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*Oil & Gas Science and Technology – Rev. IFP Energies nouvelles*, Vol. 68 (2013), No. 5, pp. 875-898

DOI: 10.2516/ogst/2013164

**Dossier**

*Second and Third Generation Biofuels: Towards Sustainability and Competitiveness*
Seconde et troisième génération de biocarburants : développement durable et compétitivité

# Algogroup: Towards a Shared Vision of the Possible Deployment of Algae to Biofuels

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**Résumé — Algogroup : vers une vision partagée du possible déploiement de la conversion des algues en carburants** — Depuis quelques années, un intérêt croissant pour la production d'algues, notamment les micro-algues, pour la production d'énergie a été observé, spécialement pour la production de biocarburants pour le transport routier et aérien, filière que l'on a coutume de qualifier de troisième génération. Les algues et spécialement les micro-algues affichent de nombreux avantages comparés aux ressources terrestres, comme par exemple une productivité nettement plus élevée et l'absence de compétition avec les filières alimentaires. Néanmoins, l'état actuel des connaissances ne conduit pas à penser qu'un développement de la culture de micro-algues pour la production d'énergie soit possible à court-moyen terme en raison de nombreux écueils à lever comme la balance énergétique, le positionnement économique sans oublier les aspects sociétaux et environnementaux.

Contrairement aux filières de première génération et certaines filières de seconde génération, les biocarburants de troisième génération sont encore loin de l'industrialisation mais la nécessité de disposer d'une analyse commune et partagée par l'ensemble des acteurs de la filière est nécessaire.

Ainsi, en 2010, à l'initiative d'*IFP Energies nouvelles*, *Airbus*, *Safran*, *EADS IW*, et l'*Académie des Technologies* ont mis en place un groupe d'étude national dédié à l'étude du potentiel de la filière micro-algues pour la production de biocarburants G3. Ce groupe, nommé Algogroup, piloté par *IFP Energies nouvelles* a eu comme objectif d'aboutir à une vision partagée d'un possible déploiement de la filière G3. Outre les membres fondateurs, Algogroup a aussi intégré les expertises dans le domaine, de *Sofiprotéol*, de l'*INRA*[1], de *IFREMER*[1], du *CEVA*[1], de *Agrimip* ainsi que de nombreux autres laboratoires et industriels. Les travaux menés au sein d'Algogroup ont donc permis de collecter un ensemble de données sur le potentiel et les limites de la filière, la position des industriels et des laboratoires, sur les axes de recherches nécessaires à mettre en œuvre pour permettre à la filière de se développer. La réflexion a été structurée selon différents thèmes. Les aspects technologiques : quelles souches, quel mode de culture, de récolte, les aspects économiques ainsi que les aspects environnementaux. Ce papier met l'accent sur les

[1] INRA : Institut National de la Recherche Agronomique ; IFREMER : Institut Français de Recherche pour l'Exploitation de la Mer ; CEVA : Centre d'Étude et de Valorisation des Algues.

résultats d'Algogroup sur le positionnement économique et environnemental des micro-algues. En parallèle, une réflexion sur le potentiel des macro-algues a aussi été conduite au sein d'Algogroup. À ce jour, uniquement un nombre limité de données est accessible pour le secteur des "algocarburants" et s'engager dans la construction d'une telle filière est encore prématuré. Ainsi les résultats provenant d'Algogroup seront de précieuses contributions à l'élaboration d'une feuille de route Algocarburants.
Sur un plan économique, les coûts estimés des futurs biocarburants fabriqués à partir de micro-algues s'étaleront dans une fourchette de 2 à 7 $/Gal. Cette situation laisse à penser qu'un large champ de possibilités est envisageable pour réduire le coût de production des huiles algales mais il faut toutefois rester très prudent car les scenarii conduisant à ces diminutions reposent sur des hypothèses qu'il faudra démontrer. En effet, ces scenarii considèrent des technologies et des localisations de production très variables. Un autre point clé des modèles économiques analysés est que dans une large majorité de ces scenarii, la viabilité économique repose sur la valorisation des coproduits. De telles options ne sont pas considérées comme acceptables sur le long terme en raison de l'incertitude qui règne sur les capacités d'absorption par le marché de ces produits lorsqu'ils seront liés à une production en grosses quantités de biocarburants.
Considérant le volet environnemental, le travail a démontré que la balance énergétique n'était pas favorable, en se référant aux procédés explorés disponibles. Toutefois, les variations enregistrées laissent la place à des possibilités d'amélioration. Concernant les émissions de gaz à effet de serre, le bilan apparait favorable mais là aussi avec une plage de variations très large. Pour les autres aspects environnementaux, les incertitudes sont trop grandes pour conclure. Par ailleurs, en raison des très grandes hétérogénéités des approches et des résultats publiés pour le développement d'une filière micro-algues, il apparait que sans évaluation fiable et robuste du secteur, il n'est pas possible de considérer à ce jour le développement des techniques comme totalement compatibles avec les critères de durabilité.
Pour les macro-algues, nous sommes encore très loin de pouvoir les considérer comme une ressources pour la production de biocarburants mais celles-ci présentent des avantages, comme pour le cas des algues vertes des similitudes avec les ressources utilisées pour les filières G1 ou G2. Concernant les algues brunes et les algues rouges qui sont aujourd'hui les espèces les plus produites, leurs compositions demandent le développement de nouveaux procédés pour leur valorisation. Bien que ces procédés soient faisables à l'échelle du laboratoire, la viabilité économique à grande échelle est à démontrer en raison de la complexité et du nombre d'étapes requis par ces procédés tout comme la compétition de cette filière avec les autres marchés, comme celui de la chimie verte.
Par ailleurs, pour que les macro-algues puissent avoir un réel devenir dans le mix biocarburants, leur production doit être considérablement augmentée. Ce point ne peut être considéré sans avoir évalué l'impact sociétal et environnemental et aujourd'hui peu de données sont accessibles pour bien apprécier ces 2 volets. Enfin, il faudrait bien analyser tous les aspects législatifs liés au développement de culture à gros tonnages en mer.
En dépit de ces aspects, le potentiel de production de grosses quantités semble réel. En conclusion, le travail effectué par Algogroup n'a pas fait émerger de réelles ruptures permettant d'envisager un développement à court moyen terme de la filière algocarburants mais des possibilités d'amélioration peuvent être envisagées. Ceci demande de poursuivre les travaux au niveau du laboratoire et à l'échelle du pilote avant de passer à une échelle préindustrielle.

***Abstract* — *Algogroup: Towards a Shared Vision of the Possible Deployment of Algae to Biofuels*** — *A strong interest has been focused from several years on the algae pathway for energy production, especially for transportation fuels called third generation biofuel or G3 biofuel, and mainly from microalgae route, considering it could be a high potential alternative strategy for renewable energy and fuel production. Algae, and especially microalgae, present significant advantages compared with land resources, such as much higher productivity and lack of competition with food applications.*

*Nevertheless, based on current knowledge, the production of an algae biomass for energy remains a difficult target to reach, due to the numerous existing hurdles such as the energetic yield and the economic positioning, without neglecting the environmental and societal aspect.*

*Unlike first generation (G1) and a few second generation biofuel (G2) processes, G3 biofuel processes are far from the industrialization step.*

*In 2010, under the initiative of* IFP Energies nouvelles, Airbus, Safran, EADS IW *and the* "Académie des Technologies", *launched a French national study of the potential of the algae sector as resources for the so called G3 biofuel production. This study was called "Algogroup" and led by* IFP Energies nouvelles. *The objective was to obtain a shared vision of the deployment possibilities. It led to the creation of this Algogroup task force with the previous partners, adding* Sofiprotéol, INRA[1], IFREMER[1], CEVA[1] *and the* Agrimip *pole to combine all available knowledge and determine the responses which could be given to the existing questions.*

*The Algogroup objective was to facilitate vision sharing between participating organisations and industrials on the technical improvements, the probabilities of success, the R&D needs and the development perspectives, while paying close attention to the obstacles which have to be alleviated to improve the positioning of the algae pathway. To reach this target, Algogroup has explored several axes, which enabled a thorough analysis of the potentials and limits of the technology: from the species selection to the harvesting (lipid extraction/recovery), including environmental and economical aspects.*

*This paper focuses on some main aspects of the Algogroup study related to economical positioning and environmental terms, specially Life Cycle Analysis (LCA). A large share of the work was dedicated to microalgae, but since it was also considered important to examine the potential role of macroalgae, a specific analysis was conducted on this aspect. It has enabled the group to issue some recommendations such as a need for an integrated approach, need for tools to run comprehensive technico-economic assessments, including co-products valorisation.*

*Despite the limited amount of reliable information currently available on the algofuel sectors, especially in terms of environmental balance, numerous challenges still remain to be taken up to make these sectors credible and profitable, both technically, economically and environmentally.*

*On the economic aspect the estimated costs for future microalgae biofuels remain in a very broad range from \$2/Gal to \$7/Gal. There remains great potential to decrease microalgae oil production costs, but this has to be considered very carefully given the large amount of underlying assumptions. Moreover, as yet underlined, microalgae biofuels are not currently being produced at a commercial scale, thus these are only potential scenarios, which will have to be confirmed. And finally, several technologies can be used to produce microalgae oil and location possibilities are proposed. Another key point is that, in a large majority of scenarios, the economic viability of the pathway relies on the valorisation of what one usually calls co-products. Valorisation of co-products is not considered a valid option in the long-term as no market identified today could absorb the quantities associated to a new fuel market.*

*Besides, environmental studies have demonstrated that the energetic balance was not favourable at present, based on current processes, but the variation range of the results let some space for significant improvements. The balance of greenhouse gas emissions was favourable, and there also the variation range was very wide. As regards the other environmental impact categories, however, the uncertainties are too great to draw any conclusions. Because of the heterogeneity of approaches and results for the development of the algae pathway, we must bear in mind that without reliable and robust assessments of these sectors it will not be possible to direct their technical development sustainably.*

*Macroalgae as a resource for biofuels production are very far from being a commercial reality, but do present some advantages such, for green algae, exhibiting several similarities with current G1 and G2 feedstock, being producers of starch and unlignified cellulose. Nevertheless, they also contain other specific compounds. Red and brown macroalgae are currently the most produced species, but their composition calls for the development of new transformation processes. Although technically feasible at lab-scale, the economic viability of such processes is being endangered by the complexity of the processes involved and the numerous steps required as well as by non-technical issues such as competition with other markets like green chemistry.*

*To have a true share of the future fuel mix, macroalgae production needs to be increase by a dozen-time fold. This increase should not be done without social acceptance or at the expenses of the environment. This issue was adressed for microalgae, but data on macroalgae are currently lacking to be able to conduct Life Cycle Assessment (LCA) on this very specific environment. There are also additional problems to be taken into account, such as the lack of legislation or conflicts of usage with existing sea activities for example. Potential for high tonnage production seems real, but the challenge is to federate existing actors and new ones to build a new agro-industry.*

*As a conclusion, no true leveraging option, leading to significant breakthroughs has really emerged as a short term solution, but wide spaces for significant improvement could be envisaged and more laboratory and pilot works have to be achieved before being able to move to a higher scale, leading to the first step toward industrial production.*

## INTRODUCTION

The search for new renewable energy alternatives is currently a major concern. Lesser dependency on fossil origin resources, lower greenhouse gas emissions and local pollution are the main factors influencing the choices. In an economically driven world, more hands-on factors such as the possibilities of deployment of the solution at low costs, including the possible reuse of existing infrastructure also have an impact on market accessibility of a technical solution. In this context, biofuels, used for ground and air transportation; or even for marine application, are presented as one of the most interesting solutions meeting these criteria. The compatibility of biofuels with existing fossil fuels allows for partial replacement and blending solutions in existing vehicles, which allows to qualify biofuels as a "drop-in" solution. Depending on the biomass used, however, the potentials for development and deployment of the sectors are more or less relevant. First generation (G1) biofuels have revealed their limitations linked to the resource used, in competition with food applications. Major studies have therefore been dedicated to new sectors using other resources which do not suffer from this limitation. Numerous developments are now under way on lignocellulosic biomass – wood and plant wastes – and this resource, which has led to a second generation (G2) of biofuels, is expected to bear fruit within the next 5 to 10 years. In addition, aquatic biomass resources also emerge as an alternative for the production of energy for transportation, although currently no demonstration has been made. Algae and especially the microalgae offer significant advantages compared with land resources, such as in particular much higher productivity and lack of direct competition with food applications. These proposed advantages generated considerable interest for the sector in the early 2000s, without however having analysed the true potential, faced with key criteria of energy balance and economic positioning. In 2010 therefore, on the initiative of *IFP Energies nouvelles*, *Safran*, *EADS-IW*, *Airbus* and the *Académie des Technologies*, the decision was taken to launch a national study of the potential of the microalgae sector as resource for the so called third generation (G3) biofuels production. The objective was to obtain a shared vision of the deployment possibilities, leading to the creation of Algogroup with the previous partners, *Sofiprotéol*, *INRA*, *IFREMER*, *CEVA* and the *AGRIMIP* pole.

While microalgae exhibit very useful and interesting properties for the production of biofuels their culture and subsequent conversion to fuels also raise a certain number of concerns. The challenge was to gather sufficient data to assess the potential of a pathway and uncover development hurdles to be overcome, while technical development of biofuels from algae is still in its infancy. Facing such a variety of process chains, it was not Algogroup's goal to determine the best one, but to evaluate despite the variety of technical options, if a conclusion can be drawn on the possible deployment of algae to biofuels. Besides the technical and economic barriers to be overcome, the environmental and social barriers must also be identified and anticipated, to avoid any arguments over the development of these new fuels.

Algogroup analysed both the studies and results available within each entity and the literature data, examining the problem from different angles and especially in environmental and economic terms. A large share of the work was dedicated to microalgae, the first two sections of this paper present a synthesis of the analysis conducted, first on the economical positioning of microalgae to biofuels pathways then on the environmental evaluation part. Although less studied so far, macroalgae also appeared of interest and a specific analysis was conducted on this aspect, thereby completing the scope of the study. The third part of this paper summarises this work.

## 1 MICROALGAE FOR BIOFUELS PRODUCTION: TECHNICAL OVERVIEW AND ECONOMIC POSITIONING

### 1.1 Description and Variability in Microalgae Oil Production

Although the concept of algofuels seems like an interesting energy option for the future, it turns out that numerous R&D studies will be required before the production of biofuels from microalgae could become economically profitable at industrial scale. Thanks to their much greater productivity per hectare than from oilseed plants, microalgae are able to produce a large volume of fuels of biological origin, but the scientific community considers that a delay of some 10 to 15 years is required for G3 biofuels to reach their technical maturity.

Technology for processing microalgae is very rapidly advancing, based on a diversity of technical approaches. Several different systems exist for growing, harvesting, and extracting the products, as well as conversion options for the production of biofuels.

The targeted products are varied: biodiesel and biojet fuel being the most investigated, but algae could also allow production of bioalcohols, biomethane, biohydrogen. The main advantages of algae are fast growth, high productivity (biomass yields 2 to 3 times greater than the maximum figures obtained for traditional agricultural cultures, and sometimes quoted as being 6 to 60 times higher for oil productivity per hectare), high lipid content (up to 70% of their dry weight), possibility of culture on non-arable land, and without light addition, limited footprint of the installations.

While the contemplated process steps are mostly similar in all studies, numerous technologies exist for each one, which choice will impact greatly important results of the global process chain such as the Net Energy Ratio (NER) or the spatial productivity for example. As the scientific community has not yet reached an agreement regarding which technological string will lead to the best results in all domains (economical, environmental, delivered quantities, etc.), no exclusion was made *a priori*.

The common process steps are: selection of the algae and cultivation, harvest and dewatering, conversion into biofuels, use of the biofuels, and co-products treatment. Figure 1 presents an overview of process steps when lipids are the intermediate for the subsequent production of biofuels, although not the only possibility, this pathway is the most documented one.

Table 1 presents an overview of different potential technologies with a summary of their strengths, weakness and current economical positioning, the different

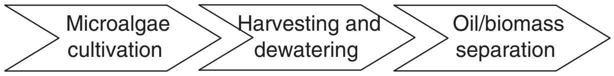



Figure 1

Microalgae oil production stages.

options being discussed in this section, although without any pretention to do so exhaustively.

The microalgal biofuels production spectrum currently comprised a complex set of steps: 1) microalgae cultivation, 2) harvesting and dewatering, and 3) oil/biomass separation[2]. Microalgae are highly versatile organisms presenting many pathways. A non-exhaustive description is provided linked to economical aspects [1, 2].

As illustration of the diversity of the technologies, the cultivation step already offers two choices: Open-Ponds (OP)[3] and photobioreactors (PBR)[4], which differ a lot in terms of energy use, investment costs and achieved productivity and therefore spatial occupation of the technology. Maximum algae concentration is also different between the two. Within this, PBR designs are also varied, quoting as illustration flat-plate PBR, tubular flat PBR, and vertical tubular PBR and so on.

Similar technology options exist for the harvest step. Dewatering can also be total, including therefore a drying step, or partial and possibly achieved during the harvesting step. The main options for harvesting are shortly discussed. Centrifugation offers a harvesting efficiency over 90% but with high energy consumption. Filtration presents a harvesting efficiency between 20% and 90% but with many disadvantages such as small volume treated, application limited to microalgae over 70 μm in size, time-consuming and risks of clogging. Flocculation shows a harvesting efficiency between 50% and 90% but applicable mostly for microalgae with low density and with the following disadvantages: need for flocculants' use, difficulty of treating or recycling the flocculants. Flotation can reach up to 95% harvesting efficiency but is an energy-intensive process. Sedimentation, which consists of dedicated ponds to increase the algae concentration by a factor of 10, is a process

[2] A fourth step is the end-use fuel production that we assumed to be the same for both microalgae oil, vegetal terrestrial oil and crude oil.

[3] Open Ponds/raceways are opened models with motorized paddle-wheels which allow to continuously circulate the culture and keep algae suspended in the water.

[4] Photobioreactors are enclosed devices used for specific strains. All PBR use a light source (either natural or artificial). Other critical inputs such as $CO_2$, nutrients, must also be entered in the system.

TABLE 1
Description of the various pathways of microalgae oil production [1, 2]

| | Various options | Strengths | Weaknesses | Costs |
|---|---|---|---|---|
| Microalgae cultivation | Open Ponds/raceways – OP [2-4, 5*] | Ease of scale up<br>Technology readily available | High water use (evaporation)<br>Low flexibility to strain selection (open to invasive species) | Low capital investment<br>High downstream processing cost (very diluted culture) |
| | Photobioreactors – PBR [2-4, 5*] | Low water use<br>High flexibility to strain selection (closed system) | Scalability (depends on PBR type)<br>Technology not demonstrated on large-scale | High capital investment<br>Low downstream processing cost (moderate density culture) |
| Harvesting and dewatering | Filtration/ Microscreening | Simple method<br>No energy intensive process | Time consuming (low flow rates)<br>Limited yields | Low to moderate |
| | Centrifugation [2-4] | Highly efficient | Highly energy intensive process<br>Second watering step needed | Very high |
| | Flocculation [2-4] | Capacity to treat large volumes<br>No energy intensive process | Complementary harvesting technique needed<br>Dewatering step needed<br>New chemical (difficult to remove) | Moderate to high (chemical flocculation)<br>Very low (Bioflocculation, autoflocculation [2, 3]) |
| | Flotation [2, 3] | Efficient for a certain strain of microalgae | Complementary harvesting technique needed | Moderate to High |
| Oil/Biomass separation | Physical [2, 3] | No caustic chemicals needed | Energy intensive process<br>Secondary extraction techniques required | Low to high (depends on the process) |
| | Chemical [2-4] | Efficient process<br>High oil quality | Negative impacts on environment<br>Energy intensive | Low to high (depends on the process) |
| | Enzymatic | No dewatering required<br>No caustic chemicals needed | Low yield<br>Significant amounts of water and energy | Very high |
| | Wet/single step | No caustic chemicals nor heavy machines needed | Very new techniques | Low |

*The Process Evaluation/research Planning (PEP) concept of microalgae oil to biodiesel process is based on non-proprietary information. The process design combines several technologies and may not represent precisely any actual operating facility.

consuming little energy but increases the land use of the algae farm.

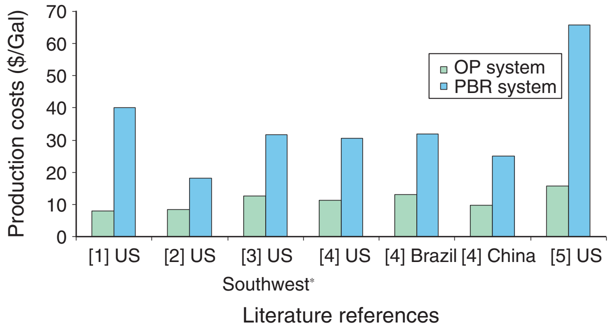
Regarding conversion into biofuels, the most studied pathway is a first step of lipids' extraction and then conversion of lipids to biofuels with technologies existing on terrestrial lipids. Oil/Biomass separation step is currently still a technical hurdle that requires more investigation. Other options include total treatment of the algae *via* thermochemical conversion (pyrolysis, gasification) or so-called wet conversion (such as hydrothermal liquefaction), all with or without catalytic doping. While the option of lipids valorisation has the advantage of using already commercial technology and producing an algae residue from which nutrients might be recycled, the option of valorising the entire algae usually allows for better energy balance.

Preparation of algal biomass before its conversion is obviously highly dependant on the downstream conversion process considered. It usually includes two steps which are involved in the environmental balance: drying of the biomass and extraction of the lipids contained within the algae. Those two steps are relevant for the production of biodiesel from lipids. Some conversion processes could render these steps optional, such as hydrothermal conversion which can treat the whole wet biomass.

Last but not least, the source of carbon for biomass growth is another possible source of process discrepancy. While most studies and publications are based on algae grown in autotrophic mode, *i.e.* using $CO_2$ as the source of carbon and solar energy *via* photosynthesis to assimilate the carbon, another growth mode, called heterotrophic, is investigated. It consists in assimilating carbon already under soluble organic matter form, for example sugars, glycerol, etc., and using energy from degradation of carbon molecules for carbon assimilation. Usually when considering autotrophic mode, it is assumed $CO_2$ from a combustion process, such as a power plant or cement plant, will be injected, frequently by injecting directly the flux gases. This is to ensure algae growth will not be substrate-limited. The growth limitation will come essentially from light-access, which is the reason behind the very dilute, 4 g/L being a commonly admitted maximum for PBR, concentration of algae in the culture media in autotrophic mode. When heterotrophy allows for higher concentration, the costs of organic substrate need to be accounted for but not only, other questions arise. While autotrophic mode truly allows for microalgae to be considered a new resource, the status of heterotrophy is subjected to debate. As illustration, should algae grown on glucose extracted from terrestrial plants, the same currently valorised in ethanol at commercial scale, really be considered a new resource? Most of the time heterotrophic process relies on the conversion of organic matter present in waste water, allowing at the same time production of biofuels and waste water treatment. If this implementation could present a lot of advantages, it should be underlined that this will limit site location for algae production. As for other location constraints, like conflict of usage in coastal area, presence of $CO_2$ source nearby, access to water, etc., the authors distress that no extensive study has been published to date to evaluate the true constrained potential of algae production around the world or at national level, now or in the nearby future.

## 1.2 Economical Key Parameters of Microalgae Oil Production

According to the production technology and production factors, a wide range of prices exists in the literature to produce oil from microalgae. Based on several credible sources, experts' opinions, and technologies, average prices for microalgae oil for these past few years vary in a wide range between 8 \$/Gal and 65 \$/Gal (*i.e.* 1.6 to 13.2 €/L), according to recent studies [1-5].




*Based on [2] but updated to $2007, and simulated with inflation costs over the 10 years modelisation

Figure 2

Microalgae oil production costs based on selected literature references.

The aim of this section is to highlight the underlying reasons of the prices variability of microalgae oil produced from autotrophic microalgae *via* both Open Pond/raceways (OP) and closed tubular photobioreactor (PBR) systems.

A first part discusses the production costs given the scenario case covering for the various technical options available. A comparison between production modes will attempt to interpret the results. Second part of the study focuses on economical key parameters and opportunity of microalgae oil on current and future fuel market.

A global overview of Figure 2 shows the wide range of production costs. PBR production costs are always much higher than OP production costs. It is not possible to compare the various results because they are based on different technologies. Only results from source [4] can be compared and a conclusion is that the technology used to produce the microalgae oil does not seem to consume a lot of energy. Indeed the prices for total utilities are not correlated to the prices of oil production. This can be an hypothesis to explain the diversity in the other results.

The graph raises another question about the advantage to use PBR technology because production prices are always higher than for OP technology. Several reasons can be highlighted such as the mitigation of exterior contamination; the elimination of issues related to seasons, weather, or night; higher biomass production and lipid yields; and finally associated costs continue to drop.

Literature highlights main key parameters allowing to decrease microalgae oil production costs. Sensitivity analyses and financial Monte-Carlo analysis have been

performed [1-3]. The main identified cost drivers for both OP and PBR systems, in order of influence, are:
– maximisation of lipid content,
– microalgae growth rate.

Globally the financial feasibility of PBR system is actually much lower than the OP one for the current microalgae yields. Indeed this feasibility and also the economic success depend partly on CAPEX and OPEX, much higher for PBR systems (around triple).

Currently the technology to produce microalgae biofuel is in constant improvement and some lack in literature hypothesis can be highlighted, due to a lack of data. Microalgae biofuels also produce high value co-products not often assessed in the studies. Similarly the cost of the $CO_2$ needed for microalgae cultivation is often neglected, as well as the credit for fossil $CO_2$ reduction. Also the feeding nutrients during cultivation phase could be wastewater treatment, which will represent the same issue as for $CO_2$ credit.

As well, neither states subsidies are included in economic analyses, nor the variation of the plants location. In an energy consuming process, plants location and besides electricity prices would probably have a significant impact on the oil prices.

### 1.3 Discussion

Sikes *et al*. [1] concludes with objectives for future microalgae biofuel prices between 1.4 \$/Gal and 3 \$/Gal[5], which are cost competitive[6], but depending on improvement of parameters and technology stages studied above, such as:
– production volume levels,
– microalgae species and production system,
– harvesting and dewatering technology,
– technology used to extract biomass,
– how by-product are valued.

Davis *et al*. [2] assesses feasible long-term research advancements in strain improvement: growth rate of 40 $g/m^2$/day for OP and 2.0 $kg/m^3$/day for PBR (currently 25 $g/m^2$/day and 1.25 $kg/m^3$/day) and a 50% content of triglycerides (currently 25%). This scenario leads to microalgae oil selling prices between 4 \$/Gal to 7 \$/Gal. With such a technological progress, yield for microalgae oil would be twice higher, which corresponds to multiply by about 50 the current yield for vegetal terrestrial oil to around 100 with research improvements[7].

There is great potential to decrease microalgae oil production costs but this has to be considered very carefully given the large amount of underlying assumptions. Moreover, as yet underlined, microalgae biofuels are not currently being produced at a commercial scale, thus these are only potential scenarios, which will have to be confirmed.

Finally, several technologies can be used to produce microalgae oil and a lot of location possibilities are available.

## 2 MICROALGAE FOR BIOFUELS PRODUCTION: POTENTIAL AND LIMITATIONS OF ENVIRONMENTAL IMPACT

From an environmental point of view, the microalgae to biofuels pathways are starting to be evaluated, as are the G1 and G2 biofuel sectors, through Life Cycle Assessments (LCA). LCA are used to draw up an environmental balance over the entire life cycle of the products studied and identify the sensitive parameters of these balances (penalising steps or penalising flows of materials or energy, identification of improvement levers). Moreover, LCA can be used to evaluate a number of environmental indicators simultaneously (greenhouse gas emissions, aquatic eutrophication, acidification, etc.), and therefore to identify the advantages and impacts of these sectors by comparing them together or with reference sectors. Few complete LCA studies have been published to date on microalgae, but they can be expected to multiply in the future with the research work conducted on these sectors[8].

[5] These prices have to be considered very carefully because potential gains and technology improvements have not been demonstrated. The range is based on 2010 statements from US Defense Advanced Research Projects Agency, Science Applications International Corporation, and CEOs of microalgae oil plants. The prices decrease could thus be a little bit high.

[6] If we consider a 900 $kg/m^3$ density for microalgae oil, this leads to prices comprise between 400 \$ and 900 \$ per ton. The 3 \$/Gal price would barely correspond to current prices for vegetal terrestrial oil (around 900 €/ton).

[7] Based on Chisti report [6], we assumed that for PBR 2.0 $kg/m^3$/day is equal to 78 $g/m^2$/day, and 1.25 $kg/m^3$/day correspond to 49 $g/m^2$/day. Based on [2], we assumed 330 days/year of operating days for both OP and PBR. This leads to PBR yield comprised between 160 t/ha/yr and 260 t/ha/yr. For OP, yields are in a range between 80 t/ha/yr and 130 t/ha/yr. For 50% triglycerides, 80 t/ha/yr < PBR oil < 120 t/ha/yr and 40 t/ha/yr < OP oil < 65 t/ha/yr. Currently oil extraction rate is more about 25%, this means 40 t/ha/yr for PBR oil and 20 t/ha/yr for OP oil.

[8] In March 2011, about 15 LCA studies, more or less complete (sometimes very limited, or forming simply environmental studies on a criterion) were published on the environmental performance of algal sectors and considered for the Algogroup work on the environmental balances of these sectors. The studies came from Europe, United States of America, Brazil, Asia and Australia, where laboratories were interested in this biomass, most published during the last two years. Since then, more studies have been published, of higher quality, providing more complete LCA results. To date about 15 complete LCA studies may be considered on the subject.

The following section presents an overview of the existing published data on environmental assessment, drawing conclusions when applicable and underlying way of improvement, both in term of environmental balance of this pathway as concerning the methodology and quality of the evaluation itself.

## 2.1 Problems Identified

### 2.1.1 Environmental Issues

In terms of results, it currently seems that the environmental balances of the algofuel sectors are highly variable and depend on the following key parameters[9]:

- algae culture modes (*i.e.* the types of infrastructure: either in Open Ponds (OP), photobioreactors (PBR); or fermenters) which determine, amongst other things, the algae concentration of the culture medium;
- algae productivity of the culture (generally expressed in g/($m^2$.day));
- $CO_2$ procurement types;
- quantity of energy consumed for algae culture, harvesting and drying;
- fertilisers provided (quantity and origin);
- water consumption and treatment of effluents;
- treatment of co-products and choice of allocating the impacts between products and co-products.

For algal biodiesel in most studies this would reduce the impacts on climate change when used in vehicles compared with Diesel or other biodiesels, which is not necessarily the case for other impact categories (pollution transfers, variable results depending on the studies). These points are detailed below. No public LCA are available for the other outlets in terms of algal-based fuel types, or at least very few: 2 studies for aviation turbine fuel from algae listed in the Algogroup studies.

Identified environmental issues are presented below, first classified by life cycle steps, then by environmental impact category.

#### 2.1.1.1 By Life Cycle Steps

##### Algae Culture

At the cultivation stage, two main areas of discussion arise when addressing the environmental balance. The first lies with the origin of the carbon used for algae growth, the second concerns variability of results of the different technological options for culture of algae.

Algae require carbon input to ensure their growth. The carbon can be provided as $CO_2$, in which case the algae will use the photosynthesis to convert the $CO_2$ into organic carbon, this growth mode is called autotrophic. Carbon can also be provided as soluble organic matter, in which case algae can use the energy released by degrading the organic matter to assimilate the carbon, this is the heterotrophic mode.

It has been estimated that 1 kg of dry algal biomass represents up to 1.83 kg of $CO_2$ fixed under good culture conditions[10]. This fixation potential however, must cope with several limitations before being considered as a promising technological solution of $CO_2$ capture: ability of the microalgae to grow in environments with very high $CO_2$ contents, optimisation of $CO_2$ solubilisation, thermal stability for the microalgae. In addition, the reuse of organic carbon before the biomass decomposes must be anticipated.

It is therefore an advantage for algae in terms of $CO_2$ capture, but this activity must be integrated in a global energy production system to ensure optimum valorisation. Coupling energy production plants and algae production sites could in fact be considered. The $CO_2$ could then come from the smoke of a nearby power plant: in this case, the two sites should be associated; but it could also come from a unit which would benefit from a $CO_2$ capture solution. This second option offers the advantage of a higher $CO_2$ concentration at the algae plant inlet. In this case, the two sites would not necessarily be next to each other, opening perspectives for companies producing energy or generating $CO_2$ (such as cement works) for $CO_2$ capture and conversion. This $CO_2$ could be transported (possibility of road transport if liquefaction of $CO_2$ or if in supercritical state). Nevertheless, $CO_2$ extraction and preparation in order to transport it in dense state are energy-expensive and therefore expensive for the environment.

For heterotrophic mode, carbon substrate must be provided in large quantity. The source of carbon substrate will greatly influence the environmental balance; most studies will consider waste water as a source of carbon (as well as nutrients), which raises again issues around defining the LCA boundaries between the algae production site and the carbon providing site.

*Environmental Issues Identified at this Stage:*

The source of carbon required for algal growth has a strong impact on LCA, but more importantly, raises concerns around the methodology to be used. Whether the $CO_2$ is biogenic or fossil and how to calculate the

[9] Observation also made in the thesis of Collet [7].

[10] From Christi (2007) [6]: 1.83 kg $CO_2$ fixed/kg of dry algal biomass, and Patil *et al.* (2008) [8]: 1.5 to 1.8 kg $CO_2$ fixed/kg of dry algal biomass.

quantity of this $CO_2$ is a first interrogation. Secondly arises the question of carbon neutrality in the global balance depending on the $CO_2$ provided, of absorption by the algae and the combustion step of the fuel produced. In terms of performing the LCA, the question of the boundaries of the sectors studied is a central one. Depending on the source of the $CO_2$, does the LCA start with the $CO_2$ entering the algae culture pond (OP) or the PBR; or with the $CO_2$ being captured in the energy production plant and which must be transported? Is the $CO_2$ captured by the algae a waste or a product? What upstream environmental load should be allocated? The possibility of utilisation and simultaneous treatment of the waste water for algae growth will lead to the same questions as for $CO_2$, how to properly model the coupling of the algae production site with another site producing waste water to ensure the environmental balance is properly accounted for.

Concerning the culture systems, for the production of autotrophic algae, the use of OP is a solution which is less expensive and simpler to operate than the PBR. But it involves larger volumes of water (including water losses by evaporation), greater demand for surface area, increased risks of contamination, less control on production conditions, lower productivity and high energy consumption, although PBR consume even more energy. For heterotrophic production, fermenters consume energy and carbon substrate in large quantities.

*Environmental Issues Identified at this Stage:*

The large energy consumption of the culture systems is a shared environmental issue for all systems considered, which in terms of LCA will greatly affect energy resources. The consumption of products for algal growth, *e.g.* nitrogen and phosphorus, and the origin of these nutrients (use of chemical fertilisers, or calculation of the benefits related to recycling the waste water from the system) are also an important factor of potential impact. The last point concerns the impacts on water: water consumption, composition of the effluents and discharges if any (eutrophisation potential, toxicity?).

### Harvesting of Algae

Harvesting is carried out to separate the algae from the water. This step is even more important due to the fact that the algae content of the culture medium is very low. No harvesting method has yet been identified as being efficient, reliable and at reasonable cost.

*Environmental Issues Identified at this Stage:*

As for culture, the large energy consumption of the harvesting systems is an environmental issue affecting energy resources. The consumption and subsequent discharge of flocculants is also a potential environmental issue, although not concerning all technologies. Lastly, the concentration of algal biomass after harvesting, still relatively low, might call for downstream steps to extract water and increase energy consumption of the chain.

### Conversion of Algae into Fuels

This includes preparation of the algal biomass and its conversion into fuels, which can be carried out by thermochemical (gasification, direct liquefaction, etc.) and biochemical (anaerobic digestion, alcohol fermentation, etc.) conversion pathways, or a combination thereof. The most documented pathway so far is extraction of lipids and subsequent conversion of those lipids into biofuels (trans-esterification – this pathway is not dedicated as a drop in one – , hydrotreatment of vegetable oil).

The extraction step generates co-products as it separates lipids, used for producing biofuels, from the residual algal biomass also named algal cake (as for the fuels obtained from G1 vegetable oils).

Drying the biomass after harvesting is a highly energy-intensive step which has a serious impact on the balance. So far it is performed before extraction of lipids but it should be questioned whether it is a compulsory step or if extraction can be performed on wet biomass as suggested by Lardon *et al*. [9]. On this issue conversion pathways from wet biomass have a true advantage (biological and hydrothermal liquefaction conversion pathways, with moisture content $> 50\%$).

Algae conversion also generates co-products, for example glycerol when esterification of lipids is carried out to produce biodiesel.

*Environmental Issues Identified at this Stage:*

Once again, the energy consumption, here mainly due to the biomass drying step but also to the other technologies employed (to a lesser extent), is one of the main environmental issue. The use of water or discharges – emissions or liquid and solid discharges – of these technologies is also a potential concern. Generation of co-products, and therefore how to allocate the impacts between products and co-products generated (physical – weight, volume – economic *prorata*, or substitution method) is a source of discrepancy between studies' results, on this point one meets with issues already raised by G1 and G2 biofuels industries. Lastly, the variability of conversion/extraction/transformation processes brings complexity in trying to interpret the results.

#### 2.1.1.2 By Environmental Indicator Categories

##### Energy and Greenhouse Gas Balances

Energy and Greenhouse Gas (GHG) balances are now starting to be drawn up for the algae based fuel sectors *via* the LCA. Results vary considerably depending on the studies and the sectors studied, and it is therefore difficult to currently conclude as to whether or not these sectors are advantageous in terms of energy ratio and non renewable energy consumption, as well as the GHG balance compared with reference sectors, fossil or renewable (G1 and G2 biofuels). The uncertainty margins on these results are still very large. They are due to the data and the methodologies used as well as the chosen perimeter. In particular for the energy balance, the lack of homogeneity between the presented indicators makes the results difficult to compare. Some trends can nevertheless be identified.

For example, since to date most studies have been conducted on the production of biodiesel from algae: the LCA of this sector show that the energy balances of the different scenarios studied would not necessarily be favourable. The overall production would often consume more energy than available in the final fuel product: the Net Energy Ratio (NER), representing the ratio of the energy supplied by the fuel to the non renewable energy consumed to produce it, of algal biodiesel would be in a range of values extending from:

- 0.09 to 0.68 for extraction of lipids by dry pathway [9–11][11];
- 0.96 to 1.34 for extraction by wet pathway [9];
- *i.e.* values less than 1, except for extraction by wet pathway and low nitrogen culture of algae [9], resulting in a negative energy balance[12].

These values can be compared with those for petroleum Diesel: 0.9, and for rapeseed biodiesel: 2.3[13].

These results are nevertheless highly dependent on the assumptions made in the studies, and highly variable from one publication to another. The dispersion of the impact values obtained depends on the scenario considered, the upgrading of the co-products and the choice of impact allocation rules.

In addition, for these sectors which consume large quantities of electricity, the considered electricity mix is a key parameter in their environmental evaluation. Use of electricity from a highly decarbonated electricity mix, as is the case in France, in fact, lightens the sector's GHG balance. Inversely, considering a highly carbonated electricity mix, as in Asia or North America, and even in Eastern Europe, could significantly penalise the sector in terms of GHG emissions.

Concerning the GHG balances, the LCA of the algal biofuel sectors (biojet fuel/biodiesel as well as hydrotreated algal oils) show that it would generate a gain in terms of greenhouse gas emissions compared with the production of fossil fuels. However, the Well-To-Wheel (WTW) emissions for these sectors vary widely: from $-31.0$ to $+193.2$ g $CO_2$ eq/MJ of energy available with the fuel produced (not including cases of $CO_2$ capture and geological storage). The high dispersion of the values obtained is once again closely linked to whether or not the co-products are upgraded and the choice of impact allocation rules between products and co-products.

Table 2 summarises the values found in the literature for the WTW balances of the GHG emissions associated with the microalgal fuel sectors (in g $CO_2$ eq/MJ produced).

Taking into account the basic values of the WTW GHG balances for the algal fuel sectors, we observe that these sectors also generate a gain in terms of GHG emissions compared with the reference fossil fuel (about 85 g $CO_2$ eq/MJ for the reference fuel) and in the range of values for biofuels (*e.g.*: 52 g $CO_2$ eq/MJ for rapeseed biodiesel – default value of European Renewable Energy Directive 2009/28/CE). The GHG balance would therefore be favourable to them in these cases, subject to the uncertainties related to these balances, without however being significantly better than for G1 biofuels according to the current studies.

However, with a perspective of industrial production of G3 biofuel in Europe by 2020, trends show that the sectors, as currently described, are unlikely to meet the objectives set by the European Renewable Energy Directive, which stipulates that biofuels must offer a WTW gain in GHG emissions of 60% compared with the fossil reference for new plants commissioned after 2018. Optimisation of G3 sectors must therefore not only aim at reducing GHG emissions but also make them 60% less than the fossil reference (taken as 83.8 g $CO_2$ eq/MJ for gasoline and Diesel in the Renewable Energy Directive).

##### Other Impact Categories

While greenhouse gas energy balances are already uncertain in algofuel LCA, this is even truer for the other LCA

[11] Lardon: NER = 0.51 for normal algae culture conditions and NER = 0.68 for low nitrogen culture; Khoo: NER = 0.23; Razon: NER = 0.4 for H. pluvialis and 0.09 for Nannochloropsis.
[12] Other studies published after the work carried out by Algogroup indicate more positive energy balances for the microalgae sector, with NERs of up to 4. In these case studies, the coproducts of the sector are systematically upgraded (production of biogas, electricity) and the production schemes optimised. Overall however, the LCA studies remain divided as regards this indicator (Benemann, 2012) [12].
[13] From ADEME 2010 report on LCA of G1 biofuels and JEC-EUCAR-CONCAWE 2008 report on future biofuels for the latter values.

TABLE 2
Literature values for WTW balances of GHG emissions [9, 13-17]

| Reference | Crop | Min | Base | Max |
|---|---|---|---|---|
| Campbell *et al.* [13] | Open ponds | −31.0 | 25.9 | 8.3 |
| Clarens *et al.* [14] | | | 56.8 | |
| Lardon *et al.* [9] | | | 65.2 | |
| Sander and Murthy [15] | | −20.9 | | 135.7 |
| Vera-Morales* [16] | | 20.0 | 31.0 | 86.0*** |
| Stratton* [17] | | 14.1 | 50.7 | 193.2 |
| Renewable Fuel Standard ** | | 21.8 | 64.5 | |
| Renewable Fuel Standard ** | Photobioreactors | 20.9 | 50.2 | |

* Studies for aviation (hydrotreatment of algal lipids), biodiesel for the other studies.
** US Environmental Protection Agency. Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis, EPA: Washington, DC, 2010 [18].
*** Value with $CO_2$ capture/storage.

TABLE 3
Algal biodiesel impacts, results of three studies

| Study | Lardon *et al.* [9] | Clarens *et al.* [14] | Collet *et al.* [19] |
|---|---|---|---|
| FU*/LCA method used | 1 MJ of energy produced by algal biodiesel/CML** | 317 GJ of energy produced by algal biodiesel/not documented | 1 MJ of energy produced by algal biodiesel/CML** |
| Ionising radiations | – | | – |
| Photochemical oxidation | – | | |
| Human toxicity | | | – |
| Ozone depletion | | | + |
| Acidification | | | + |
| Marine toxicity | – | | |
| Aquatic eutrophisation | + | – | + |
| Impacts on water | | + | |
| Abiotic depletion | | | – |
| Land use | + | – | – |

* Functional Unit.
** CML 2001, methodology of the institute of Environmental Sciences, Leiden University, The Nederland.

impact categories. Very few studies have been conducted on them, but since they are considered as less robust than the energy and GHG balances, uncertainties therefore accumulate on these impact categories.

For example, for three of the studies listed [9, 14, 19], 10 different impact categories were examined and led to different conclusions, as shown in Table 3 in the case of algal biodiesel, compared with petroleum Diesel or other G1 biodiesels ('+' indicating a benefit for algal biodiesel over the other fuels and '–' indicating potential additional negative impacts generated). In addition, these impact categories do not include any aspects concerning biodiversity, land degradation or overexploitation, or water management and use (water footprint).

*Environmental Issues Identified at this Stage:*

It is difficult at this stage of the LCA publications on algae based fuels to say whether or not these sectors offer an environmental benefit over the fossil fuel or existing or future renewable fuel sectors, in terms of the energy and GHG balances but even more for the other impact categories. The first studies would nevertheless seem to suggest that the energy balance would not always be favourable, although the GHG balance would prove better, more independently from the scenarios considered. As regards the other categories, however, the uncertainties are too large to draw any conclusions.

### 2.1.2 Social Problems

From the social point of view, no study has been conducted yet on the G3 biofuel sectors. Two reasons could account for this situation. Firstly, the fact that the G3 biofuel sectors are still at development stage and that their social impacts are *a priori* difficult to assess. The second reason is that studies conducted to assess the social impacts of the bioenergy sectors are still in their infancy, there being currently no consensus on the methodology to be used. Consequently, the available social barriers that can be identified to date, considering the limited information available on these sectors, are:

- lack of information and visibility on G3 biofuel sectors to perform a prospective social balance for these sectors;
- non-existence of a methodology to assess the social impacts adapted to these sectors;
- unclear boundary between aspects concerning social problems and environmental problems.

At this stage, we can conclude that the G3 biofuel sectors would appear to be interesting since they are not subject to some of the problems faced by the G1 and G2 sectors. The algal pathway does not require agricultural land, its footprint is smaller than for agrofuels. The environmental problems related to land use (direct and indirect GHG emissions related to the change of use, degradation, erosion, overexploitation of this land, water management, biodiversity, competition with food crops and other uses, etc.) are therefore less important.

This said, although the areas mobilised will never be as large as those required by crops for the production of G1 biofuels, the footprint required by algae cultures may be considerable in the case of open ponds.

The question of the land available for this type of installation therefore also arises: given the requirements in terms of light, water, nutrients for this type of culture, coastal areas and coastlines could represent privileged sites, but they come with a host of associated problems: coastal protection, construction, tourism, other uses, etc. Consequently, they may not be the best candidates.

Besides, the development of these sectors already generates ethical issues, such as the use of genetically modified strains of algae, especially if they are to be developed on large scale in the future.

One question currently raised by the scientific community is to know whether the algae produced using fossil origin $CO_2$ should be qualified as a biofuel, since the $CO_2$ discharged during combustion of this fuel would not be biogenic. This question reflects the ambiguity of these sectors but also of the intention behind the production of alternative fuels: should they be renewable, of biological origin, or both? Debates around the algal sectors are likely to focus on this type of question. For the time being, according to regulations (European Renewable Energy Directive), a biofuel is a fuel obtained from biomass and one which must reduce GHG emissions by 35% compared with its fossil counterparts, with no distinction on the type of $CO_2$. Furthermore, the problem could also arise in the case of G1 and G2 fuels, where the $CO_2$ absorbed by plants could be of fossil or biogenic origin.

In addition, risk studies must be conducted on the culture of algae to ensure dissemination hazard in the environment is mitigated and ensure there is no danger of proliferation of potentially invasive species.

The fallout on jobs with the development of these sectors must also be evaluated, as well as the benefits of energy independence offered by the development of these sectors in the concerned regions and countries.

## 2.2 Research Directions Considered, Barriers to Be Removed and Possible Gains

### 2.2.1 Technical Barriers to Be Removed to Improve the Environmental Balances

To obtain more favourable environmental balances, the production systems must be optimised since technological efficiency is directly related to the environmental benefits that a sector can offer. The main technological levers for a profitable sector are based on optimising the production systems, in particular those related to culture and harvesting of the algae and extraction of the lipids obtained. Optimising the algal biomass production systems involves integrated use of inputs, better productivity, lower energy consumption and a choice of species either adapted to the environment conditions or more productive.

To achieve it, a medium term industrial application initially associated with the treatment of waste water and the possibility of upgrading more profitable co-products (high added value molecules) could be targeted, with the following objectives:

- reduce inputs (*e.g.* recycle water and nutrients) and energy consumption, and therefore adopt the concept of biorefinery based on covalorisation and recycling of inputs;
- increase the productivity and algae concentration of the culture medium (automated regulation and control systems, etc.);
- size and model the transfers of scale (ensure the transition from laboratory to industrial production unit, etc.).

More precisely, the aim is also to optimise the harvesting and lipid extraction methods, relying on the most suitable, the least energy-intensive or the most versatile techniques for harvesting, avoiding if possible the drying step which has a serious impact on the balance, and favour the most suitable techniques to the considered case, providing access to the lipids.

The research projects must also cover varied fields such as process engineering and biology.

Optimisations in terms of process engineering may concern the design of PBR to increase the conversion efficiency of light energy and that of OP, their coupling, biomass stirring mode, use of membrane diffusers to improve $CO_2$ dissolution, systems to evacuate the excess $O_2$ to limit photo-oxidative damage to the cells in case of PBR, development of integrated heat exchangers to maintain the temperature in the culture medium and guarantee a good microalgae growth rate and so on.

Biology optimisations mainly concern analysis of microalgal biodiversity and strain varieties (*via* high speed screening for example), improved knowledge of the microalgae metabolism especially concerning the biosynthesis of triacylglycerols (TAG, neutral lipids) to produce biojet fuel and/or biodiesel, better understanding of the stress mechanisms related to storage of lipids. Genetic engineering, especially regarding the synthesis of TAG and biohydrogen with identification of the regulatory mechanisms and key genes is a possible improvement route, within the ethical issues previously discuss.

#### 2.2.2 Improvements Required in LCA Methodology

Lastly, it seems essential to conduct additional LCA studies to make the environmental balance of the microalgae sector more reliable. These LCA must focus on obtaining reliable greenhouse gas energy balances but not only: other environmental indicators available with this method must complete these balances. The LCA scientific community is currently trying to improve the environmental assessment method on a larger scope. The proposed methodological developments concern firstly improvement of some indicators and proposal of new impact categories better characterising the potential impacts on biodiversity, water resources and human health. Secondly, besides attributional LCA currently performed, introducing consequential LCA, which would allow better modeling of the marketing of new fuels, and of the consequences that setting up these sectors would generate on the energy and consumption markets. Consequential LCA are more complex to implement however, since they involve prospective market models, knowledge of the sectors replaced by the generated products and co-products, and are therefore more costly in time and investigations. This type of LCA is valid for an in-depth study, more than for a simplified environmental balance.

#### 2.2.3 Positioning in Time of the Studies and Problem Resolution Hopes (or Non Resolution)

The scientific and technological breakthroughs made on the various parameters mentioned above will partly contribute to size and to model the transfer of scale from laboratory to industrial production unit. As a consequence, the sale of algal biofuels on the market at industrial level is not expected for the next 10 to 15 years, according to the scientific community.

By then, the LCA methodology will have changed and the energy and GHG balances will probably no longer be the only environmental aspects to be considered when determining the merits of a sector.

### 2.3 Discussion

In conclusion, despite the limited amount of reliable information currently available on the algofuel sectors, especially in terms of environmental balance, we see that numerous challenges still remain to be taken up to make these sectors credible and profitable, both technically, economically and environmentally.

From an environmental point of view, according to the first LCA studies on these sectors, it is difficult to draw a conclusion as to whether or not they have a favourable environmental balance, considering the uncertainties that exist on the results of these first sectors (boundaries between various systems, LCA methodologies used, different technologies, non-industrial scales, highly variable results).

Some trends can nevertheless now be identified for these sectors, concerning their GHG and energy balances. The energy balance of these sectors does not seem favourable according to the production scenarios studied (except for lipid extraction by wet pathway). The net energy ratio of these sectors (ratio of the energy supplied by the fuel to the non renewable energy consumed to produce it), is less than 1 (less than 0.7), except for extraction by wet pathway (between 0.96 and 1.34, Diesel being 0.9 and rapeseed biodiesel 2.3). Their greenhouse gas emission balance is also highly dependent on the technical and geographic context, as well as on the calculation assumptions made, but looks to be lower than the fossil references and lower, or in the same range of values, than for the G1 and G2 biofuels: between 26 and 65 g $CO_2$ eq/MJ produced with algal biofuel, excluding extreme study results, as compared with 85 for the fossil reference and 52 g $CO_2$ eq/MJ for rapeseed biodiesel.

As regards the other environmental impact categories, however, the uncertainties are too great to draw any conclusions.

To obtain a better understanding of the environmental and social balances of these sectors, several discussion and development directions must be considered. Development of a methodology to assess environmental balances adapted to G3 sectors (chosen perimeter, status and method used to take into account the $CO_2$ required for growth of the algae, deliberation on how co-products are taken into account, etc.), as well as the methodologies for assessment of social balances are required. In addition, development of more robust and unified indicators to assess the impact on water resources and on the ecosystems should be conducted. Then, environmental and social balances could be conducted on concrete case studies at industrial scale, with reliable and consistent data. We must bear in mind that without reliable and robust assessments of these sectors it will not be possible to direct their technical development sustainably.

## 3 MACROALGAE AS RESOURCES FOR BIOFUELS: POTENTIAL AND LIMITS

When microalgae are in the centre of the media buzz regarding the so-called third generation biofuels, especially for biojet fuel production, they are not the only resources the aquatic environment has to offer: macroalgae are also good candidates as alternative resource for G3 biofuel production.

The term macroalgae covers a variety of species, usually divided in 3 main groups of interest: green, red and brown. Macroalgae, also known as seaweeds[14], are mainly constituted of hetero-polymers of different sugars. Some contains cellulose and/or starch (especially green and red), but other polysaccharides differing from the ones of terrestrial plants are also found. If lipids are the first choice starting material for jet fuel production, actors are also looking into processes to convert glucose, and in a broader scope sugars, into middle distillate. Despite unproven economic viability, linked to high cost of feedstock material like glucose or ethanol and distortion due to existing biofuels subsidies for ethanol, a lot of technical paths have proven possible, at least at laboratory scale.

In this context, Algogroup has decided to set-up a working group to evaluate the potential of a "macroalgae to biojet-fuel" pathway and identify current hurdles, looking at resources potential, possible technological pathways towards biojet-fuel, and preliminary economic positioning.

### 3.1 Resources Assessment

Macroalgae are photosynthetic eukaryotes plants comprising chlorophylls associated to different pigments. These variations in pigmentation allow classification of macroalgae in three main groups differing by their colour:

- brown algae, growing in tempered to cold or very cold waters;
- red algae, growing in tempered to warm waters, and especially in inter-tropical zones;
- green algae, growing in all type of water environment.

#### Brown Algae

Classically, brown algae contain few standard sugars or sugars-polymers, but are predominantly composed of alginates (copolymers of mannuronic and guluronic acids). Their reserve compounds are beta-glucans (soluble polymer of glucose). They can also contain important quantity of mannitol in autumn. These algae show a very high biomass production, can reach large size (up to several dozen of meters for *Macrocystis pyrifera*) and are suitable for open sea cultivation, even to important depths. Brown algae are the first cultivated algae worldwide, mainly for food applications. Most brown algae are marine species.

#### Red Algae

Organic fraction of red algae is mainly composed of sulphated galactans. Some species are cultivated on a large scale in Philippines and in Indonesia for extracting specific phycocolloids carrageenan. These polysaccharides are wildly used in food and drink industry for their ability to form a gel when mixed with milk proteins.

[14] From Wikipedia: seaweed is a loose colloquial term encompassing macroscopic, multicellular, benthic marine algae. The term includes some members of the red, brown and green algae. Seaweeds can also be classified by use (as food, medicine, fertilizer, industrial, etc.).

Recent works have looked into producing alcohols by fermentation of galactose present in polysaccharides in cells walls of some red algae cultivated on a large scale [20].

### Green Algae

Some species of green algae are rich in cellulose. *Cladophora* types contain usually 15% to 30% of cellulose and grow under European latitudes. *Valonia* types have been less studied so far, but can reach up to 70% cellulose content. *Valonia* types can grow under European latitudes but better results are expected in tropical conditions. Other types of green algae are starch plants, with 20% to 30% of starch. Green algae are usually associated with proliferation phenomena as they are well adapted to growth in waters rich in nitrates. Green algae include both marine and freshwater species.

### 3.1.1 Present Situation

Algae cultivation methods worldwide cover a range of practices, from simple seeding to larger scale production managing the entire life cycle of the algae. Brown and red algae are dominantly produced, mainly as food resources and in some cases for industrial applications.

Brown algae are usually produced using "long lines", the vegetal growing on supporting ropes, in open sea, the depth being controlled by buoys and weight, the settings being fixed at sea bottom, between 20 m and 50 m deep. These supporting structures are essentially implemented near natural supply of nutriment (nitrates, ammonium, and phosphates) such as river outfall, or near other aquaculture industries (oysters, fish). In some cases, external supply of nutritive elements is deemed necessary; this can be done by different means: porous containers filled with nutritive solution let to diffuse slowly, boats equipped with sprinklers, soaking of lines in concentrated nutritive solution in large ponds brought to sea before resetting the lines. Algae reproductive elements are collected and young plants developed in a closed and controlled environment (temperature, light), before seeding in open sea when the algae are about half a centimetre. Seeding is done by winding the small ropes carrying young plants around a larger rope which is then unrolled at sea. This production system is the most commonly used in China, Japan and Korea. Ropes can be put horizontally or vertically depending on location and sea currents. Other techniques such as micro-propagation are being developed but are scarcely used so far.

Harvesting techniques are also diverse. Traditionally algae are handpicked with hand-held tools (*i.e.* rake, pitchfork, etc.) especially in countries with low-wage workforce. Machineries exist in Western countries where labour is more expensive [21]:

- flat-bottomed boats also known as "*goémoniers*" in France, with load capacity ranging from 7 to 32 tonnes, using a hydraulic rotating device, called "*scoubidou*", to harvest laminaria (brown algae);
- mowing boats in Nova Scotia for algae from *Ascophyllum* specie (brown algae);
- tailored boats in the USA coupling a mowing system and a conveyor belt, with a load capacity of 300 tonnes, to harvest the giant specie *Macrocystis* (brown algae);
- in Norway, laminaria fields are exploited using special boat equipped with a comb-like dredge, and capacities ranging from 30 to 150 tonnes.

Current worldwide production of macroalgae reaches 12 Millions tonnes dry matter / year (Source: FAO statistics [22]). The main producing countries are located in Asia: China, Japan, North and South Korea, Indonesia, Philippines. These six countries represent 90% of worldwide production and market. 95% of production comes from cultivation close to shore, as opposed to harvesting in natural growth environment. Cultivation remains small-scale, low-tech methods. Algae use was essentially the food market, but since 2009 a new market has arisen: extraction of alginates. Production of brown algae has close to doubled from 2002 to 2007, with growth coming from China both in the food and alginate markets.

Two growing environments are possible for algae: open-sea, suitable for marine species; or lagoons where salinity could be lower (*e.g.* estuary) or even fresh-water.

Costs for open-sea algae are, from *CEVA* and *IFREMER* experience, around 260 €/tonne dry matter, ranging from 200 € to 300 €/tonne dry matter. Published literature on this aspect, although limited, is in line with this range. The cost published in 1982 in USA [23] have been updated to 2011 prices, and the result of the updated estimation is 250 €/tonne dry matter. A more recent work by Roesijadi *et al.* [24] gives a cost range from 230 € to 315 €/tonne dry matter for open-sea.

It should be emphasise that contrary to what is usually expected when industrialising and developing an activity, the necessary increase in open-sea cultivation and harvesting of macroalgae is unlikely to drive down the resulting cost. Although improvement and mechanisation of harvesting techniques are likely to reduce the cost of harvest, the increase in production can only be achieved sustainably by putting area to cultivation to increase natural production of biomass, as opposed to harvesting naturally grown algae which is dominantly done today. This yield increase will require more involvement during the growth stage, through seeding, nets and ropes surveillance and maintenance, possibly supply of nutriments in some area, and this will increase the cost of the algae grown in open-sea. As a result, current costs between 200 € and 300 €/tonne dry matter are seen as long-term target costs for this resource. Hypothesis of lower costs achieved thought mass production do not fit the field's reality, and should be regarded with caution.

On the other hand, cultivation in lagoons already requires man involvement today, and cost reduction could be expected in those areas. But current costs are higher than for open-sea. Roesijadi *et al.* [24] estimate costs at around 800 €/tonne dry matter for lagoons' produced algae. Integration of lagoons cultivation with other industries such as fish farming or other organic waste waters producing industries offers potential synergies. Industrialisation of harvesting and logistics simpler than for open-sea are also opportunities for cost reduction. Nevertheless, the benefits of free nutriments and agitation found in open-sea are lost. Current costs for lagoons cultivation should be reduced in the long-term, and a target to level those with costs from open-sea seems realistic.

#### 3.1.2 Focus on French Situation

French macroalgae production is entirely located in Brittany, and is around 70 000 tonnes dry matter/year. This production goes into 2 valorisation units, for extraction of alginates and coproduction of raw material for fertilizers. Current production is based on harvest in natural environment, which sustainability is supervised by the French Sea Authorities service [25]. This production ranks France as the 10$^{th}$ producing country worldwide, whereas its Maritime Exclusion Zone is the second largest (11 millions of km$^2$).

In the research area, CEVA is taking part in two French research projects:

– **Windseafuel**, which covers coupling of macroalgae cultivation and off-shore wind farm. In particular, this project includes the development of Life Cycle Analysis tools dedicated to marine environment; this task is led by *SupAgro* Montpellier [26];
– **IDEALG**, part of the 'Investissement d'Avenir' program launch by the French government [27]. IDEALG is a 45.5 M€ over 10 years research project, assembling 18 partners, looking into algae varietal selection, roll-out of aquaculture techniques and applied blue chemistry. All domains of application are covered, including energetic valorisation. A work task on societal aspects will conduct environmental impact studies using tools developed during Windseafuel. *IFREMER*, through its Roscoff entity, will take part in the life cycle analysis aspect of the project.

A lot of research initiatives are being set-up worldwide, being on the selection of macroalgae, development of cultivation method or lab-scale research in conversion processes. A short overview has been published by the Biofuel's Digest [28].

#### 3.1.3 Global Potential for Biofuels

Current worldwide production (12 millions tonnes dry matter/year) would allow producing less than 1% of current jet fuel consumption (2006 base).

Nevertheless, following available estimations [29, 30], primary biomass production from macroalgae on the globe is ranging from 1 to 2.5 billions of tonnes of carbon equivalent, which converted in dry matter represent from 2.5 to 6.25 billions of tonnes of dry matter per annum. This biomass production estimate is for current natural production in near-shore area, without exploitation nor maintenance.

If only 30% of the low value could be achieved on area put to algae cultivation, the produced resources could cover 20% of jet fuel consumption in 2050.

Different scenarii of macroalgae development have been studied to assess the potential dry matter that could be harvested from this resource in 2050, and the corresponding jet fuel production associated. Main variables are to start the current natural production of macroalgae, the portion of area that could be put to cultivation, the increase in yield in those cultivated areas, and latest the mass yield conversion for processes from macroalgae to jet fuel. Table 4 presents some scenarii, and shows that potential cover of jet fuel needs in 2050 could be as high as 100% under the most optimistic assumptions. But this would represent a 200-fold increase in current production of macroalgae to be achieved over the next 40 years! This seems rather unrealistic, and a 10% up to 20% contribution of macroalgae based biojet to the total consumption would already be a high achievement considering the challenges ahead.

### 3.2 From Macroalgae to Jet Fuel

The production of jet fuel from carbohydrates is technically possible, through a variety of pathways, as described by Huber *et al.* (2006) [31]. Although none are currently proven and no commercial technologies are available, there is a lot of current technology development and demonstration worldwide using lignocellulosic biomass as starting material.

Macroalgae harvest will lead to a feedstock with relatively low dry matter content, lower than 30% in all cases. Based on this constraint, thermochemical pathways using pyrolysis or gasification to transform

TABLE 4
Scenarii of production of biojet fuel from macroalgae under different hypothesis and contribution to total demand

| | | Scenarii | | | Current |
|---|---|---|---|---|---|
| | | High | Mean | Low | |
| Natural production | Mt dry matter/year | 6 250 | 2 500 | 2 500 | |
| % of area put to cultivation | % | 60 | 60 | 30 | Mainly harvesting of natural production |
| Increase in yield in cultivated area (% of natural production) | % | 40 | 30 | 20 | |
| Annual harvesting from cultivation | Mt dry matter/year | 1 500 | 450 | 150 | 12 |
| Conversion mass yield to jet fuel | % | 40 | 25 | 10 | 10 |
| Annual biojet fuel production | Mt/year | 600 | 112.5 | 15 | 1.2 |
| Coverage of jet fuel needs in 2050 | % | 100 | 19 | 3 | 0.2 |

biomass to jet fuel, such as Biomass-to-Liquid (BtL) processes, seem excluded. Drying of the material will be too costly, both from an economical but also energetic point of view, for macroalgae to compete with lignocellulosic feedstock for these processes. Wet transformation processes appear more suitable, such as hydrothermal conversions with or without catalysts.

The carbohydrates have the empirical formula $C_x(H_2O)_y$. The carbohydrate family is formed by four groups: monosaccharides, disaccharides, oligosaccharides and polysaccharides (*Fig. 3*). The smaller carbohydrates (mono and disaccharides) are commonly referred as sugars (monosaccharide: glucose, galactose, fructose, etc., disaccharide: sucrose and lactose, etc.). The oligosaccharides and polysaccharides are composed of longer chains of monosaccharide units: $2 \leq n \leq 10$ for oligosaccharides and $n \geq 10$ for polysaccharides.

Second generation biofuel production *via* biochemical pathways is based on extraction and microbiological conversion of sugars polymers present in lignocellulosic biomass. Cellulose is a linear polymer of cellobiose, a glucose dimere, which is hydrolysed in glucose $C_6H_{12}O_6$. Hemicellulose is a hetero-polymer constituted of different sugars depending on the raw material, including mannose $C_6H_{12}O_6$ and xylose $C_5H_{10}O_5$. Basic patterns are therefore 5 or 6 carbons chains depending on sugar's type. Those patterns are too short for jet fuel application; additional C-C liaisons must be built to obtain a fuel compatible for aviation use.

Following a thermochemical pretreatment aiming at breaking down the raw material matrix, enzymes are added to hydrolyse the cellulose into its monomer glucose. Then microorganisms are used to convert sugars into useful products. Microorganisms reduce the sugar and remove part of the oxygen as $CO_2$. Most known product today is ethanol, but other solvents or alcohol can also be produced, depending on the microorganism selected, such as butanol. These alcohols can be converted to light olefins. The molecular weight of olefins can be increased by oligomerisation reaction to obtain, after hydrotreatment of the olefinic bonds, isoparaffins within the range of jet fuel specifications.

*IFP Energies nouvelles* has worked actively on technologies of oligomerisation of those products into jet fuel cut. Total deoxygenating is mandatory beforehand. *IFP Energies nouvelles* has specifically looked into conversion of ethanol into jet fuel. Different pathways have been studied. One solution consists into a total deoxygenation of ethanol into either ethylene or light olefins, oxygen being removed as water. Then the intermediate products undertake an oligomerisation step towards a jet fuel cut. *IFP Energies nouvelles* has overcome the technical barriers of those reactions.

Deoxygenation of sugars can also be performed directly by catalytic chemical reactions. The liquid phase catalytic processing seems promising [32]. The liquid phase catalytic processing involves a combination and/ or coupling of various steps of reactions: hydrolysis,

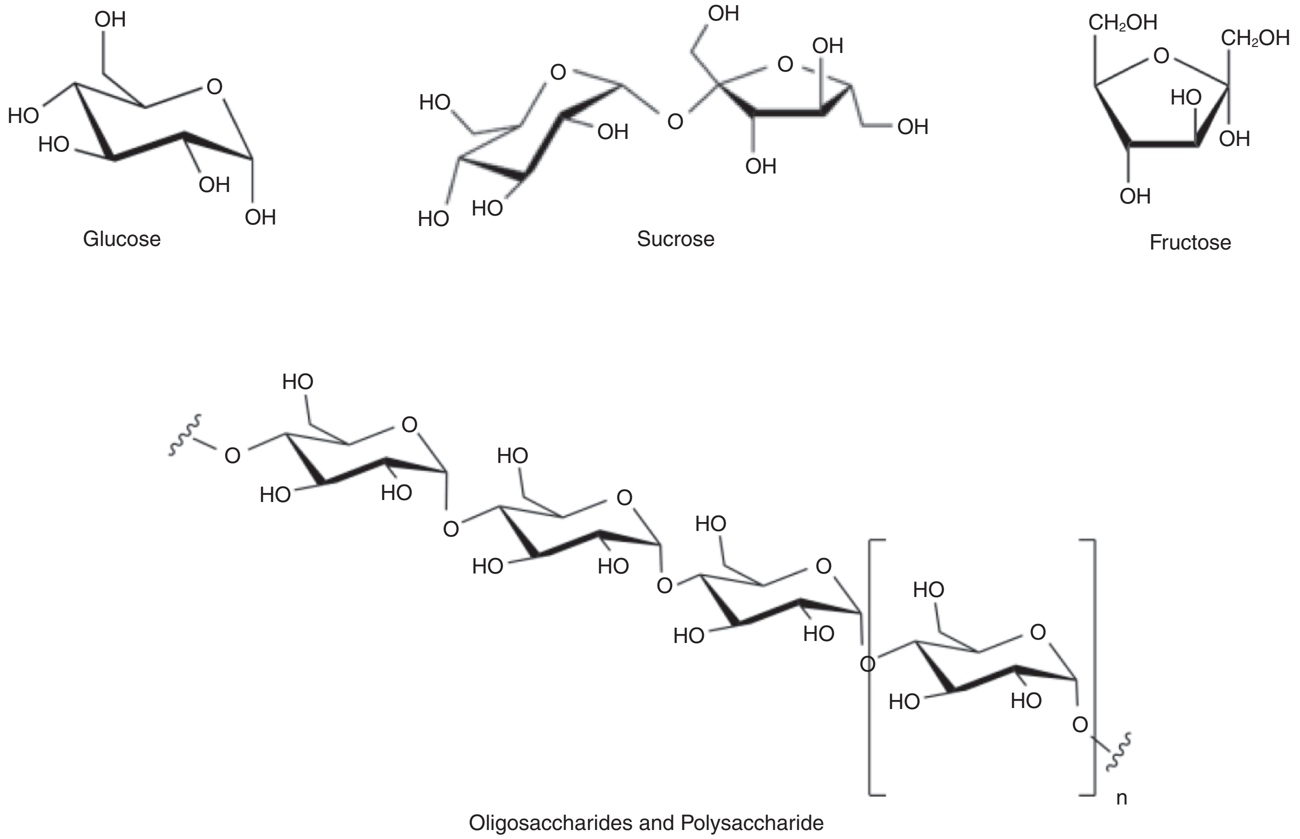



Figure 3

Saccharides examples.

dehydration, aldol condensation/hydrogenation, dehydration/hydrogenation and hydrogenolysis processing [33]. Direct conversion, in the absence of catalyst, could also be an interesting option. What is lost in term of selectivity could be regained, cost-wise, by easier process control and higher robustness to feedstock composition and impurities.

The principal problems associated with all these technologies are the low mass yield, due to the necessary removal of oxygen and the range of products obtained, which limits the final conversion to jet fuel. Nonetheless, processes are currently being studied at pilot-stage, and demonstration units should follow. Virent, technology provider of the *BioForming*® process based on APR (Aqueous Phase Reaction), is expected first commercial plant to be in operation in 2015 [34]. *GEVO*, a company developing isobutanol production process, has started the conversion of a corn-to-ethanol plant into a corn-to-isobutanol one at Luverne (USA) at the end of 2012 [35]. Although those developments are promising, so far, the final product is not a jet fuel cut. Ethylene and isobutanol are only intermediates in the sugar to jet fuel pathways. Current economic context makes further processing of those molecules into jet fuel not economically attractive, as those compounds have already a market value of their own, higher than the one of jet fuel.

As far as macroalgae are concerned, their use as an alternative feedstock to lignocellulosic biomass in sugars to jet fuel technologies is highly conceivable. Green algae contain cellulose or starch, which has the same composition as terrestrial plants. Cellulose from algae could even be easier to process in enzymatic hydrolysis as suggested by the work of Hayashi *et al.* [36], but as current enzymes' cocktails are being developed on terrestrial cellulose, work on adapting these cocktails to algal cellulose might be required. Brown and red algae contain sugars differing from the three main sugars found in lignocellulosic biomass that are glucose, mannose and xylose. For example, they can contain galactose and fructose. Sugars are also not only present as sugar-only polymer, but in acid forms or sulphated. Efficient fermentation of these other types of sugars could represent a challenge depending on the microorganism considered. As a comparison, although fermentation of glucose to ethanol has been known and industrial since several decades, the development of pentose-fermenting microorganism for ethanol production from lignocellulosic biomass has been a real R&D challenge for the last decade [37].

### 3.3 Towards Development of Jet Fuel from Seaweeds: Hurdles to Be Addressed

In its assessment of the pathway from seaweeds to jet fuel, the Algogroup's working group has identified and ranked the different hurdles to overcome to make this industry a reality. Table 5 summarises the opportunities and hurdles linked with each aspect, those are being discussed in the following subsections.

The notes displayed ranged from 1 to 10, 10 showing the highest hurdle or the most influential leverage point for helping the development of the industry. These notations are arbitrary and the result of a collegial vision of Algogroup's shareholders on the challenge ahead, the idea being to show the different impact each category can have, both as a brake or an opportunity should the hurdle be tackled. This analysis has been undertaken to help in the prioritisation of the actions, technical or not, to be taken to drive the development of the macroalgae pathway. Availability of the resource at a scale and a price compatible with biofuel production, linked with the necessity to increase dozen-fold the current tonnage, is by far the biggest challenge. Once this is tackled, one should not oversee the potential show-stopper of transformation costs which might not be driven low enough despite technical improvements.

#### 3.3.1 Availability and Costs of Seaweeds

Nowadays, exploitation of the macroalgae resources is very low, but the raw material exists. This needs to be emphasized as no process could be developed in the absence of the starting raw material. This is a hurdle sometimes overlooked when discussing microalgae conversion pathways, as the downstream processes could only be fully adapted once the large-scale cultivation and recovery processes are operational, as those affect the quality of the material to be treated (*e.g.* presences of inhibitory compounds). For macroalgae, the resource could already be recovered to start laboratory scale development of processes, or pilot-scale trials. This represents an important opportunity for this industry.

Current costs from open-sea practice are compatible with biofuels market. Lagoon cultivation is so far too expensive, a 3-fold reduction is required but this seems an achievable target.

On the other hand, the hurdle of a dozen-fold increase in worldwide production is a huge one. Development of cultivation and harvesting on a large scale will require intensification and industrialisation of existing practices. Also, the gap is too large to expect to start this industry on biofuels market alone, as biofuels' raw material quantity requirements are too large compared to existing production of seaweeds. A solution could be through the development of intermediate scale applications and valorisation of seaweeds, for example in green chemistry or cosmetics or food additives, alongside the current development of the hydrocolloids industry. By offering a market for seaweeds, those intermediate scale applications could drive the development and intensification of seaweeds cultivation and therefore help in the necessary scale-up of production and reduction in costs in order to make this resource a suitable candidate for biofuels and jet fuel applications.

This hurdle is not a technical one. The issue is to develop a biomass production industry to agro-industrial scale starting from an existing small-scale, low-tech traditional production. There is huge potential of improvement in seaweeds variety's selection, mechanisation and intensification of cultivation and harvesting techniques.

The sharp rise in production needed will not happen without governmental support and incentives: no current actor in the domain is large enough to drive the development. A federative action from governments is required.

#### 3.3.2 From Seaweeds to Jet Fuel, Technical and Economic Aspects

Production of jet fuel from sugars is technically possible, but the requirement for oxygen removal to reach the final product commands looking into multi-steps processes, potentially coupling fermentative and chemical stages. Numerous intermediate are possible which multiplies the pathways to be studied. This presents the advantage that at least one pathway should be compatible with the macroalgae resource. Also, these pathways are being developed on 2G resource, and therefore their development will happen with or without the availability of macroalgae which is another advantage. Technical hurdles are on their way to be overcome, although most processes are still in early stages, demonstrations are ongoing for some pathways. Nevertheless, compatibility of seaweeds as a feedstock

TABLE 5

Synthesis of the Algogroup's macroalgae task force analysis

| | | Opportunity | | Hurdles | |
|---|---|---|---|---|---|
| Resources | Availability | 10 | High potential production | 10 | Current production is very low in quantity and traditional |
| | Cost | 4 | Open sea production costs acceptable<br>Decrease possible in Lagoon production costs<br>Potential for coproducts | 8 | No current market to drive down production costs<br>Gap between current and target costs in biofuels might be too large to start on biofuel |
| | Cultivation systems | 8 | Two cultivations systems possible offers flexibility | 2 | Require development of two industries |
| Transformation process | Feasibility | 7 | Similar to sugars from 2G resources, existing resource | 2 | Low dry matter content, presence of specific compounds and impurities |
| | Technical | 4 | Process are being develop on 2G resources | 1 | Compatibility? Diverging optimisation? |
| | Coprocessing | 4 | Interest from 2G resources producers | 4 | Limits opportunity of cost reduction based on seaweed specificity |
| | Cost | 1 | No leverage for cost reduction regarding transformation processes identified, costs will be dependent on technical solution | 6 | Complex multi-stages pathways, unlocking technological limitations might not be sufficient to achieve cost-effective processes |
| Legislative constraints/societal acceptance | | 5 | Job creation | 3 | Share use of sea/ coastline: tourism, fishing, etc. |
| Environmental balance | | 4 | To be performed | 3 | To be performed |

will need to be check, and optimisation conducted. The earlier seaweeds are considered as a potential feedstock for those processes, the easier will be the final adaptation.

The main show-stopper is the economic viability of such complex processes. Demonstration of technical feasibility might not be sufficient to reach economic viability for these complex pathways. This is especially true as some of the possible intermediates might have higher market value in green chemistry or in the biofuels market for example than the final jet fuel produced. This reality is not feedstock related.

#### 3.3.3 Legislative Constraints/Societal Acceptance/ Environmental Balance

Sea and ocean resources are currently used by different industries such as fishing, oyster production, tourism, etc. Other uses are being developed such as offshore wind farms. Sea and coastlines are also a common environmental heritage that needs to be protected. Despite current activities, there are gaps in legislative framework that will need to be addressed by public policy and decisions bodies.

Societal acceptance is both a potential threat and an opportunity for the seaweeds to jet fuel industry.

The development of seaweeds farms will lead to the creation of local jobs in area with low employment where historical activities such as fishing and oyster production are facing difficulties. It would offer reconversion and/or diversification options for some activities. Nevertheless, competition with tourism could put a brake to seaweeds development, especially in France where sea and coastlines attract millions of tourists every year. Furthermore, recent events linked with proliferation of algae due to excess nitrates rejects in Brittany and in the Mediterranean sea could have a negative impact on public opinion. A clear and constructive communication both from stakeholders and government is important.

The environmental balance of a seaweeds to jet fuel industry has yet to be performed, and too few numerical data are available to assess the potential gain at this stage, from a GHG emissions point of view, but also on other environmental impacts and water footprint. Especially, it is mandatory to look into the impact of large-scale cultivation. While harvesting in natural growth environmental is currently done at small scale, large-scale production can only be developed sustainably in a cultivation framework, *i.e.* by increasing the current natural production and only harvesting the excess then created. Besides, creation of cultivation area could have a beneficial impact on the maritime ecosystem, as seaweeds are usually favourable for sea life development. The effect of nutriments take-off from the sea to sustain the seaweeds growth will need to be carefully evaluated as well.

A complete life cycle analysis on seaweeds to jet fuel industry can not be limited to the process side of the story, experts in maritime ecosystems and environment must contribute to ensure all impacts, both beneficial and harmful, of seaweeds cultivation implementation on the existing maritime equilibrium are properly accounted for, in order to establish whether there is a true environmental benefice linked to the development of this industry, and to which extend. As part of WindSeaFuel and IDEALG projects, the necessary tools for LCA have been developed and will be used based on the project results to evaluate the impact of the macroalgae production processes, first step for the entire pathway evaluation.

### 3.4 Discussion

Macroalgae as a resource for biofuels production are very far from being a commercial reality, but do present some advantages. Being the closest parents to terrestrial plants, green macroalgae exhibit several similarities with current 1$^{st}$ and 2$^{nd}$ generation feedstocks. They are natural producers of starch and unlignified cellulose. As such, they could prove very relevant as raw materials for existing sugar transformation processes. Nevertheless, they also contain specific sulphated polysaccharides built on uncommon neutral sugars and uronic acids. Red and brown macroalgae are currently the most produced species, but their composition calls for the development of new transformation processes.

When jet fuel is the target, all types of macroalgae will require the development of new processes, either based on sugars or on the whole biomass, to produce molecules suitable for jet fuel applications. This technical challenge is being address already for terrestrial plants other than oilseed. Although technically feasible at lab-scale, the economic viability of such processes is being endangered by the complexity of the processes involved and the numerous steps required as well as by non-technical issues such as competition with other markets like green chemistry.

To have a true share of the future fuel mix, macroalgae production needs to be increased by a dozen-time fold. Although not unfeasible, this challenge is a very complex one as it is not only a technical issue, but is highly influence by political decisions and market drivers. This increase should not be done without social acceptability or at the expenses of the environment. For the latter, it should be underlined that methodological tools and data are currently lacking to be able to conduct LCA on this very specific aquatic environment. Legislation, or more precisely lack of, could also be a problem. Conflicts of usage, with existing sea activities such as fishing or envisaged ones such as offshore wind farms, are a threat but could be turn into an advantage by integrating systems. Potential for high tonnage production seems real, but the challenge is to federate existing actors and new ones around the building of a new agro-industry, this issue can only be address by a collegial action at minima at national level with a clear and lasting support of government.

## CONCLUSION

Algogroup has been a very fruitful and interesting group to exchange and share results, vision and perspectives for algae as resources for energy. Despite the limited amount of reliable information currently available on the algofuel sectors, especially in terms of environmental balance, numerous challenges still remain to be taken up to make these sectors credible and profitable, both technically, economically and environmentally.

Today, environmental studies have demonstrated that the energetic balance was not favourable, based on current processes, but the variation range of the results let some space for significant improvements. The balance of greenhouse gas emissions was in general favourable, and there also the variation range was very wide. As regards the other environmental impact categories, however, the uncertainties are too great to draw any conclusions. Because of the heterogeneity of approaches and results for the development of the algae pathway, we must bear in mind that without reliable and robust assessments of these sectors it will not be possible to direct their technical development sustainably.

On the economic aspect the estimated costs for future microalgae biofuels remain in a very broad range from about less than \$2/Gal to \$7/Gal. There remain great potential to decrease microalgae oil production costs, but this has to be considered very carefully given the large amount of underlying assumptions. Moreover, as yet underlined, microalgae biofuels are not currently being produced at a commercial scale, thus these are only potential scenarios, which will have to be confirmed. And finally, several technologies can be used to produce microalgae oil and location possibilities are as high as the area. Another key point is that, in a large majority of scenarios, the economic viability of the pathway relies on the valorisation of what one usually calls co-products. To improve the situation a large amount of works is necessary, especially on selection of algae type, on culture conditions and harvesting and perspectives are largely open.

Macroalgae as a resource for biofuels production are very far from being a commercial reality, but do present some advantages. Being the closest parents to terrestrial plants, green macroalgae exhibit several similarities with current 1$^{st}$ and 2$^{nd}$ generation feedstocks. They are natural producers of starch and unlignified cellulose. As such, they could prove very relevant as raw materials for existing sugar transformation processes. Nevertheless, they also contain specific sulphated polysaccharides built on uncommon neutral sugars and uronic acids. Red and brown macroalgae are currently the most produced species, but their composition calls for the development of new transformation processes.

When jet fuel is the target, all type of macroalgae will require the development of new processes, either based on sugars or on the whole biomass, to produce molecules suitable for jet fuel applications. This technical challenge is being address already for terrestrial plants other than oilseed. Although technically feasible at lab-scale, the economic viability of such processes is being endangered by the complexity of the processes involved and the numerous steps required as well as by non-technical issues such as competition with other markets like green chemistry.

As a conclusion, no true leveraging option, leading to significant breakthroughs has really emerged as a short term solution, but wide spaces for significant improvement could be envisaged and more laboratory and pilot works have to be achieved before being able to move to a higher scale, leading to the first step toward industrial production.

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*Manuscript accepted in June 2013*
*Published online in October 2013*