except the Directive and IEA reports) were sent by interviewees as follow-up and hence represented a very valuable source of information;
- Documents issued by international task forces such as the World Energy Council, a think tank, namely Notre Europe;

- Platform, and indirect relation e.g. EurActiv. They enable to have some insights on the latest news and trends such as upcoming regulations at the European level.

(2) The state-of-the-art for biofuels, algal biofuels and algae growing, as well as the information on the technology and the progresses were based on:

- A book edited in the framework of the French GreenStars project. The latter includes all the actors involved in algae (micro- and macro-algae) in France within a large network;
- Academic journals and articles available from on-line databases e.g. SciVerse Hub and google scholar, providing a solid base of technical and scientific elements as well as diverse studies such as the available economic feasibility and thermodynamic studies. In addition to searchs directly related to "microalgae biofuels", "first generation biofuels" in addition to other "new technologies", "market development for innovation" and so forth were searched in order to expand the spectrum of knowledge offering the possibility to thereby deepen the analysis;
- Websites in direct relation to the topic such as Oilgae, IFP Energies Nouvelles and European Biofuels Technology, which served as sources of information at the beginning and helped find contacts for interviews;

(3) The documents providing a critical standpoint and a realistic view on concepts and offering included:

- Reports from research institutions and consortia such as the Sustainable Energy Ireland, Oilgae, and from private organizations (NNFCC, SkyNRG), consultancy firms included (Accenture);
- Reports of projects developed within the EU 7th framework programmes such as the AquaFUELs, BIOFAT and All-gas project, sent by interviewees as follow-up to interviews;
- Technical and/or general presentations from experts and consultants (TOEPS, CSIRO), the presentations from a workshop on LCA of algal biofuels under the supervision of the European Commission in 2012 and various other presentation such as the BioAlgaeSorb project;

Last but not least, literature that has been reviewed relating to the search for a framework that could be used to organize the data collection and analysis in a comprehensive and consistent way.

1.4.3 Personal communications – acquiring primary data

As mentioned above, the literature review was followed by extensive interviews with a wide range of actors, the precise list of which is available in the appendices. The interviews intended to grasp the insight of a large expertise spectrum. Private companies that are producing microalgae (not for fuel purposes because it doesn't exist yet) were most of the time not eager to divulge any information as they are working under confidential obligations. Therefore they are missing within the panel of informants. However, the latter include experts and researchers involved in microalgae cultivation demonstration projects (targeting biofuel production) and are in the end representative of what is being done at the moment in terms of production. Independent consultants, a European Commission principal administrator and scientists completed the interviewing objective in terms of gathering a diversity of expertise.

In concrete terms, although a question template (in appendix B) has been prepared and sent prior to all interviews, they were loosely conducted in order to let informants follow the structure that best suited them to divulge information. The questions were designed according to the area of expertise of each interviewee and had to be restructured to match deeper understanding needs. Eight interviews were conducted and no more informants were searched for as soon as the amount of new information gain per interview started to be limited. Indeed, except for some very marginal and specific aspects (discussed in the next chapter), after a certain amount of interviews the answers were getting similar and homogeneous. Interviews were also the occasion to ask whether the questions were consistent in order to assure that they reflected a good understanding of the subject under study. A positive feedback on the latter confirmed that most issues had been raised and offered a good picture of what was needed to include in the work.

In the end, most of them lasted fifty minutes and two of them were follow-up discussions after the interviewees had filled the question template and sent it back. Most interviews were transcribed and sent back to the interviewee for cross-checking and for them to add any useful comment that they judged necessary.

1.4.4 Theoretical and analytical framework

1.4.4.1 Initial approach

A point of departure for this part of the work consisted in searching for analysis of market development of new technologies dedicated to the energy market, which (1) could help find similarities, (2) could help build connections with the topic under study, and (3) also could help design an analytical structure to consistently organize and further analyze the collected data. Indeed, the first focus was dedicated to energy related new technologies market development. Interestingly, "energy" in most studies relates to both electricity generation and fuel production, although electricity has been much more researched than fuels, hence biofuels.

During this first part, two sources have been examined, namely a framework on the barriers to renewable energy penetration (Painuly, 2001) and a list of barriers for new energy technologies market development (IEA, 2003). Painuly developed a framework for RETs (Renewable Energy Technology) which is based on literature survey, site visits and interaction with stakeholders. The IEA listed common market barriers in the perspective of creating market opportunities for new energy technologies.

The following rationale pertains to specifics of the industry under focus: first, algal biofuels are intrinsically different from conventional fuels and crop-based biofuels which means that even though they deliver the same service, their respective development is determined by different constraints (e.g. need to have growing infrastructure, much less land use issues hence reliance on feedstock prices, etc.); second, the literature on energy market barriers is essentially focused on electricity rather than fuels which requires one to select them according to their relevance, and finally, one major characteristics of the algal biofuels industry sector is its recent emergence.

1.4.4.2 Latest approach

Consequently a second approach followed the need to explore other possibilities for structuring the findings and analysis of collected data and information. Frameworks addressing new technologies development and industrial emergence were investigates. A framework developed by Phaal et al. was chosen. Indeed, Phaal et al. created a framework for mapping industrial emergence. The latter emerged by applying the roadmapping concepts to a review of many historical industrial emergence studies and is said to particularly suit technology-intensive sectors. (Phaal et al., 2011). This framework helps depict a set of factors in a time perspective and is therefore used in this thesis for a double objective: to organize collected data, information and analysis in a more comprehensive manner, on the one hand, and to elaborate the mapping of the algal biofuel industry, on the other hand. This section aims at explaining the framework and the how it is being used in this analysis.

The authors, Phaal et al., define the objective of roadmapping industrial emergence as being to understand how and by what emergence is being driven in order to inform private and public decision –making processes. This particular framework, used by several authors for a variety of industries, requires an adaptation to the sector under focus and offers the possibility to situate the analysis of influencing factors in an evolutionary timeframe perspective.

Industrial emergence is not a linear process. Indeed according to Phaal et al., early phases are characterized by a high uncertainty, the presence of different groups at different phases, the need for organizational structures and competitive strategies. In this framework, the emergence process is being broken-down in phases in accordance with most "lifecycle models" proposed in the literature and is considered both as a complex system and an evolutionary process. The approach taken borrows from biological sciences in the sense that it considers industrial evolution as a result from complex and unpredictable interactions involved in a dynamic process of competitive selection and strategy adaptation. Those interactions lead to coherent, autonomous and self-organized structures in a context where existing technologies and institutions provide the basis and configuration for the modifications the novel technologies are going to bring along. Progression through the different phases is highly contextual and industry-specific. In addition, it is enabled by certain factors e.g. interaction between market side and technological side, and hindered by barriers that need to be reduced or removed. (Phaal et al., 2011).

An industrial roadmapping framework is a dynamic structured approach that allows "the decisions, activities and achievements of the key actors to be depicted (organizations and individuals), including both markets and technological events and their interactions, and how businesses succeed or fail over time." (Phaal et al., 2011). The framework authors define roadmaps as "dynamic systems frameworks" composed of two axes imputable to industrial emergence theory and a mapping element. All of them are being explained in the following paragraphs and consist in:

1) Time on the horizontal axis, from the historical events to the future one, representing the industrial lifecycle.
2) A set of themes or perspectives on the vertical axis that are relevant along the entire timeframe.

First, the horizontal axis was developed on the basis of most industry lifecycle available across the literature. Some elements were added to that approach, such as a focus on early stages associated to a focus on the transitions between the phases. The author explains that "transitions are of particular interest, as they are associated with significant shifts in perspective and stakeholder interests, but are rarely emphasized in industry lifecycle models". Because the algae biofuels industry is nascent, the fact that this framework breaks down clearly all early phases makes it very applicable. Although phases and transitions do not have clear boundaries, the categories proposed by Phaal et al. in his framework are:

1- *Precursor phase (or science phase)*: is a science dominated phase starting at the premise of any scientific phenomenon demonstration stimulating hope for potential, interest and investment.
2- *Science-technology transition (S-T)*: at this stage, the scientific phenomenon demonstrates feasibility to be integrated in a functional technology system.

3- *Embryonic phase (or technology phase)*: is a technology dominated phase that seeks to improve the reliability and performance so that the technology can be demonstrated in a market-specific environment.
4- *Technology-application transition (T-A)*: the improvements are to be developed to a point where commercial potential can be demonstrated through revenue generation.
5- *Nurture phase (or application phase)*: is an application dominated phase focused on improving price and performance to demonstrate business potential
6- *Application-market transition (A-M)*: the demonstrated price-performance potential is translated into market potential
7- *Growth phase (or market phase)*: is a market dominated phase involving marketing, commercial and business development.
8- *Maturity phase*: refining established applications, production processes and business models.
9- *Decline/renewal phase*: the industry either declines or renews itself by repeating the above phases.

These phases correspond to the following questions: "where do we want to go?" "Where are we now?" "How do we get there?"

Visually this would look like Figure 2. Using this framework for an industry that is nascent first requires situating it in this timeframe (naturally implying that the subsequent phases are not going to be explored) with the help of the given phase and transitions description.

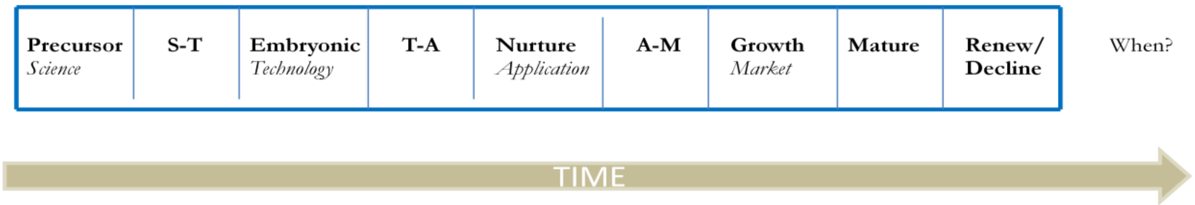


Figure 2: the different phases and transition visually represented.

Source: (Phaal et al., 2011)

Second, the vertical axis comprises the themes organized in broad categories, the sub-sections of which necessitate being adapted to the industry focused on. They are as follows:

1- *Value context*: this theme provides the "industrial landscape" for value creation and includes market trends and drivers, industrial dynamics such as competition, regulation and standards, together with customer needs. As Phaal puts it: "collectively these factors (market demand dynamics) drive the evolution of the industry, in conjunction with supply-side dynamics." It roughly represents the market pull side.
2- *Value capture*: all mechanisms and processes used to capture value e.g. business models, strategies, applications such as marketing, distribution, operations and supply.
3- *Value creation*: it includes all competences and capabilities to generate a product or a service including design, development, research, resources (financial, human and technical), management and relationships. As Phaal puts it: "collectively these factors (capability supply dynamics) drive the evolution of the industry, in conjunction with demand side dynamics." It roughly represents the technology push side.

The value-based perspectives correspond to the following questions: “Why do we need to act?” “What should we do?” “How should we do it?” As mentioned earlier those categories, depicted in Figure 3, are valid along the entire timeframe and are used in this paper for their relevance in organizing the potential constraints in a complete, coherent and market-oriented manner. The sub-categories were determined according to what was found relevant for the industry sector under focus and are the support for the entire analysis section.

Finally, when both axes are brought together, the framework emerges in its roadmapping structure as visualized in Figure 4. The content of this “canvas” is supposed to be filled with notable events and milestones from each category that took place at a certain phase, so that they can be depicted in this dynamic approach. Mapping is the last step of this thesis according to the analysis section.

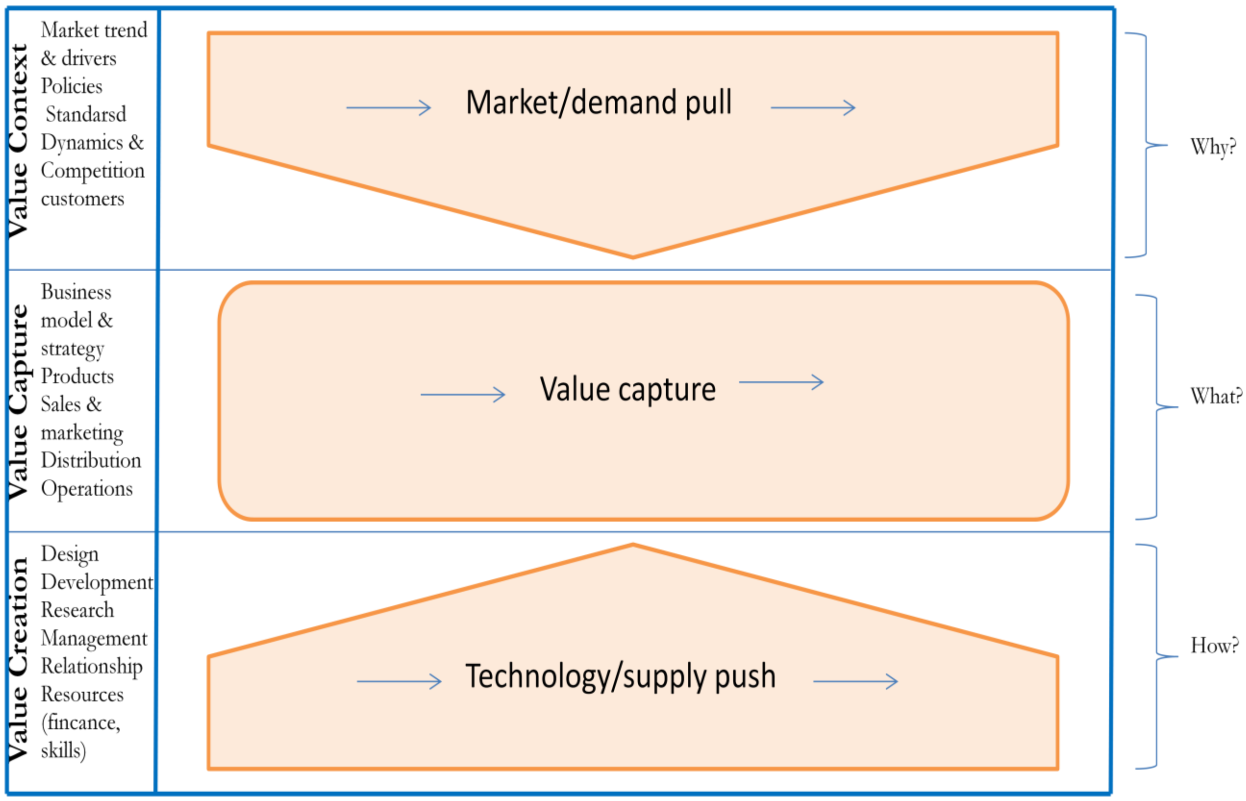


Figure 3: the different categories of the framework visually represented.

Source: (Phaal et al., 2011)

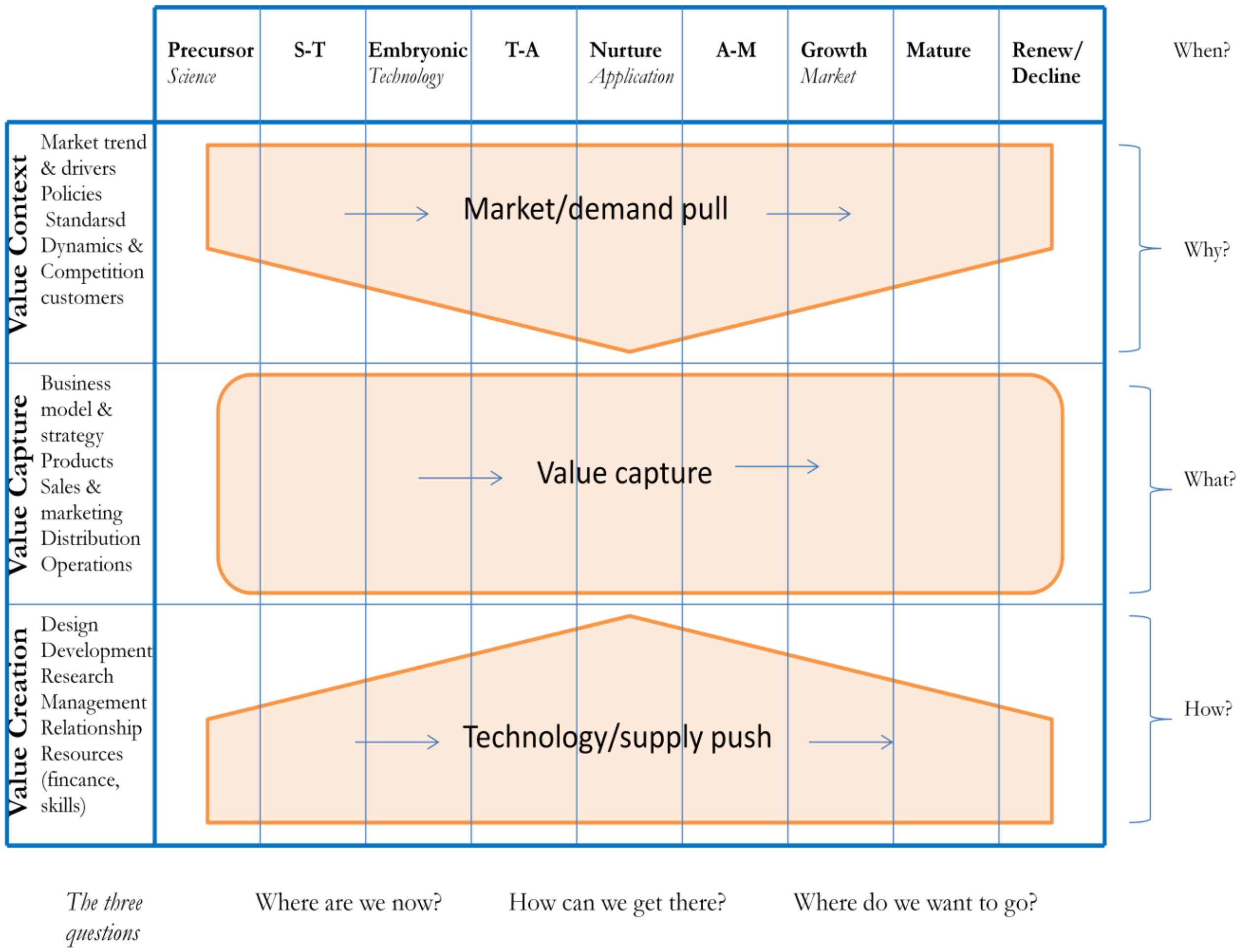


Figure 4: mapping industrial emergence.

Source: (Phaal et al., 2011)

1.5 Scope and limitations:

The element under study is alternative drop-in fuels[10] for transportation from autotrophic micro-algae. Heterotrophic micro-algae are not specifically included into the scope but this study could apply to them. Macro-algae is excluded, essentially because the technologies used are different and because they are not cultivated for their oil content and hence, are not used for making the same fuels.

This thesis focuses on the development of algal biofuels within Europe, in order to restrict the geographical scope and because European countries –at least the EU members- share a similar legal basis. It is acknowledged that the U.S is the leader in the field and the country that everyone is looking at, which makes incorporating the latest developments from the other side of the Atlantic very attractive, especially at this early technological development stage. However this would not make this research attainable. Nevertheless, this further implies that the fallout of U.S

[10] Drop-in fuels are completely interchangeable and compatible substitute for conventional fuels that do not require any adaptation of existing engine fuel system or fuel distribution network. They can be used in pure form or as blended in any amount with other conventional fuels.

leadership over the entire industry on the European side of the market cannot be ignored when having consequences. This is taken into account, when relevant.

The analytical scope is necessarily concentrated on the earliest technology development phases. Taking as similar industrial emergence progression approach as detailed in the previous section and depicted in Figure 5, algae biofuels are situated at the *embryonic/T-A* phase. This means that the analytical framework will be used according to the limited development and available empirical data pertaining to this industrial sector.

It isn't implied that the diffusion of algal biofuels will happen in the near future i.e. the entry in the *growth phase*, however, the possibility to have algal biofuels within the mix of biofuels in the coming decades is assumed. The following are excluded from that scope: macro-algae cultivated at sea; environmental, social and sustainability criteria; and, international trade.

The sustainability aspect of algal biofuels is acknowledged to be extremely important in order to assure that this alternative fuel isn't more impacting than what it is supposed to replace. However, it is not part of this thesis. What is included, on the other hand, is the concern to built business models for algae-based biofuels that are not only viable on the economic perspective but also on the sustainability perspective.

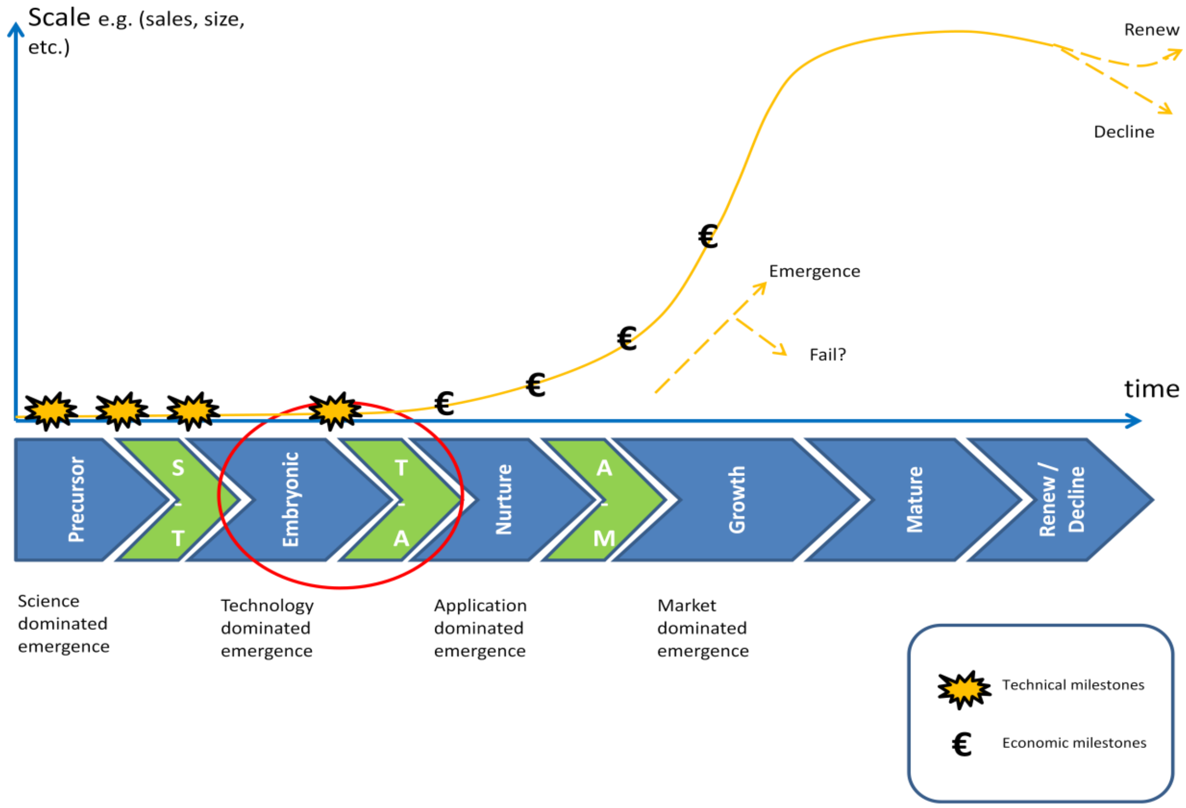


Figure 5: phases, transitions, milestones, trajectories of industrial emergence.

Source: (Phaal et al., 2011)

Restricted access to companies and start-ups, the number of which is also limited, resulted in a limited number of interviews from businesses. Actually, many organizations and essentially private ones are working under confidentiality obligations and do not wish to divulge any information. This limits the amount of knowledge that can be shared and used for research.

Additionally, there is barely any reliable quantitative data existing and obtaining it would be too difficult and subject to confidentiality obligations, so the analysis had to be qualitative.

Finally, too few reliable quantitative data limits any relevant in-depth analysis of technical and economic aspects and this is one of the major reasons why this thesis is investigating the dynamics shaping the algal biofuel production sector on all aspects i.e. technico-economical, political and social. This thesis aims at providing a macro-analysis of the algal biofuels development status and avoids too detailed analysis either on specific geographic cases or on the technology components that R&D is developing.

1.6 Intended audience

This research employs a plurisectorial approach to examine the algae market development that different actors could find useful to understand the dynamics driving the industry in its future deployment. This thesis doesn't target experts involved in scientific research for the main reason that the scientific content is rather limited and restricted to understanding purposes. However it can be useful for experts to widen their perspective on other fields outside their zone of expertise. The targeted audience is mainly non-experts searching for a reliable source of information. Indeed the approach taken can help decision-makers from public and private organizations to be reasonably aware of the future potentials to be harnessed and thereby participate in developing the legitimacy for this technology. Journalists can also find a good source of information to base short articles and green organizations can find strategic means to elaborate communication. Investors attracted by promising claims can benefit from this insight into all the challenges that they are to be aware of. Finally, this paper intends to help the identification of unexplored research areas for academics and the understanding of any third party interested in knowing more about algae based biofuels.

1.7 Thesis disposition

The main block first starts with a review of biofuel in general and of algae in a more specific manner. Indeed, how algae is processed to make biofuels is necessary to understand in order to fully grasp the concepts that are developed, and essentially the technical and economical intricacies. This state-of-the-art does not aim to provide a comprehensive detailed description of all the knowledge that exists about algae, which would be futile to attempt, but briefly provides the necessary background for a good understanding.

Then follows the analysis section based on the information obtained through the interviews and collected literature review. Any data that has not been provided during the interviews is clearly identified by its reference while the interview data are not associated with any interviewee in particular. This eases the reading process and has also been asked by some interviewees themselves. The analysis section therefore compiles the findings and the subsequent conclusions that can be drawn from them and finishes with the industrial mapping according to the used structural tool i.e. Phaal's roadmapping of industrial emergence framework.

The penultimate section is a discussion one that opens up and reflects on the major outcomes and finally, a conclusion section synthesizes the most important statements.

2. Biofuels, Algae and algal biofuels – state-of-the-art

2.1 Biofuels

2.1.1 What are they?

In 2007, biofuels (bioethanol and biodiesel) accounted for 1.5% of the total road related fuel consumption (over 34 Mtoe in 2007 and around 40 Mtoe in 2010) and with a steady growth, they are expected to account for about 4-5% by 2030 (based on estimates from the IEA) (WEC, 2010). The IEA states that "biofuels can provide up to 27% of world transportation by 2050" (IEA, 2011c).

"Biodiesel" is an alternative fuel for diesel engines. It has been defined as monoalkyl esters of long fatty acids chains produced from vegetable oils[11] (e.g. coconut oil, palm oil, rapeseed oil, soybean oil, etc.), recycled cooking greases, or animal fat that consists of triglycerides. Triglycerides are glycerides derived from the combination of three fatty acids (see Figure 7). Biodiesel is obtained from the triglycerides by transesterification with methanol. Actually the use of vegetable oils was first used when the inventor of the diesel engine itself, Rudolf Diesel, first ran his compression ignition engine with peanut oil in the late 19th century. The main component of biodiesel is fatty acid methyl esters (FAME) (see Figure 6). Biodiesel production and consumption is the highest in Europe, especially since a reform of the Common Agricultural Policy (providing mainly price support) and high fuel taxes providing indirect subsidies i.e. tax exemption, contributed to develop this sector. (Balat, 2009).

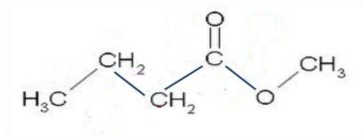


Figure 6: a FAME.

Source: Queen's University school of chemistry website.

"Bioethanol" has several "end-uses" namely beverages, solvents for industrial applications and fuel. The latter can be used as pure (as a substitute for petrol) or in blends with petrol at various percentages[12] and can be produced from any sugar-, starch-, and lignocellulose-based materials, which represent currently more than 30 feedstocks although the main feedstock are sugar cane or molasses (Brazil) and starch crop e.g. maize in the U.S. (Rosillo-Calle & Walter, 2006).

2.1.2. Technical considerations

There are consequences in replacing regular fuels with biofuels because they have different combustion characteristics and major concerns are related to engine performance, durability and fuel storage. For instance, biodiesel tends to have a higher cloud point (temperature at which wax forms a cloudy appearance), a higher solubility and a lower flash point (temperature at which it can vaporize and form an ignitable mixture in the air) than regular diesel. Both bioethanol and biodiesel have better combustion efficiencies than mineral fuels but lower power outputs, although that really depends on the engine. In the end using biodiesel and bioethanol have benefits and drawbacks (the former and latter depend on the blending percentages). Some drawbacks can be compensated for with engine settings e.g. a lower energy content, while others are trickier to tackle e.g. phase separation. In direct relation to this, there is a real need for technical standardization to spur biofuels in the global arena. Standards are needed because the variety of vegetable oils and animal fats that can be used to make biodiesel for instance introduce

[11] It has to be noted that vegetable oils and biodiesel are not hydrocarbons because there is an oxygen atom present in their structure while petro-diesel (and even gasoline) are only carbon chains composed of carbon and hydrogen atoms

[12] Ethanol is used as an "oxygenate" as it contains oxygen in its molecular structure, which increase the octane, extend the petrol supply and enhance the engine's operation.

a variability in fuel characteristics and hence in quality. Sustainability criteria standardization is also important in the case of international trade development. Low-level blends e.g. 10% ethanol in gasoline and 20% biodiesel in regular diesel[13], generally do not require engine modification, although not all engine manufacturers cover this in their warranties. (WEC, 2010).

Specifically for biodiesel, the oil that it is made from has a great influence on the biodiesel specification, because each fat/oil has a specific type of fatty acid chains, with a specific length i.e. number of carbon atoms. According to Pinzi, the fatty acid composition influences the conversion rate of fatty acid methyl esters (FAME) during the transesterification process. The following chemical characteristics determined by the fatty acid composition will influence the fuel specifications (there isn't an exhaustive list):

1. Cetane number[14] (CN): biodiesel tend to have higher CN values, which means better engine performance (engine run smoothly and are less noisy) and less emissions. High level of unsaturation[15] usually comes with lower CN;
2. Viscosity: high viscosity hinders the injection and atomization processes. The transesterification process helps reduce the molecular weight of glycerides, hence reduces the viscosity and increases volatility so that they are closer to diesel fuels. Glycerides are any of various esters formed when glycerol reacts with fatty acid; fatty acids can react with one, two, or all three of the hydroxyl groups of the glycerol, resulting in mono-, di-, and triglycerides, respectively (see Figure 7).

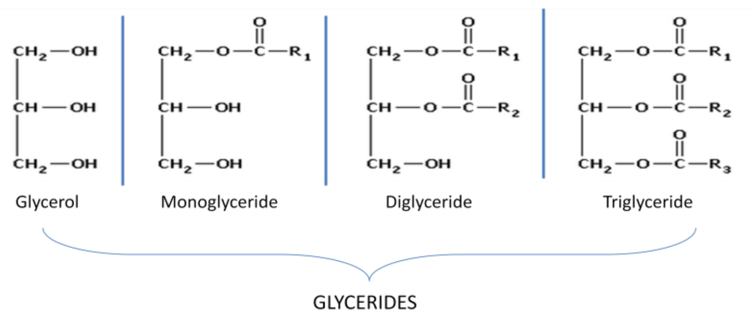


Figure 7: glycerides

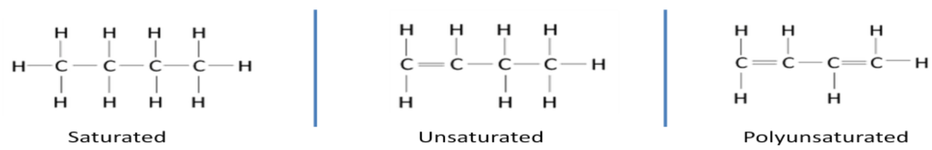
Source : azaquar.com

3. Oxidative stability: biodiesel coming from high unsaturated sources may oxidize more rapidly than conventional diesel and can affect engine operability through degradation. In that regard, the European biodiesel standard EN 14214 excludes several oil sources from potentially interesting crops such as sunflower and non-edible low cost crops.
4. Cold-flow properties i.e. cloud point (CP), pour point (PP), and cold-filter plugging point (CFPP): they represent the capacity to be used at low temperatures. Biodiesel has higher CP and PP that several options such as adding additives can remedy by modifying the chemical composition;
5. Gross and net calorific value: this indicates the suitability of fatty compounds. FAME has lower heating value because of a higher oxygen content which requires an increasing

[13] Ethanol can be blended with diesel to make "e-diesel" (WEC, 2010)

[14] The CN gives a measurement of the combustion quality during ignition; a low CN tend to generate incomplete combustion.

[15] In organic chemistry, a carbon atom can bond with four elements in case of four single bonds, three elements if there is one double bond with one element and two other single ones, and so forth. Unsaturated means that the carbon structure has a double or triple bond and hence saturated refers to the inexistence of any double bond, triple bond or ring structure. In the case of no bonding, each carbon is attached to two hydrogen atoms (except the ones at the end of the chains) and two other carbons to maintain a chain structure as depicted bellow (source: Studieblue.com, online chemistry material) :



injection of volume. This value isn't included in most standards but is in the European EN 14213 for FAME;
6. The mono-, di- and triglycerides (TG) or triacylglycerols (TAG) content: there are standardized limits for those components set within the EN 14214 because they can cause deposits in injector nozzles, pistons and valves.
7. The free fatty acid (FFA): this is a problem because during regular alkaline transesterification, the alkaline catalyst reacts with the FFA to generate soap, hence affecting the biodiesel yield, increasing the viscosity but leading to gel formation, etc. This requires a pre-treatment with an acid catalyst.

Pinzi concludes that because the requirements between the low-temperatures, the oxidative stability, the emissions and the CN are antagonistic, no feedstock has the perfect fatty acid profile, although some have a better profile, ideally a high percentage of monounsaturated fatty acids, a minimum amount of polyunsaturated acids along with a controlled saturated acid content, and meet the different EU standard, in particular the EN 14214 (for the U.S. the equivalent is the ASTM D 6751-02). Changing the profile characteristics is possible but requires extra steps, hence imputable costs. Finally, the author pinpoints that biodiesel performance tests lack standardized methodology that make comparisons difficult. (Pinzi et al., 2009).

Concerning biofuels from microalgae, determining a fatty acid profile is an emerging field, the specifics of which has to deal with a multitude of different species spread over several taxonomic groups (Lang, Hodac, Friedl, & Feussner, 2011). The stake is to evaluate the acceptability of micro-algal biodiesel in regard to the existing standards i.e. the European EN standards (the U.S. equivalent being the ASTM standard). The current biodiesel standards have been established for plant-derived fatty acids, although microalgae contain a much bigger variety of them (Woo et al., 2012). In addition to that, according to Woo et al., microalgal fatty acid diversity is affected by the culture conditions, which remains an extra step to evaluate.

2.1.3 Sustainability issues

It is claimed that there are heavy sustainability concerns for those biofuels from the first generation that arose in relation to competition with food and water consumption on the one hand, and economic concerns mainly due to reliance on feedstock prices and incentives on the other hand (Balat, 2009). However, no consensus exists within the scientific and political world on "food vs fuel" as there are many other factors involved in food price increase (WEC, 2010). Indeed, according to Rathmann et al. some advocates that there is no proven competition for land use between food and fuel essentially because of (1) increased agricultural productivity, (2) use of marginal lands and availability of land and (3) the promising development of cellulosic ethanol from crop residues and waste products. In addition, the agricultural market has always been tied to the energy market and with biofuel production the latter now creates a demand for the former and thus creates a "lower limit for agricultural prices" (Schmidhuber, 2007). Schmidhuber further advocates that rising demand for biofuel feedstocks would drive up their prices and, hence limit their use, thereby generating in the long-run a "ceiling price effect" i.e. agricultural feedstock prices will remain low enough to keep biofuels in the market at a competitive price in relation to petroleum prices. This also implies that in the case of rising prices at an uncompetitive level for crop-based biofuels to be maintained in the market, they would no longer be produced. Nevertheless, this is certainly a long-term effect and short-term price increase is a reality although the ceiling price effect stipulates that it is not an open-ended increase. Some, especially farmers, may benefit from higher prices for their production and/or produce their own fuel (WEC, 2010), but the impacts are not going to be uniform which poses food security problems when the poor would be hit harder as they would suffer from a concomitant food and energy price increase (Schmidhuber, 2007). Crop-based biodiesel, of which 80% of production costs are due to feedstock, is also more expensive to produce than conventional diesel and wouldn't be competitive without any tax incentives and exemptions (Demirbas, 2009a). Even though crop-based biofuels are not the only reason for increased food prices, there are tighter interconnections between the food and energy markets, which can have detrimental consequences for poor people even in developed countries (Keyzer, 2008) and those arguments do not deny a possible competition at least in the short run until technology and agriculture practices develop. Finally, biofuels production becomes a human right issue when it "endangers food security or displaces local populations from the land they depend on for their daily subsistence" and when it "destroys ecosystems or natural resources that are critical to the health and subsistence of people" (Keyzer, 2008; Tait, 2011).

2.2 Algal Biofuels

2.2.1 Microalgae

Microalgae encompass a wide range of species spread in a heterogeneous way along the tree of life given their long history of evolutionary adaptation (Leite & Hallenbeck, 2012). There are at least over 30,000 or 40,000 known species of microalgae –it depends on the literature- and there might be as high as 10,000,000 species (Bruton, 2009; IEA, 2011a). The research task is to select the ones that can have commercial relevance, that have preferable composition, are easily cultivated and so forth (Bruton, 2009). The term "algae" is therefore grouping organisms with an incredible variety of morphologic and physiologic types, as well as metabolism types (i.e. heterotrophic, autotrophic or both) that contain lipids, sugar and proteins in variable proportions. Most species develop in aquatic habitats; either fresh, saline or brackish waters but some are also found in rocks and soil, moist or dry environment. (Leite & Hallenbeck, 2012).

Autotrophic algae species, which represent most of them, are capable of capturing sunlight and carrying out photosynthesis to provide the energy necessary to reduce the carbon compounds by fixing CO_2 and the formation of sugars and lipids. However, it has to be noted that each species has its own specific capacity for uptake and utilization of organic compounds, which has some importance when choosing an algae strain for fuel making purposes. The dependence of photosynthetic organisms on sunlight has them store energy-rich reserve compounds such as fatty acids to avoid starvation during shade or night time. Fatty acids are a hydrocarbon chain of different lengths that can be converted into biodiesel. (Leite & Hallenbeck, 2012). This lipid content has been proved to be augmented when algae are stressed. Indeed, lipid production is not a natural process but is experienced when algae face a stress such as nitrogen deficit. However, after a period of stress the entire metabolism is dedicated to return to the pre-stress period with the help of enzymatic activities which also occurs rapidly after cell death and tends to release free fatty acids. This has major consequences on the chemical quality preservation to obtain a higher biofuel yield. (Bruton, 2009). Finding the right algae strain is then as important as developing the right process to optimize its oil production.

2.2.2 Microalgae cultivation and lipids conversion to biofuel

Algae can be grown either in closed photo-bioreactors (PBR) or in open ponds, also called raceways. Open ponds are simple tanks or natural large earthen-bank ponds with water and nutrients in which algae grow in suspension. There are natural gas exchanges with the atmosphere and lighting is natural. Raceways are an optimized open system to enhance productivity with shallow depth and with an elliptical shape which requires mechanical mixing (avoid settlement and increase gas exchange). PBRs are closed systems in which algae also grow in suspension in water circulated by pumps with nutrients and either natural or artificial lighting. Nutrients and gas levels are constantly monitored and growth conditions are kept under control. The main advantages are a higher productivity, less contamination, efficient CO_2 capture, but this comes with disadvantages such as potential fouling, and hence the need for maintaining a turbulent flow, the need for cleaning (to maximize photosynthetic potential), very high embodied energy load (this is a concern regarding the energy balance), potential over-heating and over-exposure to sunlight, excessive Oxygen release etc. There is no consensus among the scientific community on whether open ponds, PBRs or a combination between both is the most favorable i.e. open ponds have lower capital and operation costs but lower productivity (due to less control over certain parameters) while PBRs offer better control over the process, higher productivity but at much higher capital and operation costs. There are many different set-ups that have been designed and on trial worldwide. (Bruton, 2009). Very recently, the NAA (National Algal Association) released that raceways ponds will never be used for industrial production because even though they are relatively inexpensive to build their biggest problems i.e. low productivity and contamination, after years of testing have still not been resolved while the price of closed-loop systems has substantially come down over the last 5 years.

The cultivation and further down-processing is depicted in Figure 8 and detailed in the following section. This cultivation process that is presented is the mainstream option but it does not necessarily imply that it is the only option existing and especially the one that years of demonstration research will, in this particular form, retain. Biodiesel is the transportation fuel under focus as it is the major biofuel used although in theory algae as a feedstock can generate a wide range of liquid and gaseous transportation fuels such as biodiesel, gasoline, jet fuel, methane, synthesis gas, hydrogen and straight vegetable oil (IEA, 2011a).

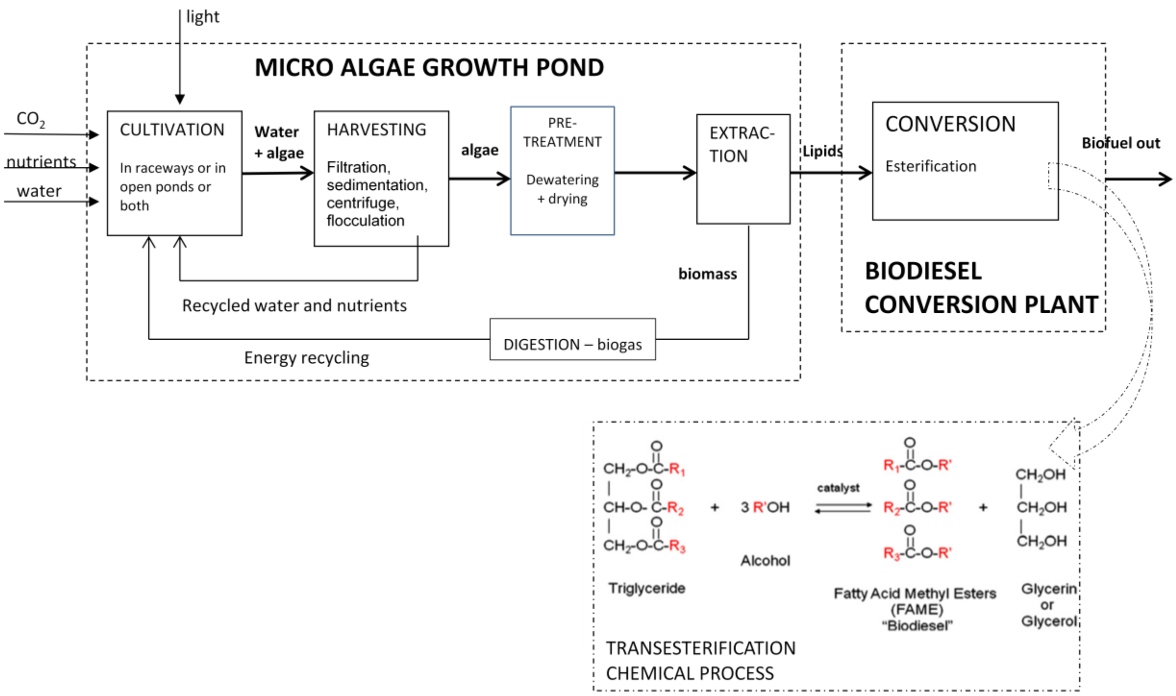


Figure 8: microalgae cultivation and algal biofuel production.

Source: (B. J. Gallagher, 2011) for the production process + (Cheng & Timilsina, 2011) for the transesterification chemical process.

Light: it can be natural or artificial lighting (artificial lighting is possible for PBR but is much more expensive) (Cheng & Timilsina, 2011). One major limitation for algae growth is self-shading in high cell density culture which requires a good mixing ((S&T)², 2005) The temperature has to be maintained to a certain level (Cheng & Timilsina, 2011). Indeed, when the temperature falls under a certain limit, the algae growth is inactive and may require some heating. Additionally, PBR under natural sunlight are prone to overheating and necessitate a cooling system (adding a lot to costs and energy requirements)(Leite & Hallenbeck, 2012).

Nutrients: a substantial amount of nutrients is needed, essentially nitrogen and phosphorus. The use of chemical fertilizers is possible although their production is energy intensive and impairs the sustainability of algae cultivation. Another source of low cost nutrients is wastewater, which benefit both processes i.e. wastewater treatment and algae cultivation (Lam & Lee, 2012). It has to be noted that algae is already used for water purification purposes even though not harvested afterwards for any further application.

Water: fresh water can be used, as well as wastewater as just mentioned. "Wastewater" includes agricultural run-offs, industrial and municipal wastewaters (Singh & Olsen, 2011)

CO_2: at least 1.65 kg of CO_2 is required per kilogram of micro-algae. Exhaust gas from plants emitting high level of carbon can be used in order to avoid purchasing CO_2 at high costs while helping some industries to lower their emissions (however, this is not always compatible with the production of high-value products such as food or pharmaceuticals). (Bruton, 2009).

Harvesting: there are basically four harvesting methods namely sedimentation, flotation, filtration and centrifugation, that gives a slurry of roughly 2-7% total solid matter. The two former, usually used for open ponds, have the lowest costs and the two latter usually apply to PBR and have much higher costs.

Pre-treatment: chemical esterification requires no water. The drying process is the most energy intensive and accounts for the lion's share of the total costs.

After harvest the algae dry content is around 20% while dry lipids are needed for esterification, unless specific techniques such as the use of direct lipase for direct esterification is developed.

Conversion i.e. transesterification: lipids (triglycerides or oil) with an alcohol (preferably methanol) convert oil into fatty acid alkylesters which is the material used in diesel engines. The main by-product is glycerol. No water is required, as well as no free fatty acids for this reaction because this leads to soap formation. Strains of algae have to be selected according to the unsaturated fatty acid content i.e. an excess of them is a problem for biodiesel production. Nonetheless, poly-unsaturated fatty acids are a potential co-product retrieved before the esterification process for being sold as vegetable alternative to fish oils (rich in omega 3).

2.2.3. Biomass and oil productivity

Concerning yields and productivity, some laboratory research claims a 70% oil content for some algae strains although this has never been demonstrated on an industrial scale. (Bruton, 2009). "It is widely stated that microalgae can produce 30 times more oil per unit area of land than terrestrial oilseed crops". For instance, with an oil concentration of roughly 42%, a 365 t/ha/yr biomass productivity[16] would equal 153.3 t/ha/yr of oil produced for PBR and with a 20-30% oil

[16] For this figure the author doesn't precise whether it is dry matter or not but that is most likely the case

content, a productivity of 300 t/ha/yr of biomass (dry weight) would provide 60-90 t/ha/yr of oil for open ponds (Singh & Olsen, 2011). In the most recent economic assessments regarding algae, the average biomass productivity taken into account is $30g/m^2/day$ i.e. >110 t/ha/yr (AquaFUELs, 2012). It has to be noted though that algae biomass productivity, oil content and oil yields vary a lot in the literature (and that productivity varies from one region to another). There is also some confusion e.g. between short term growth rate and annual productivity (Bruton, 2009). The most likely productivity, established in the framework of European demonstration projects, is (for outdoor systems) of 40 t/ha/yr which represent an overall biomass productivity of 80-100 t/ha/yr (oil content is around 25%) obtained in a latitude of 53° N, i.e. The Netherlands (Bruton, 2009). This is confirmed by an LCA analysis review presented during a European Workshop in February 2012, "we should be very cautious in using PE (photosynthesis efficiency) >2% and productivities >50 t/ha/yr for LAC because these figures have never been actually reached in large scale algae plants."(Tredici, 2012). From an experimental algae cultivation under nitrogen starvation conducted in 2006 the oil production was $5\text{-}9g/m^2/day$ (18-32t/ha/yr) in PBR and $4\text{-}5g/m^2/day$ (14-18t/ha/year) in open pond (Tredici, 2012). Finally, the on-going European demonstration projects aim at achieving yields equaling 90t/ha/yr and this is already optimistic according to the project coordinators (personal communication with Pr Tredici, 2012).

Few cost estimates for algae growing plants are available in the public domain (Haq, 2012) and reliability is doubtful. Thus the subsequent analysis focuses more on qualitative trends than deep quantitative cost projections.

Finally, opportunities exist with algae to extract and produce high-value products (proteins, pigments, pharmaceuticals, chemicals, etc.) and additional commercial material such as fish feed in a biorefinery-type concept. This also includes fermentation to get bioethanol or digestion to obtain biogas (Bruton, 2009). The microalgae industry is presently a very small industry with a global production of less than 10,000 tons that are not dedicated to fuel but rather to high value products such as pigments, proteins, pharmaceuticals, etc. (what can be extracted depends on the algae strain).

3. Algal biofuels industrial emergence analysis

3.1 Analytical considerations

This work was conducted using Phaal's framework for mapping industrial emergence. The first step is to position the industrial sector somewhere on the industrial lifecycle timeframe and the second step is to examine this sector through the light of each "value pillar". In the end, the mapping will produce a visual support for finalizing the work.

As mentioned in the scope section, the industrial emergence phase in which algal biofuels currently evolves is situated around the *embryonic phase* and the subsequent transition i.e. *technology-application transition (T-A) (Phaal et al., 2011)*, represented by the red circle on Figure 9. According to Phaal's emergence categories, the *precursor phase* establishes a scientific phenomenon which progresses through the *science-technology transition (S-T)* once it has shown that it could be functional in a technology system. Oil extraction from microalgae for biodiesel production has been scientifically proven to be feasible and functional on the strict technology perspective. Besides, transesterification as a conversion pathway to produce biodiesel is also a very common and widespread process. The next emergence, the *embryonic phase*, introduces the ability for a technology to be demonstrated in a market environment through reliability and performance improvements (Phaal et al., 2011). In the continuous logic, the *T-A transition* emphasized on improvements that target commercial potential (Phaal et al., 2011). Considering that the proven technology faces improvement needs in order to achieve economic feasibility, the algal biofuel industrial sector is situated somewhere in the *embryonic phase* and the *T-A transition*. Not only the boundaries are blurry but as there are a wide range of processes that are being tested for demonstration, it is futile to narrow down the position on the timeframe. In addition, because the next *nurture phase* rely on price and performance to demonstrate sustainable business potential, this stage has certainly not been attained yet, at least in Europe and for processes that target biofuel production. Thus, algae is at the *embryonic phase* and *T-A transition*.

The vertical "taxonomy" represented by the green circle in Figure 9 has two major components organized around the *value capture* pillar, namely the *value context* and the *value creation* pillars respectively representing market/demand push and supply/push technologies. The content of each "taxon" is briefly described by Phaal and serves as a base to attribute each observed constraining aspect to one of these taxonomic divisions. It has been decided that the context would be examined first as it appears logical to start with drawing up the background, then the value creation aspect is tackled and finally the value capture dimension is analyzed in respect to the idea that the former aspires at designing the latter.

The *value context* aspect describes the background set up in which this industry evolves and is here heavily influenced by the policy framework and especially the ensued blending mandates, which aim at ensuring a market for biofuels. Certification and standards are also to be mentioned as they belong to the industrial development process. Phaal also includes market trends and drivers i.e. social, economic, environmental and technological drivers, along with competition and customer needs, which are identified as market/demand push in this "taxon" (Phaal et al., 2011). Market aspects are touched on but as the technology faces difficulties in proving its economic viability, market related constraints are not overwhelming. Furthermore, competition is taken into consideration through the attitude of incumbent technologies.

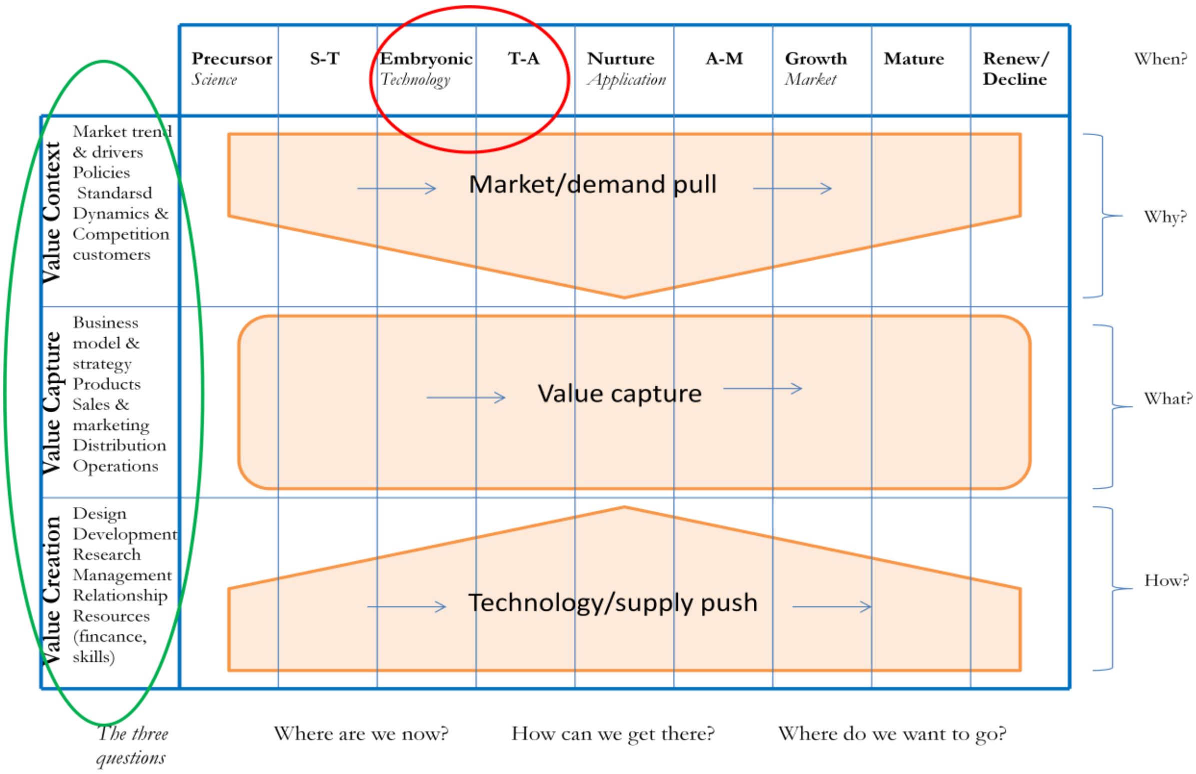


Figure 9: roadmapping industrial emergence framework.

Source: (Phaal et al., 2011)

As for the supply/technology pull "taxon", referred to as *value creation*, it incorporates design, development and research considerations, together with financial, human, management and relationship considerations (Phaal et al., 2011). Technological design, development and research are central to the *embryonic phase* and *T-A transition* as both are technology dominated phases and are fully integrated in the following analysis, together with financing and investing issues pertaining to the algal biofuel sector. Moreover in line with the description of the elements of this category, everything that relates to communication, information disclosure and acceptance matters will be included, as well as attractiveness, potential and general interest generated.

Finally, the *value capture*, the central motive for the industry, consists of the "mechanisms and processes used by organizations to appropriate value through delivering products and services" and includes business models, strategies, applications and the systems and processes for in-service support (sales, marketing, distribution, operations and supply) (Phaal et al., 2011). In the case of an industrial sector that has not attained any industrial growth stage, in-service support considerations have not been developed and therefore cannot be assimilated as development constraint. Consequently *value capture* is restricted to existing economic related dynamics.

3.2 Structured analysis for industrial emergence constraints

All information in the subsequent sections is based from personal communications (see in the appendix C the list of informants and interviewees) and referenced literature review.

3.2.1 Value context

Policy

The policy framework has a major role in shaping the background in which the energy sector evolves. Its influence goes beyond the political sphere and has implication within all other "value spheres" and "sub-spheres". For example, policies aim at providing certainties for investors and encourage technology development (EC, 2009) such as typically feed-in-tariffs with long time horizons. They also can provide the necessary learning opportunity to reach technological break-even points much faster, as explained later on.

According to Lamers (2011), support policies for biofuels can either push e.g. mandates or pull e.g. tax incentives biofuels into the market. Biofuel support policies are categorized according to whether they promote domestic consumption (through consumption mandates or incentives), they promote the domestic production (through production mandates, investment support, feedstock support or tax incentives) or they relate to trade (through import or export tariffs), although most countries implement a portfolio of measures (Lamers, Hamelinck, Junginger, & Faaij, 2011). The general triple EU policy objectives that the designed policies try to achieve are namely: competitiveness of the EU economy, security of energy supply and environmental protection (along with boosting rural income and employment) (Demirbas, 2009b).

- **The policy framework: description and explanation**

The Biofuels Directive 2003/30/EC introduced quotas by energy content with increasing targets to be met by member states (MS): 2% by 2005[17], 5.75% by 2012 and 10% by 2020 and the Energy Tax Directive 2003/96/EC introduced tax incentive possibilities for MS such as biofuels excise duties exemption or reduction (Lamers et al., 2011). As a Complement, "the Fuel Quality Directive introduced blending and the Common Agricultural Policy supported the growth of energy crops", although the support mechanisms developed by the latter terminated in 2010 (Amezaga, Boyes, & Harrison, 2010). A European strategy for biofuels came along in 2006 with seven policy areas namely, (1) stimulate demand for biofuels, (2) ensure environmental benefits, (3) develop the production and distribution of biofuels, (4) expand feedstock supply, (5) enhance trade opportunities, (6) support developing countries with potential, and (7) support research and innovation to improve production processes and lower costs (EC, 2008).

In 2008, the policy framework was revised after realizing that the 2005 target had not been met at the EU-level and that serious concerns over sustainability of biofuels had arisen (Lamers et al., 2011). The Renewable Energy Directive 2009/20/EC (RED), repealing Directives 2001/77/EC and 2003/30/EC, states that:

> "the Commission communication of 10 January 2007 entitled 'Renewable Energy Roadmap – Renewable energies in the 21st century: building a more sustainable future' demonstrated [...] a 10% target for energy from renewable sources[18] in transportation would be

[17] The 2005 targets was not met at the EU-level despite the tax incentives in place

[18] The target is defined as a share of final energy consumed in transport and is to be achieved from renewable sources as a whole and not only biofuels (EC, 2009)

> appropriate and achievable objectives, and that a framework that includes mandatory targets should provide the business community with the long-term stability it needs to make rational, sustainable investments […] it (the European Council of March 2007) endorsed […] a mandatory 10% minimum target to be achieved by all Member States[19] for the share of biofuels in transport[20] petrol and diesel consumption by 2020, to be introduced in a cost-effective way."

Historically, the Directive 2003/30/EC set indicative targets to be met with the idea of retaining implementation flexibility i.e. MS had to decide on their own strategy. After the 2007 Renewable Energy Roadmap proposal of setting legally binding targets, this was enforced and the 10% transport fuel that had to be met by biofuels became 10% of the energy in transport that has to be sourced from renewable energy (this has allowed the introduction of electricity and hydrogen technologies).

In 2008 the European Council emphasized the necessity to develop effective sustainable criteria for biofuels to ensure the commercial availability of second and third generation biofuels[21] (EC, 2009). Indeed, blending mandates are necessary to increase biofuels production but as they target the total production the cheapest options will dominate, as the market only accounts for the real costs and not the environmental performance, and therefore, there is a need to enforce policies that remedy this fact (Sletten, 2012) which is very likely to be the purpose of the sustainable criteria. Those criteria (1) include increased targets of greenhouse gas emission savings, (2) forbid the use of land with high biodiversity value for growing raw materials, (3) forbid the use of land with high carbon stock for growing the raw material, (4) forbid the use of peatland for growing the raw material and (5) ensure that the raw materials comply with the support schemes for farmers under the common agricultural policy and with the minimum requirements for good agricultural and environmental condition defined within the Directive (EC, 2009). Overall, the sustainable criteria are likely to become more stringent and the discussions going on at the European level on indirect land-use are also very likely to have consequences on the first generation biofuels. This could imply higher incentives to develop new biofuel technologies.

In conjunction with the RED, each Member States (MS) had to issue a national "renewable energy action plan" (REAP) by June 30, 2010 describing the renewable energy sources they will use to meet the 10% target (EC, 2009). In those REAPs, when it comes to biofuels, the majority share goes for biodiesel, 25% to ethanol and the remaining shares are for electricity (electric cars) and second generation biofuels (Vierhout, 2011). Therefore it was forecast that the large majority of the EU biofuels market penetration would be achieved by biodiesel (from conventional biofuel sources i.e. first generation). It has to be noted that a 10% target is set in energy content and represents 11.5% in volume (similarly, the 5.75% target equated 6.5% in volume). Recently published news suggested that conventional biofuels fail to attain 35% GHG emission savings as they would be most of the time under 30% (Mascalister, 2012). Confirming this fact, the most recent European Union legislation news indicates that a limit will be put on crop-based biofuels (the contribution of which to the total energy consumption could be limited to 5%) and all public subsidies for them will be ended after 2020 (EurActiv, 2012b). In light of such news, the question on how to attain the 10% target remains.

[19] A 10% target is set at the same level for each Member State to ensure consistency in transport fuel specifications and availability, biofuels being easily traded (EC, 2009)

[20] In its article 3 paragraph 4 the RED specifies that the 10% target concerns "all forms of transport"

[21] The Renewable Energy Directive mentions explicitly second and third-generation biofuels without providing any definition or distinction between them. It is assumed than advanced biofuels are mentioned.

- **The policy framework: critical consideration**

First, the policy framework established through the RED has defined mandatory targets in both the energy sector and the biofuel sector, representing a massive legislation to be enforced. From an interview it has been declared that there has been a much larger focus on renewable energy production from wind and much less on biofuels, which have been "a bit forgotten" by some national authorities, leading to a situation where the biofuel target completion was to be realized through massive imports of biomass. Having left aside the biofuel aspect of the renewable energy mandates, those authorities have become "desperate" to meet the EU biofuel targets, which keep going up every year. In the eyes of the European Commission, the fact that governments are rushing to meet the targets does not provide a satisfactory justification and does not explain why more sustainable biofuels are not given more attention. The rationale behind lies in the fact that the RED provides sustainable criteria, the completion of which is the condition for MS to quote the biofuels within their target scheme. Indeed MS wouldn't be allowed to promote non-compliant biofuels and to report in their annual targets and it is unlikely that individual enterprises are going to propose biofuels that are not compliant (mainly for image related reasons). However, it was conceded that the Commission was disappointed by what MS proposed for advanced biofuels after the double counting had been implemented to promote good and high CO_2 saving biofuels (double counting means that advanced biofuels account for twice their contribution towards the target). This could therefore reveal a discrepancy between the expectations at the EU level and the attitude of MS towards the level of ambition to be reached, despite the efforts of the former.

In line with that observation, so far pessimistic views on algal biofuels' potential has been said to stem from unawareness and lack of knowledge from national authorities. Indeed, it has been pointed out that, typically, at the government level there are departments that do not necessarily exchange information, while some sectors are very powerful in getting what they want. Companies try many things, have R&D departments and invest money, while governments are commonly a bit late to catch on the things. In addition to that, in some European countries, unsolved red tape issues also exist; they include the inexistence of any license to operate for algae growing (usually any living organism growing is subject to licensing) and the unsolved algal biofuels classification and assignment to a particular sector i.e. is it agriculture or aquaculture. This particular example may be important because people have a lot worse perception of the sustainability of the fish farming than agriculture. This information highlights that, in the case of new technologies for advanced biofuels, the institutional structure is as much as in its "infancy" stage as the industry sector is.

Second, among the many other concerns, there are two notable features touched on above and that the literature raised concerns about, which illustrate relevant constraining forces: the GHG emissions saving issue (1) and the sustainable criteria (2):

1. Interestingly, the RED requires that the biofuels save a given percentage of GHG in comparison to fossil fuels and provides in its Annex V a set of default values are available for the saving calculation (Vessia, 2012). However, Abengoa, an international company developing energy and environmental related technologies, pointed out that there is no GHG emissions default value for algal biofuels (Montero, 2012), especially because it cannot be calculated yet. The amount of GHG savings that algal biofuels can reach together with its correct incorporation within the policy framework is a litigious aspect that still needs to be solved, at least for practical purposes. Indeed, reliance on GHG emission savings predictions is also a major concern in the case of the double counting, which bases its rationale on the idea that some sources would save twice as much CO_2.

One can question the accuracy of the entire system. Indeed, as explained by Amezaga et al. (2010) this double counting enables the second generation biofuel, more precisely biofuels produced from waste, non-food cellulosic material and lignocellulosic material, to account "for twice their volume/energy contribution towards the target […] (and) Member States can theoretically achieve their target obligations by achieving only a 5% biofuels share when those biofuels are second generation" (or waste). In consequence, the volume of biofuels in the mix would be reduced and the emission savings that are expected to occur in the case of a 10% share met by only first generation biofuels relies on the exactitude of the GHG emissions saving predictions of those second generation biofuels. (Amezaga et al., 2010).

It has to be noted that double counting is a concern that has been raised by specialized organizations reviewing European legislation while the next point, the sustainable criteria, is much more widely spread in the literature.

2. The feasibility of the application of those sustainable criteria has been seriously questioned as is their effectiveness, mainly because of their weak aspect and the pertaining loopholes e.g. definition problems concerning highly "bio-diverse" lands which thereby fall out of the protection scope of the criteria. Another strong criticism is their inability to incorporate any social dimension such as food insecurity and violation of land rights (social criteria were dropped from the final Directive version due to potential trade related incompatibilities with the WTO agreements) (Amezaga et al., 2010). However, the latter seems less relevant in the perspective of the development of advanced biofuels that reduce those negative social effects and also because corrective actions have been planned in the case of reported negative social effects.

   The indirect land use change[22] (ILUC) was excluded so far from the criteria which in return excludes the emissions pertaining to the latter to be accounted for (Amezaga et al., 2010). This is supposed to be remedied through upcoming legislation on ILUC. At the beginning of the year, the European Commission seemed to have favored assigning GHG default values calculated with a the full lifecycle approach, hence taking into account ILUC, and leaking information suggested that crude oil outperformed some first generation biofuels from feedstock such as palm oil, soybean and rapeseed (EurActiv, 2012a). The leaked default values were refuted as scientifically unreliable and the policy framework was criticized for not sending "a clear signal to the markets about which are the future biofuels that we want" (EurActiv, 2012a). Very recently, as mentioned above, the use of crop-based biofuels is to be limited in the future and the production of advanced biofuels is to be encouraged (EurActiv, 2012b). A clear message to the market on that perspective is now sent, although one can still pinpoint that such a u-turn in legislation still carries uncertainties.

   Algal biofuels production requires some surface area for algae growing, but it can be done on any land; thus there isn't any need for arable or "good quality" land. In terms of quantity, given the amount of scientific and technical uncertainties and the fact that no one can predict how much is going to be produced, it would be very inaccurate to bring up some numbers. Thus, as "land quality" issues are minor for algal biofuels production, one can think of the ILUC legislation as not being a major concern for this type of fuels, especially since they are said to already perform better on LUC avoidance (Brentner, 2012) and can only encourage its development.

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[22] There are two types of land use change: direct and indirect. Direct land use change refers to a situation where a land that is "not used for agricultural production gets converted to produce biofuel feedstock" and indirect land use change refers to a situation where a land that is "not used for agricultural production gets converted to produce agriculture commodities in response to biofuel-driven displacement of commodity production in a different region, country or even continent" (OECD, 2009).

As pointed out by Amezaga (2010), although creating a policy framework for biofuels had to generate a demand and, hence, certainty for investors, the Commission's obligation to report certain aspects and operate changes in the legislation adds ambiguity and ironically increases uncertainties. Criticized for not sending right messages to the market about what biofuels are wished, at least there is a clear message sent on the willingness to select the best-performing biofuels.

Finally, schemes that grant money for sustainable energy production or carbon reduction do not discriminate between the different raw materials used. This implies that the given framework is the one that applies to algal biofuels as to any other fuels while raising the question of policy options that were chosen with regard to the need to steer the market in order to obtain the expected outcomes and complete the policy objectives. MS biofuels support measures are of two kinds, blending objectives coupled with biofuels tax exemption and/or reduction (including budgetary support), although each MS defines what particular support scheme suits better its system configuration (cf the REAP).

A favorable tax regime is linked to high market penetration as shown by past experiences in Germany, France, Sweden and Spain (Wiesenthal et al., 2009). Differentiated tax schemes are the ones for which the implementation appeared to be successful and high fossil-fuel tax rates also brought success to tax exemption biofuel policies; "For tax exemption schemes to work well, the fossil fuel tax must be high enough to result in fossil fuels price which is higher (after tax) than the price of biofuels (with or without partial tax)" (Amezaga et al., 2010). However, this represents a loss of revenues for governments (Amezaga et al., 2010; Wiesenthal et al., 2009) that Wiesenthal argue can be compensated for by higher fossil fuel taxes e.g. in Belgium. Based on scenario results, a 10% biofuel share with an oil price around €50/bbl and a maximum import rate of 30% would result in a tax revenue loss of €7.6 bn in 2020, representing a €80 bn cumulative loss between 2007 and 2020 (Wiesenthal et al., 2009). Therefore the trend shifted in favor of obligation schemes (or a mixed system) where fuel suppliers are required to achieve a certain share of biofuels in their total sales. The additional costs are thereby passed on to the fuel suppliers, and then to the transport users, signaling the unwillingness of governments to bear the costs of environmental policies. (Amezaga et al., 2010; Wiesenthal et al., 2009). Mandatory biofuel shares fall onto oil companies/fuel distributors and thus ensure a predictable market volume, hence investment security. In that latter case there are some additional costs, notably implementation and monitoring costs, which are very likely to be passed to the final users (hence reducing transport demand), but in comparison to the tax revenue losses, this option is far less burdensome for governments. The mixed systems that are implemented in some MS are set so that some quotas are limiting the number of biofuels benefiting from a tax exemption or the exemptions only apply to some biofuels. An additional features in which both options diverge lies in their possibilities to promote a specific type of biofuel i.e. tax exemption/reduction can easily be developed so as to target a specific type while an obligation blending system is very likely to have fuel suppliers opting for the lowest cost biofuels. Finally, promoting specific biofuel pathways can also be achieved through complementary policies such as capital investment support. (Wiesenthal et al., 2009).

A legitimate question is raised on the impact, essentially the economic impact, on having mandates and tax reductions. As suggested by de Gorter (2009) there are some contradictory effects that stem from adding tax credits to mandates, for instance, offsetting the benefits from the consumption reduction due to mandates alone. De Gorter argues that a tax credit alone is a subsidy that benefits biofuel producers which can lead to reduced conventional fuel prices as the biofuel displaces the conventional one. When the tax credit is introduced in parallel to mandates, then the tax credit still benefits biofuel producers indirectly and acts as a subsidy for fuel consumption and not anymore for biofuel consumption.(de Gorter & Just, 2009). Most policy impact research, in the EU, concentrates on the social and environmental consequences of these policies. This is legitimate in regards to the objectives set by the RED and related strategies. The fact that there are notable differences in the implementation of the U.S. and the EU policies suggest that it isn't possible to conclude that policy impacts overseas are of the same range but intuitively would argue for the necessity to take this element in consideration for further research.

Certification and standards

Standards are crucial to ensure market penetration and raise confidence of stakeholders (Wiesenthal et al., 2009). First and foremost, the biggest certification enforced is the one ensuring that biomass for biofuel production has been sustainably produced i.e. according to the sustainable criteria previously mentioned. MS are given the compliance burden of proof and, thus, elaborate systems such as voluntary certification schemes that have to be recognized by the Commission.

Then, in terms of fuel standards for compression ignition (diesel) engines, algal biofuels will have to follow the same system as any other oil-based biofuels i.e. biodiesel, especially since the blending mandates are not feedstock specific. The existing biodiesel standard, the EN 14214 issued in 2008 by the CEN (European Committee for Standardization), gives "all relevant characteristics, requirements and test methods […] for FAME […] to be used as automotive diesel fuel". The EN 590 (the ASTM D975 being the U.S. equivalent) standard relates to the fuel specifications for petroleum-based diesel fuel and allows a 7% biofuel content (20% in the U.S.) that do not affect the manufacturer's warranty provided that it meets the requirement of the EN 14214.

Concerning the aviation industry, stringent fuel specifications apply and each new fuel needs to be incorporated into the jet fuel specifications. There are four up to date "conversion pathways" that have the potential to serve as alternatives to conventional kerosene, namely Fischer-Tropsch[23] (also referred to as CtL, GtL, BtL, WtL according to the feedstock used), Hydro-processed Esters and Fatty Acids (HEFA, also known as HRJ, HVO), sugar conversion and direct liquefaction (essentially pyrolysis). The first two pathways have implemented certifications, respectively DEFSTAN (2009) and DEFSTAN (2001), can be sourced from respectively any material containing carbon and vegetable oils or animal fat, and, can be used up to 50% as blends with fossil jet fuels. The last two pathways do not have any certification yet (Faaij & van Dijk, 2012). In that regard, utilizing algae oil for the HEFA conversion pathway is a possibility that is compatible with the current certification. The FAME pathway carries uncertainties (Faaij & van Dijk, 2012) and is still under testing procedures. In 2008 the world's first algae-based jet fuel was produced in the U.S. and passed the specification tests required by the U.S. standard (ASTM D1655) and since then many private and public organizations are working on developing an algal based jet fuel that would meet the stringent specifications (EBTP, 2009). Indeed, the aviation industry is interested in algal biodiesel , "due to its superior cold-temperature performance, energy density and storage stability" (Bruton, 2009).

[23] Fischer-Tropsch is a succession of chemical reactions that convert a mixture of carbon monoxide and hydrogen into liquid hydrocarbons. The mixture can be obtained from various feedstocks i.e. coal, gas, biomass and waste and according to the feedstock the process is referred to as Coal-to-Liquid (CtL), Gas-to-Liquid (CtL), Biomass-to-Liquid (BtL) or Waste-to-Liquid (WtL). However, only BtL and WtL would be considered as a sustainable source.

The standard explicitly states that it is based on the interlaboratory testing of the applicability of several source of FAME produced from the "vegetable oils that were available on the market at that time, i.e. rapeseed, palm, soy and sunflower oil." (CEN, 2008). Although there are new sources of FAME available, it seems no to be a problem at all as the standard works well.

There are many blending possibilities, but there are "technical limits" that constitute the limiting factor and participate in the existence of a certain amount of constraints, that, actually, are not necessarily purely technical. According to the European Commission, the blending percentage for biodiesel of 5% in volume was set according to fuel standards "mostly to ensure a compatibility with conventional power trains and refueling infrastructure" (EC, 2012b). This percentage was brought up after the revision of the Fuel Quality Directive and reached 7%. According to some the "technical limit" for biodiesel is 7% and corresponds to the maximal blending percentage for which no change of the vehicle engines or the delivery infrastructures is required (EC, 2012b), although other advocate that there isn't any technical limit per se and blending percentages could easily reach 30% without any problem. For instance, the EBB (European Biodiesel Board) is currently working on bringing the EN 590 up to 10% blending. With a 10% target by the RED, even though the target is not to be achieved only with biodiesel blending but also with other biofuels such as bioethanol essentially (the "technical limit" for bioethanol is said to be higher and reaches 10%), the question of the participation of engine manufacturers and delivery infrastructure operators is raised (their attitude will be discussed through the "incumbent technology" section). Overall, any constraints on the access to the market for biofuels will ultimately have consequences for algae biofuels as there isn't any discrimination between biofuel sources at the pump.

In the end, as touched on in the biofuel section (section 2), there is a lack of standardized methodology, for instance algae fatty acid profiling is subject to discrepancies in analysis methodologies (Lang et al., 2011; Woo et al., 2012) and biodiesel performance tests lack standardized methodologies (Pinzi et al., 2009). This hinders the real potential of relevant comparison and introduces uncertainties for further economic-related engineering decision.

Incumbent technologies and competition

Very cheap fossil petroleum-based oil makes it hard to compete and there is a direct competition because biofuels aim at delivering the exact same service. In that sense, any other biofuels are also direct competitors, especially first generation biofuels as they already are commercialized.

Resistance from incumbent technology and established firms is often pictured as a resistance to change from other groups having different interest e.g. the agricultural sector (Hammond, Kallu, & McManus, 2008). This makes even more sense in an industry sector where the market infrastructure is very well developed and controlled by very powerful incumbent players. If the business model develops itself toward a more multiple integrated outcome production, it is acknowledged that production would be limited to rather small amounts that will not affect much the different industries. However when focusing on multiple markets one is also less dependent on one single market, potentially dominated by strong incumbent technologies and reinforces strategic positioning.

For algal biofuels the incumbent technology that could enter into that picture are the oil industry and the agriculture sector. The oil industry is interested in "having a foot inside" and seems to be likely to take advantage of the benefits that this alternative fuel could bring if it happens. Some oil companies have R&D departments that have conducted some research and some, especially in the U.S., have invested in partnerships with start-ups in order to gear up algal biofuel production. In the European Union oil companies are the buyers/blenders of biofuels to deliver the blending in gas stations and in that regard they had to learn to accommodate these new commodities. The agriculture sector is very powerful and crop-based biofuels are very lucrative, therefore it is legitimate to think that if sustainability criteria for biofuel production put them at a disadvantage in combination with pressure put from environmental organizations regarding land-use change and water competition, they are likely to resist a shift of biofuel production towards more advanced technologies. However, there are very few clues that can help conclude on that at this point and it seems that farmers could also see in algae an opportunity for diversification and new revenues.

As mentioned in the earlier section, the car manufacturers' attitude towards biofuels is a contributing factor to the entire industrial sector development. Europe is the biggest biodiesel producer and manufacturer of biodiesel vehicles, so a closer look at the attitude of vehicle manufacturers appears to be necessary. Some equipment and car manufacturers took some actions in line with their green publicity campaign e.g. to warrant B20 (20% biodiesel blending) but in general their efforts have been minimalist and even opposed. Indeed, they used to block an increase blending requirement from 5% to 7% and some of the attempts to test higher fuel blends e.g. 30% are marginal and restricted to some vehicles. Curiously, this was reported to be a general trend regardless whether biodiesel was part (e.g. for Renault) or not (e.g. for Volvo) of the car manufacturer's CO_2 reduction strategies. It appears to be that an opposing attitude emerged from some car manufacturers confronted to issues with some filters in engines, for which they blamed the biodiesel viscosity and impurity content. However, other car manufacturers didn't experience such issues, which discredited any resistance attempt based on the biodiesel quality. Blends higher than B20 require some engine modifications and special transportation and storage management for the fuel (Demirbas, 2009a), but in the overall it is possible to run on much higher blends. For instance, Ford approved the use of B20 in its Super Duty trucks in the U.S. but not in Europe, justifying itself saying that "availability, feedstocks and government policies influenced Ford's geographical biofuels strategy"(Zeman, 2012). Therefore their attitude towards biodiesel policies and standards is still questionable and would deserve further investigation.

It is intuitively understandable to think of first generation biofuels are competitors for more advanced biofuels, especially when some will reach scaling-up and commercialization. Bergek et al. argue that the conventional approach on TIS[24] (Technology Innovation Systems) sees them as competitors especially since the telling of classical economics in seeking cost-efficiency upon policy making framework leads to the creation of tools e.g. green certificates, which create space for competition between the TIS (Bergek, Jacobsson, & Sandén, 2008). This has some relevance for our matter in order to look at beneficial co-evolution features between both generations of biofuels as the development of first generation ones might generate what Bergek et al. refer to as "positive external economies". The latter suggests that the relatedness among TIS emerging from sharing structural elements e.g. actors and institutions, can benefit each other as the development of one feature in a TIS can ease the development of another TIS, hence the former can generate positive externalities for the latter. Overall, all alternatives to the system in place are complements in the perspective to achieve a system transformation. (Bergek et al., 2008). In terms of structural elements that are shared, the most obvious might be some infrastructures such as blending

[24] Bergek defines TIS as composed of the technology as such (artefacts and knowledge), actors (firms along the supply chain and organizations, private and public), networks and institutions (hard regulation and cognitive norms) that contribute to the development, diffusion and application of a particular technology. Those components are part of a system, the structure of which is unique to some extent, but those components are also simultaneously part of other systems

infrastructure and gas stations and the policy and incentive framework. The objective here is less to list them than to account for the fact that the development of first generation biofuels can benefit the development of second generation ones.

3.2.2 Value creation

Technical feasibility considerations are by far the ones that have received the most focus. The process to produce algal biofuels being too costly for now, algal biofuels are not competitive with petroleum based fuels and crop-based fuels, leading to huge concerns about the subsequent development stage. R&D activities are still vital as it is acknowledged that there is space for major innovation that would bring capital and operational costs down but the need to gain experience from larger-scale applications is crucial for testing the different technological options and obtaining real data. Indeed, it has become crucial to test in “real” conditions i.e. out of laboratory conditions and at a much larger scale the best options that research has demonstrated in order to optimize the system. Besides, the technological and process options that are found to be the best within laboratory conditions are not necessarily the optimal ones in other conditions (outdoor and large scale set up), which also underlines the need to have flexibility in thinking. Testing in real conditions enables developers to go back to the design process and bring improvements towards a better economic viability through an organic learning process.

The direction in which the industry will further develop in the mid-term and in the long-term is also uncertain and depends essentially on the economic rationale that will define suitable and viable business models.

Technical process & research

As mentioned earlier there is much research performed to test all sorts of process design and research on the best algae strains that combine high oil productivity, robustness (especially applicable for open ponds) and ease of process. It is likely that there will not be any “one-size-fits-all” design but a multitude of designs that adapt to the geographical locations, hence climatic conditions, where they are implemented. The following sections present the major trends in the research field.

- **First milestone: overcoming stumbling blocks and gaining consistency**

According to the coordinator of the European Mabfuel research project, from the research perspective[25], at the moment the major current stumbling block is harvesting. Many different harvesting methods have been tested (coagulation, filtration, centrifugation, etc.) and even though membrane technology seems the cheapest option, it remains a very costly process. Harvesting is “algae-specific” because some strains tend to naturally agglomerate and settle but others excrete synthesized chemicals which impairs settlement (interestingly when the algal oil content increases, algae tend to float more) (Bruton, 2009). The second biggest issue is consistency. Indeed, within the same process you sometimes have great oil content and sometimes not. Obtaining a constant output is very important. Consistency is also a major issue when waste water effluents are used for instance. Waste water effluents have already been using algae for a long time in order to finalize the treatment and remove the last nutrients and gain a better quality of discharged water. However, algae were not harvested for fuel production, which

[25] This especially applies for the research performed within the European FP7 i.e. the European funding allocated to support R&D

is still under research. The European sponsored All gas project, for which the third biggest –in the world- water company is trying to define an achievable way to produce fuel from algae, is very likely to recover fuel from the extracted oil and from the digestion of the left biomass in order to supply local communities with fuel, that is to say biodiesel and biogas. However, although the biogas production process is fairly easy to operate, the biodiesel production is the least advanced option as algae growing and oil extraction for that specific purpose faces reliability and consistency issues. For instance, according to an analysis conducted by Woo et al., the yields of extracted FAME dropped two-fold when extracted from microalgae that where cultivated in wastewater in comparison to yields obtained from algae grown in fresh water. This analysis also showed an amount of unsaturated acids, when wastewater was used, that was higher than required by the EN standard making them unsuitable for biodiesel production (Woo et al., 2012). Removing those unsaturated acids is technically possible but adds a step, hence increases costs. Those results are algae strain specific and then dependent on the one that was used for the analysis. It is reasonable to think that others strains would have lead to different results; nevertheless, this example highlights the scientific and technical challenges ahead.

Using waste water effluents would not only increase the water treatment process at lower costs but would also provide nutrients for algae growth without the need for separate expenditure. Indeed, nutrients source are a concern since artificial nutrients are made from fossil fuels and require a substantial amount of energy. Accounting for such an energy input in the perspective of evaluating the life cycle of algal biofuels would negatively impact the energy balance. Nutrient shortage is a global concern as there is "a strong demand for fertilizers in terrestrial agriculture" and "having a new large scale demand for microalgae may results in fertilizer shortages. Particularly potassium availability could be a problem if a significant part of transportation fuel is replaced by microalgae fuel" (Bruton, 2009). Nutrient shortage highlights the dependence of algae growth –or any other living organisms- on an element that could generate some sort of indirect competition with land-based crops at a certain point of development and that impact the energy balance of the system. Obviously this is relevant on a long-term and in the perspective that algal fuels make it to the large-scale diffusion stage. Taking a multitude of parameters into consideration as well as the limiting factors is an added challenge that technical design faces in terms of process development. However, nutrient recycling from wastewater or run-off fertilizers from cropland increases the possibility of turning a problem/waste into a solution/resource. Reducing eutrophication[26] in waterways and seas is definitely where a huge potential for this technological application lies.

- **Second milestone: improving the energy efficiency**

The energy efficiency, in line with technical and economic viability, has to be demonstrated in order to gain reliability. The energy balance is an issue that comes up regularly in discussions, not only because it highlights the technical challenges in direct relation with the economics but also the sustainability challenges, as it doesn't make any sense to have a process that needs more energy input than it delivers [27]. Indeed, the NER (Net Energy Ratio which expresses the ratio of the energy produced (lipid or biomass) by the energy requirements calculated) for an LCA[28] of algae biomass production in a one hectare plant (the embodied energy for the raw materials, machineries, nutrients and buildings as well as for operations entered the system boundaries) is 0.57 under Italian climate and 0.84 under Tunisian climate (Tredici, 2012). Interestingly an LCA

[26] Eutrophication is a process whereby water bodies receive an excess of nutrients due to runoff from the land that stimulate an excessive plant growth, often referred to as algal bloom. This reduced the oxygen content in the water leading to death of organisms.

[27] Almost all crop-based biofuels have a negative energy balance, but palm oil

[28] There is an effort at the European Commission level to harmonize the LCAs among all projects

of microalgal biodiesel presented during an EU workshop on LCA for algae-based biofuels delivered three major outcomes: first, the allocation of co-products makes a significant difference in the outcome of LCAs, second, the biggest burdens come from the materials used for PBRs and synthetic fertilizers and, finally, microalgae perform better than other commodities in water conservation potential and LUC avoidance (Brentner, 2012).

A feasibility study published in 2012 by Ofori-Boateng highlighted the challenges faced by algal fuels on the thermodynamics perspective i.e. a high entropy[29] generation and rather low process efficiency (64% of the useful energy within the input resource was destroyed in order to obtain the final product). This underscores the loss of exergy[30] that tends to reduce the efficiency of the plant and hence, the energy intensity of the designed production process. The study also stated that there is a huge potential for improvements through mainly minimizing the exergy losses from the emissions to the environment and process adjustments to increase purity and yields of the products. (Ofori-Boateng et al., 2012).

- **Third milestone: innovating and fostering breakthroughs along the process**

Major breakthroughs have been done in order to decrease the energy intensity and simplify the process, such as in situ transesterification using microalgal biomass rather than oil in order to avoid the energy intensive extraction process (Xu & Mi, 2011). There are still major gaps in research along the production process such as strain selection, harvesting, pre-treatment and esterification and while those basics are still being investigated, some major breakthroughs are also being researched such as the possibility to eliminate some of the steps by choosing different algae strains or engineering them to excrete oil.

The possibility to combine open ponds and PBR in order to combine the benefits is an interesting area of research. Indeed, a two-step approach would benefit from the close and controllable closed PBR system for the early development of algae and from the open system for a stress cultivation time once they have reached a certain growth (and are much more robust and capable to face potential contamination risks). A stress cultivation time means without nitrogen (this would increase the lipid content while decreasing contamination risks). (Bruton, 2009).

Finally, in terms of algae strain selection the stake is to find the ones that offer the best yields (biomass vs oil) and biodiesel quality while suiting the production process in terms of robustness. Each strain has its specifics and milieu requirements for growing, as well as its own fatty acid profile, which means a specific biodiesel "quality". In that regard, the spectrum of possibilities is very large. The literature revealed that the establishment of fatty acid profiles as well as their occurrence in different lipid classes is an emerging field that aims at classifying the identified strain into specific categories (Lang et al., 2011). Finding suitable biomarkers e.g. fatty acid distribution patterns, to build relevant categories for classification has been at the center of recent studies which focused essentially on the marine microalgae (Lang et al., 2011). Lang et al. pinpoint that there is a lot missing in that regard, especially systematic analysis of multiple genera of microalgae from freshwater and terrestrial habitats (Lang et al., 2011). As it has been mentioned earlier, there are an enormous amount of species that have not still been studied and despite that fact that some claims assume genetically modified strains could be the answer to all the challenges around their production, many believe that better strains are to be found within

[29] The entropy is the measure of the disorder within a close system and measures the amount of thermal energy not available to do work: higher the entropy, higher the disorder and lower the availability of the energy within the system to do useful work.

[30] Exergy is the part of energy that has the potential to be fully converted into mechanical i.e. the most valuable form of energy (Ofori-Boateng, Keat, & JitKang, 2012).

the algae strain pool that is already existing, while not risking public opposition to genetically modified organisms.

Financing and investing

The algae sector is characterized by a lack of access to investment money for its development (this actually applies to all advanced biofuels). High capital costs in combination with an uncompetitive market price and no successful commercialization plant is a reality that hinders any rapid scale-up. Aggressive and over-stated claims during the past decade as well as many algal biofuel producing companies that failed economically have also generated distrust, which, in return increases the stake of scaling up examples in their responsibility to demonstrate positive and promising outcomes. There isn't any European commercial implementation to produce fuel from algae so far that is a success story and can really illustrate any viable business model.

- **Understanding private investment issues**

"Producers of algae-based fuels need to find patient investors as there are major technical issues that can take years to be resolved before biofuel can be commercially acceptable" (Guzman, 2011). Scientific work takes a long time in the case of algae for several reasons; for instance there are several hundred thousand of strains that have to be researched all of which have different medium and growing condition requirements.

Public investment essentially relates to R&D stage and research money while the deployment stage (demonstration to commercialization), which algae has not reached yet, is driven by private investments mainly. However, there aren't many private investors now to take over. Any supply-pushed by public policies technologies (R&D funding and biofuels mandates in the case of algae) need to find their way in the market place and need to be taken over by private investors in order to be market driven (see Figure 10).

The two major barriers that hinder optimal private investment in clean RD&D (Research, development & deployment) are the uncertain and long-term commercial payoffs and the "unwillingness […] to bear innovation risks" (Olmos, Ruester, & Liong, 2012). In the case of algae there is a lot of work that has not been proven yet and many stumbling blocks to be triggered, which increases risks for investors who do not see any sign of their investments coming back. All the companies that were attracted by promising claims and created a business targeting algal biofuels as a purpose either went bankrupt or converted into other high value products (especially in the U.S.). Indeed, there has been incoherent or unclear published scientific research and too early aggressive announcements claiming algae's enormous potential, generating a big infatuation for algae. Unrealized promises coupled with bad experiences are necessarily precursors to distrust and skepticism for whomever wishes to get involved in the business. Venture capitalist Vinod Khosla reviewed all existing business models and decided not to invest in any projects. There are still a lot of technical challenges that need to be triggered in order to access economical viability and this is something not appealing to investors, the logic of which is different and mainly centered on rapid return on investment. "The problem remains how to convince investors that there are sustainable business models when considering the supply of a commodity item such as biofuels with the expensive production via current state of technology".

Many experts face situations where eager to invest businessmen or entities do not really accept the realistic situation that it is not at the moment viable to produce only fuel from algae and that a lot more work has to be performed before any real profit could be achieved. Such a message is difficult to get through and lead to unsuccessful stories reinforcing the skepticism and distrust mechanisms.

Besides, there is a geographical component added to that. It seems that the willingness to make investments is indeed also geographically related. For instance, Ireland is conducting many R&D activities even though the financial crisis combined with perceived unfavorable climate conditions (algae cannot be grown all year long there) hinder private investments within the country. The countries where oil activities are already going on seem to be countries where private investors are more eager to take risks.

In addition to the high risk perception and skepticism coupled with a geographic inequality, banks tend to be looking only at the economic aspect of a given industry. This also applies to the European Investment Bank which has not supported any advanced biofuel project since 2007. It has been stated during an interview that private banks were not willing to give loans due to the market aspect of algal biofuels that is perceived as a weak point: there isn't any take-off agreement like feed-in-tariff acted for electricity to guarantee long term income for the new plants. However, this statement is not consensual among the interviewees who do not think of the market for algal biofuels in a problematic way.

Improperly addressed externalities and uncertainties regarding the real benefits delivered by innovation add obstacles to private investments (Olmos et al., 2012). Grubb further states that there are low market drivers for innovation within the fuel sector because innovation doesn't lead to differentiation. The reason being that innovations in that field always deliver the same service, which makes innovation investments less attractive and risks higher (low attractiveness of massive public adoption and returns) (Grubb, 2004). This explains, in conjunction with very long investment timeframes, why the energy and fuel industries allocate a very low share of their turnover to innovation in comparison to other sectors like pharmaceuticals.

An appealing discourse to private investors could lie in the potential of technology synergies and technology cooperation. An example would be residual biomass that is converted into recycled fertilizers: fertilizers would then pay for the entire investment and energy, which additionally can be marketed as strategic positioning and therefore coming as a bonus on the investment perspective. Furthermore, strategic benefits are also coming from fuel or energy produced locally as it reduces dependencies on outside markets. Fuel would then be worth more than the market price. It is advocated that a more careful attention given to what the market needs and to the strategic positioning offered to a client by a specific outcome, would help provide outcomes that sell better and would link the market demand with the technology offering.

- **Public funding, public-private partnership and developing learning experiences**

On another perspective, literature on innovation within the energy sector and how to finance markets for new energy technology recognizes the role of public funding as a necessary help: "Well designed policies according to the stage of development along the learning curve can help innovation to reach large diffusion" (Grubb, 2004). Grubb explained that low carbon technology options wouldn't have arisen without governments' direction for innovation as the private sector wouldn't have taken the risks to invest massive capital without any good reason. Intuitively it is understandable why market creation for new energy technologies has been widely investigated.

Although technology stage development is not a linear process (as stated in the introduction section), neither are the "technology push" and "demand pull" concepts, the public financing perspective has some benefits in reflecting with the help of a rather linear simplified vision (see Figure 10). Indeed, first, the technology push stages are true for the early R&D stages where one finds publicly-financed technologies, second, the demand pull applies later when public policies ensured private returns and, finally, in between it is a transition phase for which public policies have to assure this transition towards private funding.

The existing pull measures within the EU i.e. carbon pricing and the target in terms of renewables set by the Directives are insufficient to properly address this issue which requires more public support (Olmos et al., 2012) and governments adopt deployment programmes in order to achieve the targets (IEA, 2003). Olmos et al. further advocate that those market failures, long term policy objectives and standards, first, do not favor new technologies that cannot yet compete with the mature ones but favor the latter as they are closer to the market and, second, cannot replace complementary public funding.

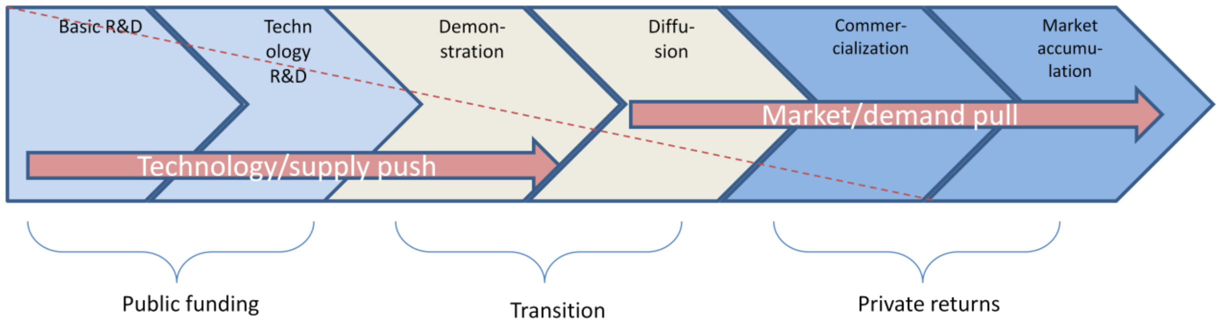


Figure 10: innovation stages and funding transition.

Source: (Grubb, 2004)

Learning curves analysis for various energy new technologies has proven that a cost reduction of 10-25% is experienced during the initial phases of commercialization and deployment after production has been doubled. Although it is not certain whether the costs reduction drove the rising market shares or the other way round, the implication appears quasi systematic. (Grubb, 2004). The expectation behind the learning curves rationale is that the costs will fall below the market price defined by incumbent technologies so that the break-even point will be reached (and programs phased-out) as sales and operational experience accumulate (IEA, 2003). Before the break-even point is reached, the learning opportunities (representing extra-costs) need to be covered by learning investments ($(S\&T)^2$, 2005) (see Figure 11).

The costs imputable to pioneer plants are always higher as it represents a first-of-a-kind construction with higher cost factors such as contingency and risk as well as cost escalation. Therefore the nth plant economics bear lower contingency and cost escalation factors which participate in the learning experience. (Haq, 2012).

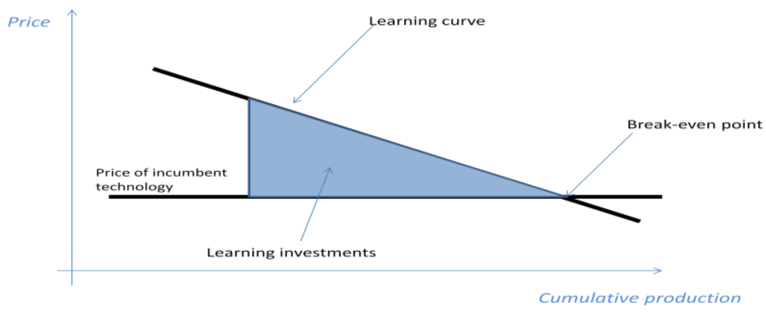


Figure 11: learning curve and investments.

Source: (IEA, 2003)

The IEA advocates that the learning investment can be provided by both governments and private actors. On the one hand, as stated before, private actors are reluctant to invest in technologies that haven't reach the break-even point and government deployment programmes can provide the necessary incentives in order to attract private investments and reduce the time horizon for commercialization. On the other hand, this time horizon may also be reduced by niche markets i.e. special buyers ready to pay a premium for items produced through those new technologies (IEA, 2003). It has to be noted that niche markets can be of a whole series as their exploration and protection may be necessary to be used as "bridging markets" to mass markets (Jacobsson & Bergek, 2004). Those bridging markets enable a larger volume of production providing, as Jacobsson and Bergek (2004, p. 7) put it, "…space for the elements in the technological system to fall into place" in addition to incentives for other firms to enter the market, thus bringing knowledge, other resources, specialization and experience. "Ideally, there is a match between the size of the niche market and a commercial production facility. This allows one or more facilities to be constructed to satisfy just the niche market. In many cases, this is not possible and the niche market opportunity can absorb only a small portion of a commercial plant output and little benefit can be gained from the niche" ($(S\&T)^2$, 2005). As depicted in Figure 12, in situation 1, the cost of the technology is still higher than the willingness to pay from the early adopters and in that situation public money[31] is needed to reach the point where their willingness to pay will take-over -situation 2- and allow subsidies to be phased out. As the learning opportunities are still going on, this take over will shorten the time at which the costs will be competitive with incumbent technologies. The aviation industry can represent a niche market for advanced biofuels as this industry is bound to liquid drop-in fuels as a substitute for fossil kerosene and is really looking for alternatives. Indeed, kerosene price increase really affects the business and, after the entry within the EU ETS, this sector is also looking at decreasing its GHG emissions (the biofuel share is not accounted for the GHG emission calculation which is, indeed, based on the fuel consumption).

[31] Despite the argument of the author argues that public money is needed, private investment money cannot be excluded from the scope of possibilities

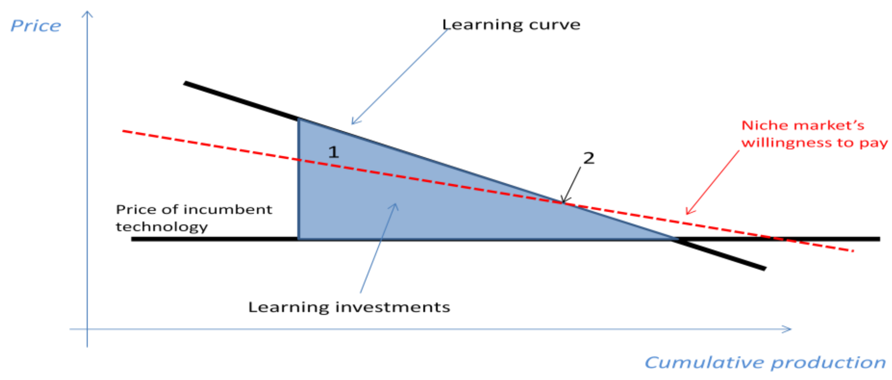


Figure 12: learning investments and niche markets.

Source: (IEA, 2003)

The interaction between the public sector and industry R&D in a "virtuous circle" can be depicted as follows (see Figure 13): the role of experience and learning curves by industry lies in reducing costs and lining up the whole distribution chain. Market facilitation programmes and consumer legitimacy in combination with product standards are non negligible factors. All of that helps to phase out subsidies. (IEA, 2003).

The European Commission supports research and innovation efforts through the Seventh Framework Programme (FP7). The FP7 is the EU's primary instrument for funding research and demonstration activities from 2007 through 2013 (Decision No. 1982/2006/EC). Worth a total of EUR 8.1 billion, the set of calls for proposal is open to organizations and businesses in all Member States (Commission, 2012). Research projects are directly managed under the Directorate-General for energy (DG ENER), which is in charge of the implementation of the European energy policies. To support demonstration, the European Commission created the Algae Cluster[32] in 2010 that participates in the funding of three large-scale demonstration industry-led projects (€8 to 9 million allocated per project). The quantitative targets of those demonstrations of biofuel production from algae are, on the one hand, to be of a minimum of 10 hectares and, on the other hand, to have a minimum productivity of 90 tons (dry matter) per hectare per year. On a qualitative perspective, all projects had to demonstrate the complete sustainable value chain from algae strain selection to biofuel production and use. The European Commission acknowledges that there is a need to develop funding in a "market-friendly" way in order for the industry to find its way. The Renewable Energy Directive states that "when designing their support systems, Member States may encourage the use of biofuels which give additional benefits, including […] algae […]. Member States may encourage investment in research and development in relation to those and other renewable energy technologies that need time to become competitive." (EC, 2009).

[32] For more information see http://www.algaecluster.eu/

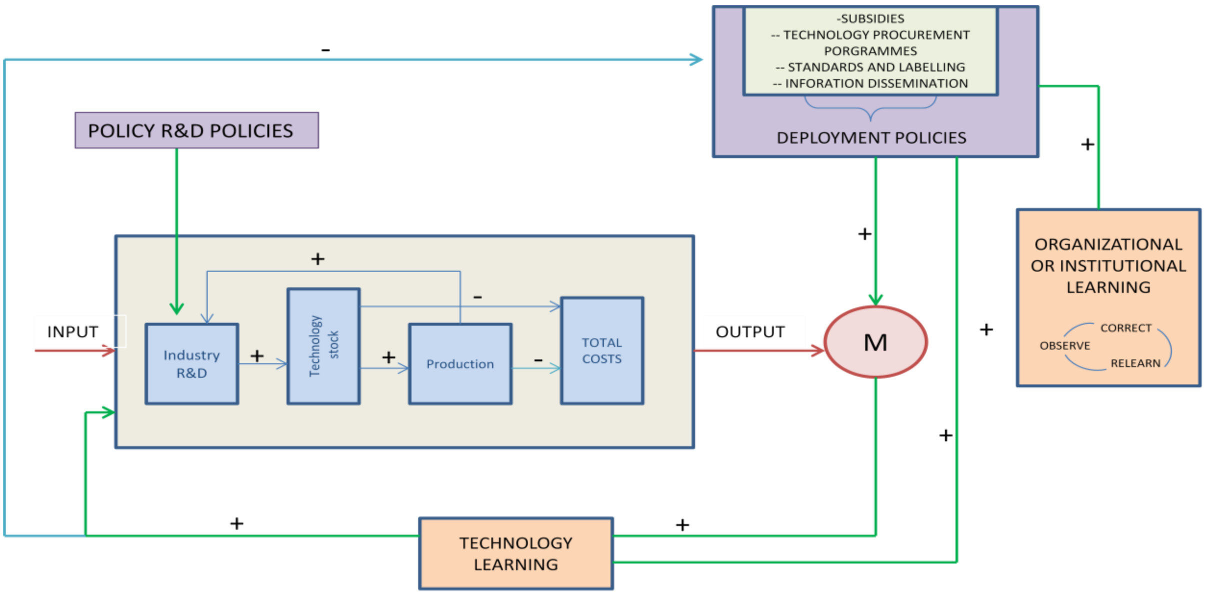


Figure 13: influence of policies on the learning experience.

Source: (IEA, 2003)

In addition, Member States can use the regional fund system from the Commission if they are willing to specifically support renewables i.e. the algal biofuel sector (although the Commission pushes to use the money for climate change mitigation oriented projects, those regional funds can be used for any industry sector). Finally, there are private investors that show willingness to invest in what has been portrayed as a very promising technology and experts agree that investors (but not only) tend to underestimate the complexity of the challenges that are still to be overcome in order to have a viable production of algal biofuels, either as a main or as a co-product.

Communication and acceptance

In this section two communication aspects are analyzed in the following order: first, in relation to the algae sector itself and then, in relation to the biofuel world, followed by a section advocating the strategic communication potential.

- **Communication issues for algae**

Aggressive claims made earlier that over-promised the technology too fast and too soon, especially from the U.S., negatively affected the industry (Guzman, 2011). As an example, the very active U.S. company Solazyme, produced a good share of algal biofuel used by the U.S. Navy to complete its biofuel target. However what has not been explicitly specified is the price at which these biofuels were sold to them i.e. $424 per gallon (€1605 per liter) (current diesel prices in the U.S. vary between $3-4 per gallon (€11-15 per liter) but that is just an indicative value as there are no certainties on what is the price paid by the U.S. Navy). Recently the hype went down and the situation is better regarding that particular aspect, even though it is still going on. As the market place doesn't know the technology very well, stakeholders, especially investors, are now more aware that they have to conduct research and need reliable sources to confirm or invalidate claims. Nevertheless, this has affected the trust and credibility of the entire system, while an unrealistic image of algae potential is still widely broadcast.

The idea of having an alternative to fossil fuels is a very attractive one and many companies are craving for such an alternative, whereas many have gone bankrupt. Over stated claims and over promising statements generated a gap between a scientific community that is very much aware of the complexity and the challenges ahead of the technology and other stakeholders such as some investors, public authorities, etc. who have been promised unrealistic outcomes. The fundamentals of microalgae growing for fuel production are quite easy to understand and, indeed, very well illustrated in articles, videos, and so forth i.e. algae need sunlight, CO_2, water and nutrients, and once harvested the extracted oil can be converted into biodiesel. In combination with arguments stating that CO_2 uptake can increase revenues from carbon credits, generate a carbon neutral fuel and avoid the loopholes of crop-based biofuels, the algae sector had no real difficulties in picturing an attractive business model, although the reality has a total different aspect. This has attracted many investors thinking that capital costs would be paid back in a few years and a lot of money made out of that.

This attitude relates to an aspect of communication that has great influence over the perception of a message. It is highlighted by Wegener & Kelly (2008) through laboratory social psychology research on attitude change addressing the type of message to disseminate efficient information (characteristic of the source of the message and the message itself, of the recipient and the context of reception). They argue that when motivation or ability is lacking, the quality of arguments has little effect. When people are ambivalent on a topic (the positive and negative aspects of some bioenergies typically generates ambivalence) they are more likely to listen carefully to the information that would reduce their ambivalence (i.e. the content that is more agreeable). When the message disagrees with the previous message view, message recipients avoid thinking about the info. Therefore the processing is different across messages whether they are perceived agreeable or disagreeable. (Wegener & Kelly, 2008).

There has also been incoherent, or at least imprecise, scientific data published even in reputable sources, and this incorrect published knowledge obviously doesn't lead to building trust and, hence acceptance. Imprecise data would be for example unclear calculation of the percentage of oil i.e. dry or wet weight. In addition, in most reviews the range of data regarding the oil content - from 15 to 75% dry weight (Cheng & Timilsina, 2011)-, the biomass productivity and then the oil productivity –from 58,700 to 136,000 L/ha/year (Cheng & Timilsina, 2011)-, is extremely wide without necessarily providing any explanation for that e.g. is it depending on the algae strain? In order to remedy the issue of unreliable scientific data, a small Bulgarian start-up has decided to develop an ontology[33] based system to rate all statements per algae strain, including semantic ontology, text vocabulary and text mining techniques, which is obviously a very complex undertaking.

The number of publications on algae has tremendously increased over the last years. Nevertheless, in spite of many technico-economical analyses there is very limited reliable information on the real productivity and economics of algae. For instance, one very attractive figure that is common throughout the literature is the extraordinary performance of algae productivity that is claimed to be hundreds of times higher than the best crop. This is completely wrong according to some scientists as there is no reason why algae would achieve a higher photosynthetic efficiency when grown outdoor at large scale[34]. The main reason that explains false assumptions across the literature is that the figures are mainly assumptions, i.e. based on extrapolations from results obtained in labs under artificial lighting and sometimes heat. Besides,

[33] Ontology deals with setting the entities presupposed by an entity.

[34] Algae can potentially achieve 50, 60 or even 70 tons of biomass per hectare, which is a bit more than most crops but less than sugarcane

algae productivity rates are dependent on the location where they are grown, which isn't clearly stated and productivity is not equal all year round: "Short terms growth rate is often mistakenly extrapolated to annual productivity"(Bruton, 2009) although some temperatures inhibit algae growth (AquaFUELs, 2012). Experience has shown that when growing algae is performed in much larger scales and outdoors, the productivity of algae is totally different. Moreover, it has even been found that larger the scale is, the smaller the productivity is (this has been experienced from lab- and pilot-scale facilities from which interesting productivity are achieved but once the scale is larger productivity seems to decrease).

In addition, promoters of algae technologies for biofuels pushed the photosynthetic efficiency of algae to 3 to 6% which is beyond what is globally acknowledged to be the efficiency for plants (1%), thus totally unlikely to be ever reached under natural conditions (Bruton, 2009). Those extrapolations from laboratory conditions, which are part of the assessments but not really discussed, have not contributed to depict a realistic picture and real messages have some difficulties to get through. Efficiency issues also apply to CO_2 fixation efficiencies which vary from one cultivation system to another. The report form EU sponsored aquaFUELs project estimates that the fixation efficiency is less than 10% in open ponds, 35% in thin layer cultivation and maximum 50% in PBR (to increase this efficiency, advanced technologies are needed at considerable costs). This report further advocates that most recent economic assessments assume the quantity of CO_2 required per kilogram of dry algal biomass taking into account the carbon content of the algal biomass regardless of CO_2 fixation efficiencies (AquaFUELs, 2012).

- **Communication issues in relation to biofuels**

In Ireland, the percentage of biofuels within the blend is written at the pump (it is a legal requirement). The writing is very tiny for the following reason: some people think that biofuels are not as good as regular diesel and some are looking for pumps that have the least percentage, therefore tiny writing aims at not noticing there is a blending. Still in Ireland, the skepticism that the electric cars stimulated tends to be contagious and affects people's opinion on any alternative to regular petroleum based fuels. Biofuel companies wish they could have for instance a national postal company or police cars using their fuels to demonstrate that it works perfectly. In that particular Irish case, education was pointed out as a deep need. Additionally, the successful example of omega-3 from fish farming even though fish farming has been heavily criticized illustrates that a good PR can really turn public opinion around.

Biofuels are the target of many environmental organizations that denounce their harmful effects on poor countries like in Africa where European companies have planted biofuel crop (Allen, 2010). Major environmental organizations are fiercely opposed to crop-based biofuels but support algal fuel. Whether the arguments stating that biofuel crops aiming at the European market increase deforestation, food prices, landlessness and carbon emissions isn't the question. The question is instead, to which extent the public outcry around first generation biofuels could harm the second generation biofuels considering the degree of terminology analogy between them i.e. they are all biofuels (articles do not all explicitly discriminate between them) and the fact that there is little chance that the knowledge of the general public on the difference existing between them might be high.

All those communication related examples show that there are misunderstandings and a lack of knowledge that can lead to unpredictable behaviors that a communication strategy could try to push in a defined direction where choices are made with more awareness.

- **Communication strategy to raise awareness and create acceptance**

There is a consensus on the poor public opinion on biofuels. The European Commission agrees that communication and better awareness are areas on which both the Commission and the industry are weak and it is very easy to broadcast an unfavorable image of biofuels. However, whether a communication strategy would be helpful to raise awareness and subsequently acceptance is not a consensual point. Actually, a communication strategy was proposed during the interviews as a solution to the previously mentioned issues and skeptical stands towards any solution can be perceived as surprising. Skepticism stems from the large number of publications that are in both directions i.e. positive towards algae and negative towards them, so the question arises whether or not new ones on a pile of hundreds would make a difference. In addition, even though a good communication on those issues could help, first, there is still the issue of who is going to pay for it and, second, there is the issue of multi-stakeholders to gather into one communication plan knowing that everyone wants to ensure that their own stake and business come out.

Acceptance of algal fuels is probably much higher than for fossil fuels and higher than for first generation biofuels, due to unpopular competition with food, but not necessarily due to knowledge (Oltra, 2011). However, what is sold at the pump is a mixture of biofuels blended with conventional fuels and thus differentiation between all sources of biofuels is lost. Consequently the problem arises that within the blending there is a variety of biofuels produced from various raw materials and in that sense, communicating on the sustainability of advanced biofuels as opposed to the crop-based ones won't help. Indeed, there is no discrimination possible within the blending and that means that a low acceptance of biofuels is affecting any kind regardless of the raw material they were produced from. This intuitively appears to be a real communication challenge for a sector in which public understanding is really low.

Nevertheless, a lack of communication and implication of consumers shouldn't be underestimated for the acceptance of the final product. Indeed, lack of acceptance has shown to be a precursor for local resistance to renewable energy projects. Resistance, which is not easy to overcome, influences projects in different ways from adaptation of projects, delay or complete failure of them and it is defined as negatively influencing the success of the projects (Raven, Jolivet, Mourik, & Feenstra, 2009). In addition, for new activities to realize their potential there is a need to develop trust among stakeholders and win institutional support through spreading knowledge and understanding about these activities (Aldrich & Fiol, 1994). (Andersson, 2012, unpublished IIIEE research work).

Aldrich and Fiol (1994) argue that there are two types of legitimacy that have to be obtained, namely cognitive and socio-political. This legitimacy is necessary for an industry to move from the pioneer stage to one of fully realized growth. On the one hand, cognitive legitimacy refers to the spread of knowledge about the new activity and what is needed to succeed in an industry. It can be assessed by measuring the level of knowledge about a new activity and is fully achieved when the activity is taken for granted. On the other hand, socio-political legitimacy refers to acceptance of an activity by the general public, key stakeholders, key opinion leaders and officials and can be measured by assessing public acceptance of an industry, government subsidies to the industry, or public prestige of its leaders. Aldrich and Fiol's approach recognizes the role of the social context in putting constraints and opportunities on new activities. Promotion of both types of legitimacy includes development of trust, perception of reliability, reputation of the new activity and legitimacy through the development of knowledge at each step. (Andersson, 2012, unpublished IIIEE research work)

Bergek argues that involving interested parties is central to acquiring legitimacy and uses the example of the advertising campaign from Saab, the Swedish car manufacturer in helping the process of building up this legitimacy that a well orchestrated "bottom up evolutionary process" can guarantee (Bergek et al., 2008). This advocates for asking the question of who is in the best place to start engaging different actors which, followed by positive experiences, will create conditions for acceptance.

Putting forward and promoting sustainable criteria as the mean to develop sustainable biofuels and favor advanced biofuels, all of them being more sustainable than conventional fuels, could be strategic to develop any communication tool. It is easy to put into a message and it carries the essential i.e. it avoids being too explicit on all the biofuels that exist. It is straightforward (it gives the feeling that the criteria will provide for better alternatives) and in line with the European political target to achieve. According to the European Commission, the direction of which sustainable criteria is to evolve is still uncertain although the GHG emission reduction to be achieved are increasing as time goes by in order to market always better biofuel (the number of certification schemes for biofuels that were approved by the Commission are also increasing). Moreover a promising outcome comes from the Directive on land-use change that is very likely to have some consequences on first generation biofuels. In the line of Bergek advocacy on the "development of positive external economies", first and second generation biofuels share structural components that can mutually benefit each other (Bergek et al., 2008). The question on the consequences that a negative perception of first generation biofuels can have on advanced biofuels can be solved by using the first generation biofuels as a "bridging technology" towards advanced biofuels with the help of sustainable criteria (and potential indirect land-use change related restrictions). This might be the rationale behind the necessity to have those criteria but, as demonstrated, this can also be used as an easy way to convey communication messages to foster legitimacy for biofuels regardless of their kind. Avoidance of difficult to transmit messages such as all the technologies behind biofuels and their differences is part of the above mentioned "communication strategy" the aim of which remains to avoid the case of Ireland (avoidance of biofuels at the pump), to curtail and prevent any other resistance behavior while merging the interests of potential competing technologies.

Attractiveness, potential (level of skills and knowledge) and generated interest

There is a lot of knowledge among experts, especially the ones that have been researching algae for decades and are still trying to bring algae toward economic viability. Knowledge is, however, restricted to the scientific community and the experts in the field and a lot of misunderstanding highlights the fact that spreading a more realistic message has a lot of potential.

Undisclosed information in relation to processes, especially quantitative ones, or inadequate data, as mentioned in the previous section, hinders research and understanding. Seeking valuable and verified data is complicated. There are certain issues that are superficially mentioned but on which there is nothing to be found; this is, for instance, the case of genetically modified algae. According to some experts, algae as they exist in nature do not provide enough oil productivity because the only possibility to produce algal fuel is through "improved" organisms. At the occasion of discussing this issue, it has been pointed out that there are two ways of protecting any work that has been done: patents and secrecy. There are patents on modified algae but there is also a lot of secrecy going on.

There is still a lot of effort put to take up the algal fuel making challenges and there is hope that demonstration project results will give some interesting outcomes within the next 3 to 4 years. As stated: "There is clearly a high risk side for anyone who believes that the area holds out the prospect of high returns without the need for very deep and practical understanding of the challenges and appreciation of the hard work required. Breaking out of the existing and proven business models into a new generation of value does not appear to be as simple prospect". (Bruton, 2009).

In terms of cooperation and coordination within the actors involved in the field there are some projects that aim at fostering cooperation but, especially at the global level, it has been declared that the uncoordinated actions for newer proposed business models such as biofuel making suggest that a better cooperation would lead to a faster development.

3.2.3 Value capture

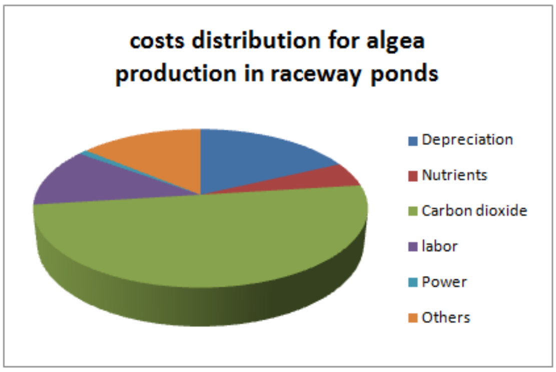
On the demand perspective, due to a blending mandate, the market for biodiesel already exists and any biofuel source can be part of the blend as soon as it reaches price competitiveness. On the supply side there is barely any production from algae yet, so sourcing is very difficult (this is an issue, for instance for the aviation industry that needs to run tests and develop fuel standards). Growing and harvesting algae in order to produce drop-in biofuels encounters real profitability and cost-effectiveness issues that does not make it competitive in comparison to the other fuels i.e. petroleum based fuels and first and second generation biofuels. To provide some order of magnitude, algal biofuel production is situated around €4-5/kg while biofuels feedstocks are available at €0.5/kg (AquaFUELs, 2012).

Economics

- **Costs projections**

One delivery of the AquaFUELs project sponsored by the EU after reviewing the most up to date economic assessments available in full transparency of the fact that no industrial scale process exists yet is that there are all, to some extent, hypothetical and there is a "lack of critical thinking about how reliable the sources and assumptions are" (some data and assumptions are two decades old and over-optimistic). The report further states that apart from different assumptions for yield, productivity and so forth there are also differences in the economic valuation approach i.e. production costs, discount rate choices and lifespan of equipment.

On an engineering development perspective, excluding for instance cost of finance and cost of land, the main factors for the production of microalgal biofuels to account for any economic analysis are: (1) the algae strains and the specific growth parameters, (2) the location of the facilities and weather conditions, (3) design of the reactor (open, flat or tubular), (4) the harvesting method, (5) the water and nutrient supply options, and (6) the carbon (CO_2) source. Overall, as illustrated in Figure 14, producing PBRs is 5-10 times more expensive than in raceway ponds as it faces very high capital costs. In raceway ponds raw materials and production costs dominate the cost distribution (carbon fixation efficiency is lower in such systems). (AquaFUELs, 2012)



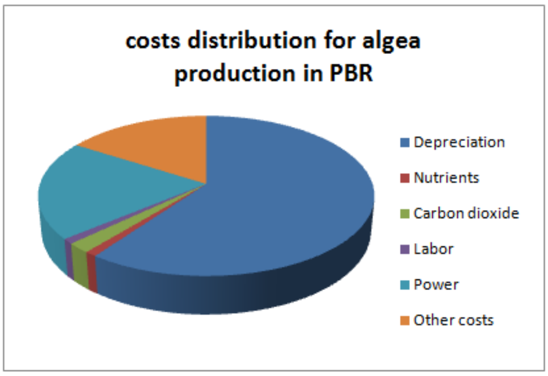


Figure 14: cost distribution for algae production.

Source: (AquaFUELs, 2012)

- **Developing successful business models- biorefineries**

The key indicator to assess short term economic viability is the break-even point of various products (Schmidhuber, 2007). Looking at the break-even point curve of different product categories it makes economic sense to produce first low-volume/high-value products i.e. pharmaceuticals, nutraceuticals[35], feed and chemicals, and later high-volume/low-value products such as fuels. The former would develop learning experiences for the industry, leading to cost decreases and hence help the latter breaking even faster. The already operating plants grow algae for high-value and small-volume products such as pigments (e.g. astaxanthin), proteins, nutraceuticals (e.g. ß-Carotene) i.e. products on the left side of the break-even point on Figure 15. Looking at the technical process aspect, the "from multiple products to fuel production" pathway contains small changes in technology. As a consequence, the pathway that is going from food, to feed and other products to fuel encounters less hurdles on the fuel price perspective, than the pathway from food to fuel, as technology changes have been reduced. "This gives the direction of evolution" (Vincent Toepoel, personal communication, 2012).

[35] Nutraceuticals is a combination of the words "nutrition" and "pharmaceuticals" and are food products that have health and physiological benefits

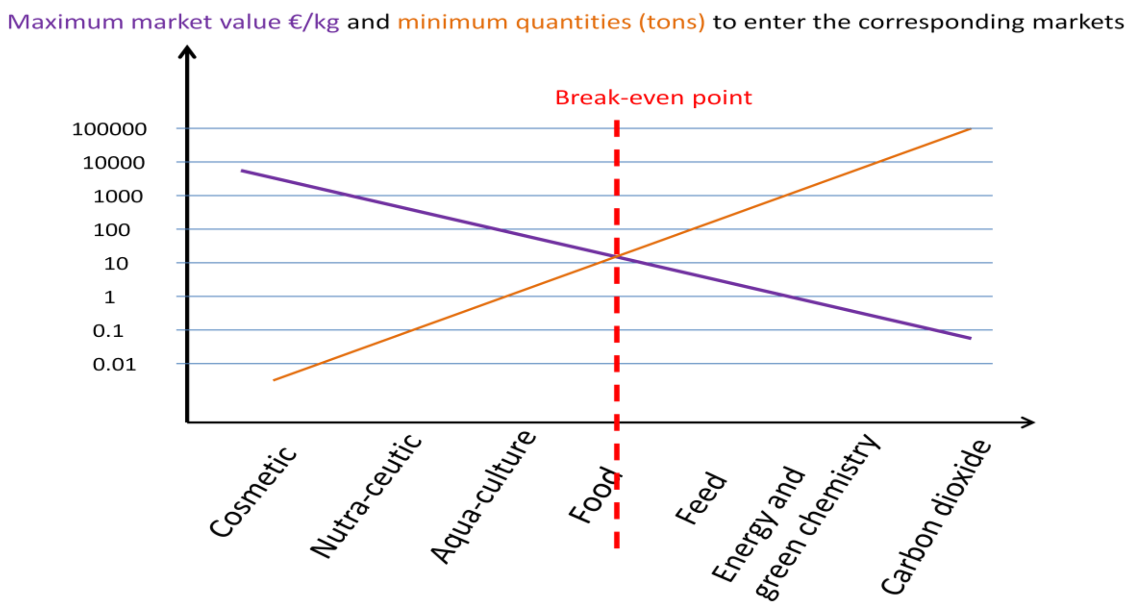


Figure 15: simplified product values and break-even point.

Source: personal e-mail exchange with the French AlgoSource company

Multiple outcome production falls under the principle of biorefineries. The International Energy Agency defined the concept of biorefinery as "the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)" with the necessity to be designed for sustainability along the entire value chain (IEA, 2010). Within the biorefinery concept, energy generation can include fermentation to obtain bioethanol and digestion of residues to produce biogas –oil extraction, for instance, leaves 70% of the total biomass that mainly contains proteins and polysaccharides (Bruton, 2009). Figure 16 illustrates the possibilities that an algae based biorefinery offers, which are many opportunities to be strategically positioned in multiple markets and to develop a viable business model.

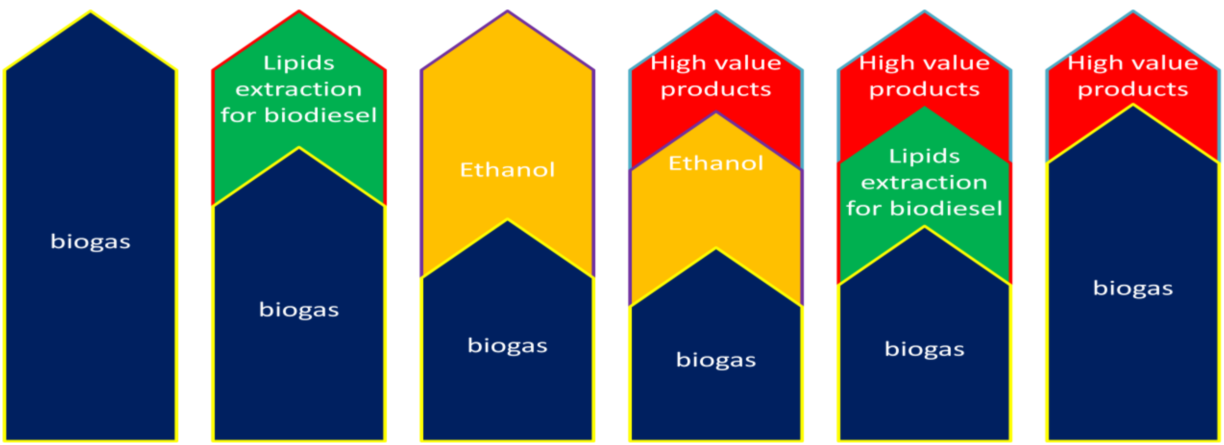


Figure 16: potential outcomes for the biorefinery concept.

Source: (Bruton, 2009)

To integrate algae growing and fuel production with other industries carries a lot of potential to improve the economic feasibility, especially industries emitting CO_2 and generating waste nutrients (waste water, fish and food industries, etc.) (Bruton, 2009). Carbon dioxide obtained at almost no cost, reducing the emissions of a given company at the same time (possibility to benefit from carbon credits trading), as well as heat from manufacturing processes can be utilized. This is also applicable to nutrient rich waste which can be recycled, although this comes, as detailed in the technical section, with technical constraints and hence further economic constraints. It has to be noted that the use of flue gases may come with restrictions for health and environmental reasons (AquaFUELs, 2012) and that high value products production might require the selection of flue gases coming from industries that have high standards, such as the food industry. Industry integration has the potential to decrease the environmental impacts and enhances the life cycle perspective while optimizing the economics (over 50% cost reduction can be achieved if water, nutrients and CO_2 can be obtained at no costs (AquaFUELs, 2012)) but there is a need for further research as there are knowledge gaps surrounding this concept as well as the biorefinery concept, for instance, the composition of flue-gas used for CO_2 can contain inhibition substances such as sulfur and be incompatible with high-value product commercialization.

Carbon credits could be of an additional value to optimize the economics of the developed system and increase profitability (they still make less money than any other product, fuel included as depicted in Figure 16). It is also a good communication asset. The difficult parameter with carbon credit lies in the fact that you know how much credit you can have only once the system design is set up.

Glycerol, the by-product of chemical esterification has, once purified, a market value for the food, cosmetic and chemical industries, together with the possibility to be used as a substrate for anaerobic digestion (EBTP, 2011). Nonetheless, with the recent increase in biodiesel production, some evidence shows that the glycerol market has reached saturation. Indeed, in 2007 the market price for refined glycerol was really low after it had lost more than half of its value due to a surplus of glycerol from biodiesel production (Yang, Hanna, & Sun, 2012). According to Yang et al., refined glycerol has a high-value with thousands of uses but the interest after this surplus of crude glycerol from biodiesel lies in finding new applications for both, refined and crude glycerol uses. Application for crude glycerol would avoid any costly purification process and could include feedstuff for animals and feedstocks for chemicals (especially 1,3-propanediol, a useful chemical material and monomer), butanol, hydrogen, lipids and syngas (from glycerol gasification) although there are still some research to be performed on those promising uses such as the influence of impurities (Yang et al., 2012). A Dutch company, BioMCN is converting crude glycerine (equivalent of glycerol) to bio-methanol which is chemically identical to regular methanol and can be used as a fuel as such, as a feedstock for biofuel or even for non-fuel application including plastics and paints. One can think that as the glycerol industry develops, this by-product will acquire a market value that, in returns, can increase the biofuel industry revenues, hence the economic viability of algae-based biofuel production.

Glycerol is a by-product of bio-diesel production for which the development of commercial applications can provide economic diversification, further revenues and a base for building a strategic positioning. However, glycerol as a potential valuable by-product isn't specific to algae. Looking at the potential to generate a competitive advantage from algae cultivation for biofuel making over all other biofuels can be done using Porter's and Barney's definition of strategic positioning and competitive advantage. A strategic positioning is in essence the fact to do something different from rivals (Porter, 1996). To bring a sustained competitive advantage, a strategic positioning has to be accompanied by a uniqueness that others cannot reproduce

(Barney, 1991). As for algal biofuels, the potential for the creation of a unique, valuable and inimitable position lies essentially in their possibility to use waste water for its growth, together with CO_2 from flue gases. Indeed, features such as glycerol as a by-product and LUC avoidance are also shared by other biofuels and hence, cannot provide a competitive advantage, although they remain an important asset for economic viability.

- **Scale for deployment strategies**

Smaller scale, local and multiple outcome production is the business model that has the most chances to be developed by entrepreneurs in order to capture higher market value for their products and increase their competitiveness. The latter would be reached through strategic positioning and other features such as reducing risks for clients. Indeed, when a small scale producing plant is built closer to the market it allows not only faster delivery, but also easier adaptability that makes things easier for the clients. Therefore, even though in terms of price it is hard to compete, the value of closer-to-the-market products is higher than the market price as the clients' operations become less risky.

However, this set up requires flexibility, especially on the design perspective, because local production means that every geographical area having its own constraints, there is a need to adapt the design to the local specifics. Design flexibility reduces overall efficiency while increasing costs on designers' perspective, which appears to have become an extra obstacle to be overcome.

Additionally, coming back to the learning opportunities, the magnitude of the latter is influenced by the economies of scale and as capital costs represent the major part of the product costs, large plants with their economies of scale tend to have lower required total learning investments than the small scale ones. Nevertheless, although there are economies of scale in building larger plants, especially in terms of return on investment, multiple smaller plants present the benefit to increase the learning opportunities as they can learn for each other and thereby reduce the costs of each plants i.e. lower per unit capital costs. ($(S\&T)^2$, 2005). Therefore, because small scale deployment carries the potential of gaining learning opportunities per se and of suiting high value product strategic positioning, which in returns offer industrial experience, this could be a good strategy for the actual and coming industrial emergence phase. A deeper analysis of the opportunities that economies of scale can open at further development stages is worth investigating in the future.

Market barriers

New technologies have to compete with everything else, especially the incumbent technologies, in order to ensure that resources are allocated efficiently (IEA, 2003). However, market barriers that usually stem from market failures such as price distortion favor incumbent technologies (Owen, 2006). Indeed, market failures tend to tilt the balance in favor of existing, close to the market, clean technologies (Olmos et al., 2012). Market barriers, whether are not they originate from market failures (information costs for consumers, environmental externalities, etc.), distort the real costs and hinder the visibility that is necessary to compare different commodities.

Externalities are market failures as it refers to "the inability of the market to capture full social costs and social benefits, therefore sending the right price signal to producers and consumers of a given commodity" (Bhat, 2012). As opposed to private costs (those paid by private entities) borne and private benefits enjoyed by a decision maker, social costs to, and social benefits of, the one affected are not included in this decision making process. The difference between social costs and private costs are called negative externalities and the difference between social benefits and private benefits is referred to as positive externality (Bhat, 2012). Although private costs are easy to account for, a full inventory of social costs (e.g. use of natural and environmental resources, social capital, knowledge freely available in the public domain) and hence a comprehensive assessment of their true extent is not attainable as it isn't possible to attribute a monetary value to everything (Verbruggen et al., 2010).

The Renewable Energy Directive states that "it is desirable that energy prices reflect external costs of energy production and consumption, including, as appropriate, environmental, social and healthcare costs." (EC, 2009).

Environmental negative externalities are classified in two categories: costs due to damage to health and environment by emissions of pollutants and costs resulting from the impact of climate change. The former are generally based upon exposure-response epidemiological studies and methods that attribute a value on human life (very controversial). The latter are highly contentious and practically impossible to precisely account for with the current level of knowledge (Owen, 2006). External costs of electricity production in the EU have been calculated, which has underscored calculation challenges. Nevertheless, the much bigger external costs of fossil fuels in comparison to renewables are visible (Owen, 2006). Life cycle analysis of algae underlines that processes are very site specific and multiple which makes any calculation a doubtful approximate (Lam & Lee, 2012). Calculation issues will also derive from allocation problems of multiple product processes that could be the reality of algae.

Those market failures justify governmental intervention in the economy (Cowen). Policy instruments try to influence consumers' behavior on the one hand and implemented economic instruments e.g. carbon taxing and carbon credits offer flexible mechanisms to minimize negative impacts on communities. Carbon taxing isn't a reality[36], is politically difficult to implement and would require thorough implementation procedures in order to avoid any loopholes. Carbon credits are the current internalization mechanisms (Owen, 2006) but uncertainties regarding the EU ETS and the price per carbon ton question the efficiency of the entire system. At the current price level of carbon credits, revenues that can be generated cannot shape any business model but only contribute to increase profitability through economic optimization.

In relation to price comparison issues with renewable energies, the efficiency of renewables is very site specific while fossil fuel technologies are internationally traded and have a similar cost throughout the world and therefore, price comparison is not really optimal and shall be made "on the basis of "optimal conditions" costs, rather than the full range that may incorporate old technologies and inappropriate siting decisions" (Owen, 2006). Fossil fuel price volatility isn't incorporated in price calculation, thus placing an implicit value of zero on renewable price stability (Owen, 2006). Direct and indirect subsidies and tax exemptions are not externalities but act in a similar way regarding market distortions (Owen, 2006) and hence hide the real cost of first and second generation biofuels.

In the end, environmental negative externalities are not properly addressed through pricing policies, positive externalities, such as patenting, are also not visible within the market price, which is the case for any feature such as the above mentioned price volatility/stability parameter. Total invisibility on real costs surely benefits fossil fuels in creating an artificial cost gap between fossil fuels and other alternatives, hence reducing the possibilities for them to reach cost competitiveness.

[36] Some countries have implemented a carbon tax namely Denmark, Finland, the Netherlands, Germany, Norway, Sweden and the UK, even though they do not have the same tax based, and some have an energy consumption taxation system that isn't called a carbon tax (Owen, 2006).

3.3 Mapping

In accordance with Phaal's framework, the mapping of the algal biofuel industrial emergence is depicted in the following Figure 17. The mapping approach being iterative, this mapping offers a "quick scan" integrating the major events that participated in the progression of the algal biofuel. As such this approach also serves as a simplified tool easing the understanding and communicating process of the complex dynamics that an industrial emergence is experiencing.

This mapping helps visualize how and by what emergence is being driven and constrained by placing "events" in a chronological manner and according to where they belong in the value-based perspective. Those events are of different types and therefore categorized according to the type of influence they have i.e. either enabling or constraining the emergence and to the nature of their influence i.e. technical or economical. Future events that are projected to participate in accessing next development phases are also depicted.

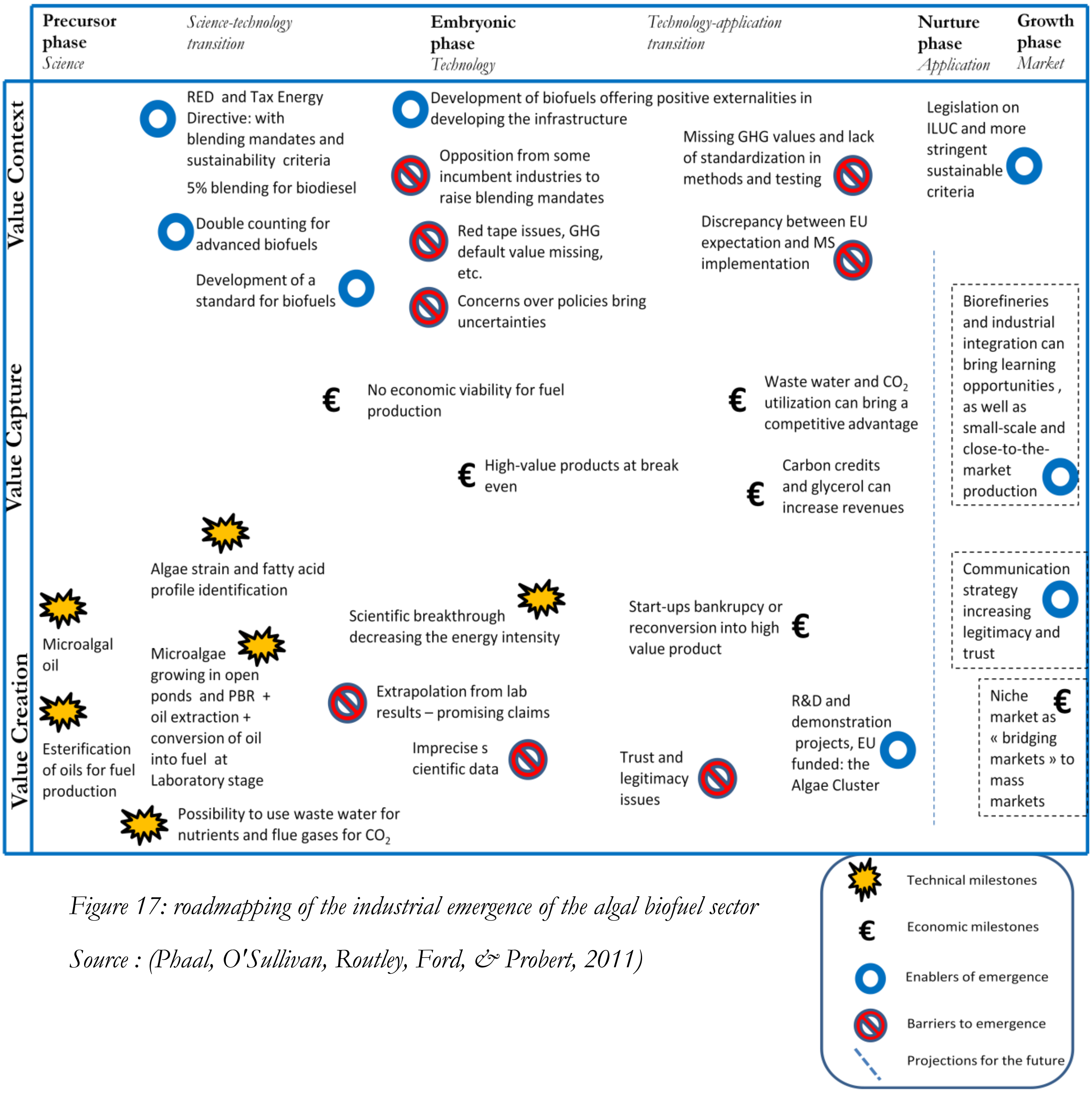


Figure 17: roadmapping of the industrial emergence of the algal biofuel sector

Source : (Phaal, O'Sullivan, Routley, Ford, & Probert, 2011)

As mentioned earlier the industrial lifecycle for the sector under study is focusing on the so-called *embryonic phase* and *technology-application transition*; so is the mapping. The technical milestones that participate in building the premise of the industrial lifecycle and enablers for the future development are present while a larger space is dedicated to those phases under focus.

Mapping is conceptualized with the idea of being dynamic and of being a tool for supporting strategy and decision making for managers, thus the version presented here only reflects this particular moment in time.

4. Discussion

This section aims at looking back at the analysis, opening up on interesting perspectives and bringing a critical view on the work.

4.1. Enlarged perspectives

Experts called for caveats and more critical thinking regarding the state-of-the-art of algae and also the future prospects. Despite the upbeat signals from proponents of the fuels from algae, this analysis finds that the algal biofuels industry is situated at the research –mainly- and demonstration –in a minor degree- stage and has not entered the realm of commercialization. The economics remain unproven and the question to be addressed is how the economics of algae can be improved as the applications move towards larger scale. In the eyes of the expert informants for this study that are aware of all the challenges ahead in the industry we might end up with a biofuel from algae but it will take some time and we should keep researching and testing. As Bergek notes, some "formative phases" can be very long, some technology needs decades to materialize (Bergek et al., 2008) –this does indeed seem to be the case for algal fuels. In the end, as it has been said during an interview, biofuels from plants is a rather new way to use crops but plant cultivation has been harnessed for thousands of years while microalgae is totally new, so it is even more difficult to understand what it is to grow algae.

Looking at other industrial sector development reveals that predictions on time to market i.e. the length of time it takes for a product to be available for sale, are sometimes much longer than what actually happened. For instance 20 years ago solar PV were said to need a cost drop of at least 90% to become cost competitive, which hasn't yet happened in reality and now solar PV are at a much more advanced market phase. This can indicate that the time to market for algal biofuels could be shorter than what some have stated and also shortened by other events that may or may not be directly related to research within the specific field of algae-based biofuels. Reflecting on other innovations and industrial sector emergences also shows that there are unpredictable forces and discoveries that can steer the market in unexpected direction. For instance, the first large-scale use of bioethanol in Brazil was not aiming at replacing fossil fuels but at solving sugar production and export difficulties. There are industrial co-benefits that can emerge; one high profile example of such being the huge benefits to electric cars that the development of batteries in cell phones brought. It is well established fact that gaining of experience in some sectors has potential to generate knowledge that spills over, creating positive externalities. In the end, Rudolf Diesel invented the diesel engine that originally ran on peanut oil and stated himself a century ago: "The use of plant oil as fuel may seem insignificant today. But such products can in time become just as important as kerosene and these coal-tar-products of today".

Coming back on the Brazil example, all fuels and biofuels have been subsidized and most of them are not competitive under current market prices, maybe with the exception of sugar cane-based bioethanol in Brazil. Some argue that industries that need subsidies are not economically viable and therefore not investable (an argument used, for example, by Vinod Koshla, the American businessman and clean technology venture capitalist). This argument sounds odd when knowing to which extend those subsidies are supporting biofuels, and even fossil fuels in many regions. It is true though that the extent to which governments can push the industry has a natural limit and the industries respond to the market place signals.

The rationale behind the learning curve theory for new technologies that implies that producing higher value products to run viable business models can help gain experience and thereby lower the cost (IEA, 2003) has to be verified in reality for the algal biofuel new technologies. Indeed, it has been pointed out that interestingly high value producers have not ventured into low value products or at least not yet ventured into it. Some companies that have converted into higher-value products after being unsuccessful with an elusive algal biofuel production do not preclude the latter as a potential opportunity for the future. This is how the bridge between both activities has been built and how intuitively one can think that economically viable items can support what is not yet viable and needs time to become competitive on the market. So, one cannot conclude that making biofuels from algae is the only scenario that algae as an energy carrier will follow. There are many other ways to extract the energy potential from algae that could make sense for the industry on the economic perspective.

In the words of the World Energy Council (2010) "in general, as an alternative to oil, biofuels are not a safe investment today. As a potential help to climate change regulation, biofuels look like a good investment" (WEC, 2010). This is an interesting statement because it illustrates that there is a need to look at a much bigger picture when thinking about the different options that new challenges such as climate change, energy security and so forth, are creating a need for. Following the food controversy for crop-based biofuels, algae of certain type contain many nutritious elements such as carbohydrates, proteins, lipids rich in omega-3 and there are two direct implications: the industry might focus on those products in case of food shortage for instance or for other economically sound reasons and green organizations may criticize algae production to be directed to fuel production while foodstuffs could be produced. Criticism by organizations reveals the degree of expectation that the need to develop sustainable new technological options raise. Biofuel development and sustainability are intertwined to the extent that cost-effectiveness, competitiveness, social opportunities, along with employment and lower overall impacts on the environment, are expected from those biofuels. This is a massive undertaking in relation to concepts that are not fully understood and sometimes controversial. In line with that observation it is natural to think that the pace at which technology evolves is much faster than the degree of understanding, awareness, legitimacy and acceptance from public and private actors, although it seems that there is a deep need to address those issues.

Finally, some other new technologies face similar industrial emergence issues than algal biofuels. One such example is the glycerol industry that has been touched on during the analysis and for which similar work to this thesis can be utilized. Another example are the other algal applications, for fuel making or not, from macroalgae and autotrophic microalgae, which have been excluded from the scope of this study.

This thesis explored the possibilities of gaining learning opportunities for algae growing through concepts such as biorefineries and industrial integration. It also explored the opportunities that business models based on market proximity, small scales and flexibility can bring in order to gain economic viability. All of those participate to a paradigm shift in the traditional economic model for fuels. As Richard Buckminster Fuller, the famous American engineer and architect stated: "in order to change an existing paradigm you do not struggle to try and change the problematic model. You create a new model and make the old one obsolete".

4.2. Critical considerations

This thesis process had a turbulent start after the company it was supposed to be written for retracted shortly before starting the process. The motivation for the topic was intact; thus switching for a different focus area had to be made. Such as thing, as well as defining a research focus that has not been specifically required by anyone, takes some time. These unexpected adjustments slowed down the process and very likely limited the level of in-depth analysis that was brought.

Looking back on the method used, and especially the interview methods, it would have been interesting to have carried out face-to-face interviews because there are always richer in details but that was practically impossible as interviewees were spread all over Europe. Finally, the choice of theoretical framework, using industrial emergence mapping, brought an interesting value to the structure of the work. However, the mapping per se is limited in its capacity to add a real value in the end; apart from maybe a visual perspective on the work.

5. Conclusion

In the following section, the research question is revisited, in line with the aim of the work, so that the findings can provide an answer, further completed by remarks.

For this analysis, the research question was: How is the emergence of the algal biofuels industry currently constrained? And the aim was defined as providing a comprehensive understanding of various technico-economical, political and social elements that constrain the progression of algal biofuels in the European Union, based on an objective and realistic assessment of this industry.

The algal biofuel industry is at an embryonic development phase and seeks opportunities for its further development. Although there are many drivers for this industrial sector to emerge, there are also many constraints that need to be overcome in order to fully harness the market potential. The main constraints are listed as follows:

- Technico-economical constraints
- Political constraints
- Social constraints

5.1. Technico-economical constraints

There are many scientific and technical challenges to be addressed, at both research and scale up levels, in order to reach economic viability, a positive energy balance and process consistency. Algae growing and harvesting is a new process, the complexity of which is surely underestimated. In parallel, there are tens of thousands of algae strains existing with as many different fatty acid profiles, many of which have not been studied yet or even discovered. Thus, complexity also stems from the fact that each strain is specific regarding its growing requirements, which in returns also influences the fatty acid profile. Additionally, the lack of standardized methodologies for fatty acid profiling and biodiesel performance testing participate to the lack of clarity this industrial sector is suffering from.

Using waste water, in light of a potential future nutrient shortage and rising nutrient prices, and utilizing carbon dioxide from flue gases are very promising in their ability to greatly improve the sustainability of the industry as well as its economics. This uniqueness also gives the algal biofuel industry a competitive advantage over other biofuels. However, this comes with additional technical challenges to reach consistency and a good enough quality of biofuel.

The sector also has a funding problem. There is a need for investment money with a long term perspective, knowing that new technologies carry uncertainties, risks and long term pay offs. Algae biofuel production is a new technology that certainly belongs to the ones that need decades to reach commercialization. Such time frames do not match with the investing world short term vision. In parallel, the sustainable potential that this new technology carries, hidden behind a very long industrial emergence time frame, is not accounted for in the eyes of many public and private stakeholders.

Importantly as one looks to the future, this study indicates that the learning curve theory implies a cost reduction over time so that break-even points are reached through learning opportunities brought by both public and private actors; there is a transition from public funding to private ones as the technology matures and subsidies phase out. After a certain cost reduction, niche markets can help serve as “bridging markets” toward mass markets. The aviation industry can serve as a bridging market as it is bound to liquid drop-in fuels and is looking at alternatives to fossil kerosene. While high-value products already break even, coordinated developments such as biorefineries and industrial integration carry economic viability potential, and all of those models represent learning opportunities and hence potential for cost reduction. Learning opportunities and cost reduction, reinforced by a strategic positioning, can also be attained by a deployment phase characterized by smaller plants, closer-to-the-market with flexible design. No need to say that design flexibility is more complex and thus can be a constraint per se.

Cost reduction can also be achieved through revenue diversification. Carbon credits from using CO_2-rich flue gases are an avenue for increasing the profitability of the system although it cannot sustain a business model. Indeed, the price of a ton of carbon within the EU Emission Trading Scheme (EU ETS) is currently too low. Glycerol – the diesel production by-product- also participates in the possibilities to diversify the revenues from biodiesel production. Nevertheless, as the market reached saturation, it will be the case only once new applications will be found, especially new applications for unrefined glycerol.

Finally, market failures are a redundant problem for the competitiveness of technologies that perform better on the sustainability perspective since negative externalities are not borne by the ones that generate them. In the case of algal biofuels, market failures tend to favor existing technologies and not new ones. In addition, negative externalities hinder visibility over the real costs and positive externalities are not accounted for within the current system. A realistic comparison between all the existing fuels is thus biased.

5.2 Political constraints

There is a strong policy framework at the EU level that one can think as the major driver for ensuring a market and bring certainties. Nevertheless, the concerns over some of its aspects are instead bringing ambiguity and hence uncertainties. Misleading market signals on the kind of biofuels that were to be accepted by the European certification scheme is one example. Nevertheless, it seems that the latest European legislation in relation to addressing the indirect land use concerns is about to remedy this uncertainty and promote the development of advanced biofuels. However, there is still no GHG default value for growing algae for fuel making while the importance of GHG emission saving predictions has been demonstrated. Indeed, the GHG default value allows accounting for the GHG emission savings achieved through the production of any biofuel, in order to comply with the sustainable requirements of the Renewable Energy Directive.

At another level, regarding certification and standard, there is a European standard for biofuels that all biofuels need to comply with and there is a European diesel standard (EN 590) that allows the blending of up to 7% biodiesel (this implies that up to 7% there is no effect on the engine's warranty). The fact that the technical limit for which there aren't any engine modifications required is much higher than 7%, raises the question of what is limiting this percentage from being upgraded. There are certainly opposition and resistance to change from incumbents such as very likely the engine manufacturing industry. In addition, although the 20% renewable transport fuel target can be met by a wide range of biofuels, a maximum 7% biodiesel blending seems to impose an intrinsic limiting factor that needs to be revised. Any constraint on access to the market for biofuels has ultimately consequences on algal biofuels as there is no distinction of the fuel source within the blending available at the pump station.

At the Member State level, biofuels may suffer from a lack of priority, probably because of a lack of awareness. Indeed, their behavior towards biofuels has been so far a bit disappointing in the eyes of the European Commission. There are still red tape issues with algal biofuels such as licensing for operation and institutional classification that need to be addressed.

In addition, Member States' support schemes reveal the unwillingness to bear the costs of environmental related legislation; those schemes are a mixture of tax exemptions and mandates for which there isn't any assessment e.g. economic assessment on potential contradictory effects. Economic assessment and critical thinking on the system in place would certainly benefit the policy enforcement process.

5.3 Social constraints

The attitude of the other incumbents than the engine manufacturing industry i.e. the agricultural and the oil industries, is hard to predict for now but one cannot exclude any constraining attitudes from them, especially from the agricultural sector now that the use crop-based biofuels is to be limited.

Aggressive claims that overstated the current potential and industrial development of the algal sector contributed to depict an unrealistic picture of this industry, and also contributed to the unsuccessful experience of many start-ups. Indeed, unawareness of the real challenges and uncertainties ahead of the algae-based biofuel industry, in conjunction with attractive claims and the tendency to have willingness to believe in them, lead to many bankruptcy. This underlines that realistic messages from experts have trouble to get through. Although lately the hype has been toned down, those claims in addition to imprecise and unreliable scientific data based on extrapolation from laboratory results, have affected the credibility and degrees of trust in the industry. This has to be regained through a strategic communication and advocates for more honesty when communicating to the outside world.

The fierce opposition to crop-based biofuels (food crops), the weak communication around advanced biofuels, the terminology analogy and the low level of knowledge and understanding on all those issues are a set of communication constraints that raise the question of how to gain legitimacy and acceptance. This work proposes a communication strategy based on the sustainable criteria promotion as a leverage mean for first generation biofuels to become a bridging technology towards more sustainable advanced technologies. In addition the concept of bridging technology accounts for the positive externalities that the development of first generation biofuel may provide for the advanced technologies.

Finally, the algal biofuel production is an attractive sector that still encounters a lot of undisclosed information and secrecy, highlighting a need for better cooperation to foster development.

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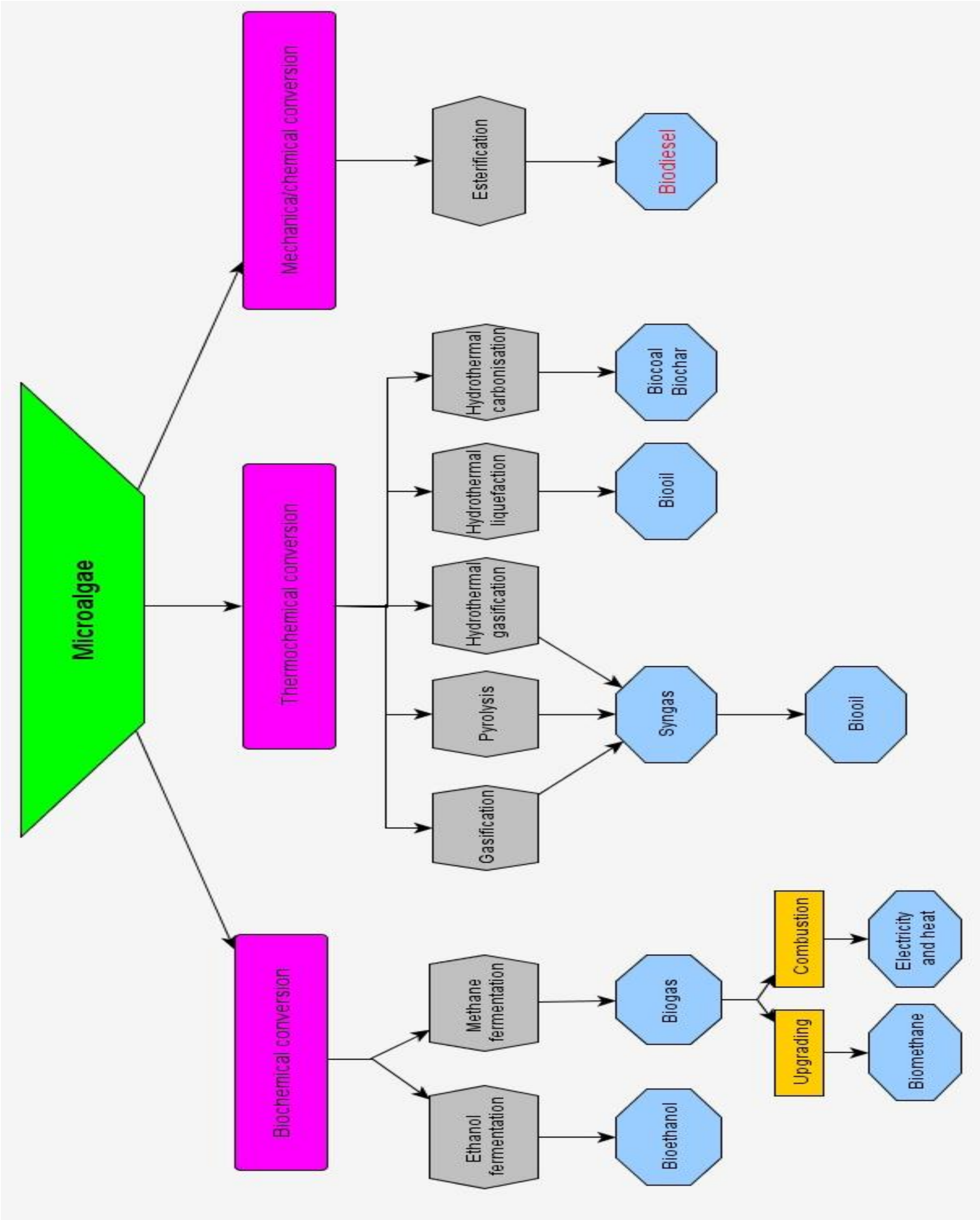
Appendix A: conversion pathway for microalgal biomass



Appendix B: question template for interviews

Technical constraints

What are the major challenges that are encountered on the economical (techno-economical) perspective? Are there cost-effectiveness challenge?

What about the negative energy balance (input>output) that has been claimed about algae-based biofuels production, is it affecting the perception that third party have?

Economic challenges

Are there challenges faced in getting investment money (equity and debt) for deployment and commercialization? If yes, what are they and why?

What strategy could increase investors' knowledge, certainties and interests?

What is the proportion of public and private investment money?

Are there identified market barriers and market to entry barriers that are faced?

If algae-based biofuels production emerges from a business reality that has a broader picture (valorization of high profit margin co-products, energy as a by-product, carbon credits and so forth), what are the challenges and opportunities that stem from that?

Perception of the policy framework & Competition

What is the current perception of the way policies have been designed in order to promote biofuels (especially blending mandates)?

Are there any constraints emanating from the policy framework?

What about incumbent technologies (regarding resistance to change) and sectors with interests that could enter in conflict with algae-based biofuels (e.g. the agricultural sector)? Is it an issue?

Communication and acceptance

What is the perception on those aggressive claims that were made earlier on and the way it affected trust?

What kind of communication is being developed? Is there a need for a communication strategy that could ameliorate the trust and perception of the entire sector?

What is the level of cooperation and organization within the sector and among different actors (political, academia, private organizations)?

Is the algae sector an attractive one? (Regarding possibility to attract skills and knowledge)

Certification and standard issues

Are there any current or future certification and standard issues?

Appendix C: Personal communications

- Discussions

Anselm Eisentraut – IEA; bioenergy specialist, France

Francis Couillard – Safran/Snecma; Environment Director and European Affairs Director, France

Jaap Van Hal – Energy research center of the Netherlands; Professor, the Netherlands

Jean-Philippe Steyer – Inra; Research Director and scientific contact for the GreenStar project, France

Maarten Von Dijk – SkyNRG; responsible for Business Development and Sustainability, the Netherlands

- Interviews

Asen Nenov – Greon Ltd; R&D Manager and Owner, Bulgaria

Frank Rogalla – Aqualia; Innovation and Technology Manager (All-Gas project), Spain

Fredrika Gullfot – Simris Alg AB; founder and CEO of Simris Alg, Sweden

Isabelle Maurizi – European Biodiesel Board; project manager, Belgium

Jerry Lewis – Center for Process Innovation; Technology Specialist and Senior Public/Private Manager, Great Britain

Julie Maguire – Daithi O'Murchu Marine Research Station; Research Director and Manager (European Mabfuel project), Ireland

Kyriakos Maniatis – European Commission; Principal Administrator in Unit C2, Directorate General for Energy, Brussels

Mario Tredici – University of Florence; Scientist and Professor at the Department of Agricultural Biotechnology, Italy

Matteo Prussi – University of Florence; researcher, Italy

Vincent Toepoel – TOEPS; Independent consultant, the Netherlands

- e-mails

Janet Cotter on the behalf of Greenpeance International Science Unit

Steve Cain on the behalf of Friends of the Earth