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Sensitivity of Technical Choices on the GHG Emissions and Expended Energy of Hydrotreated Renewable Jet Fuel from Microalgae

Laure Patouillard* and Pierre Collet

IFP Energies nouvelles, 1-4 avenue de Bois-Préau, 92852 Rueil-Malmaison - France
e-mail: e-mail:laure.patouillard@ifpen.fr - pierre.collet@ifpen.fr

* Corresponding author

Abstract — *Taking into account the environmental impacts of biofuel production is essential to develop new and innovative low-emission processes. The assessment of life cycle GreenHouse Gas (GHG) emissions of biofuel is mandatory for the countries of the European Union. New biomass resources that hardly compete with food crops are been developed increasingly. Microalgae are an interesting alternative to terrestrial biomass thanks to their high photosynthetic efficiency and their ability to accumulate lipids. This article provides an analysis of potential environmental impacts of the production of algal biofuel for aviation using the Life Cycle Assessment (LCA). Evaluated impacts are GHG emissions and the primary energy consumption, from extraction of raw materials to final waste treatment. This study compared two management choices for oilcakes generated after oil extraction from microalgae. In the first system, these cakes are treated by energetic allocation and in the second by anaerobic digestion. In both cases, the steps of cultivation and harvesting have the highest impact on the results. Sensitivity analyzes are performed on technical choices of operating systems (choice of the type of nutrients, mode of harvesting, drying and oil extraction) as well as a Monte-Carlo analysis on key parameter values for GHG emissions (concentration of microalgae in ponds, productivity and oil content). The results highlight the impact of the use of chemical fertilizers and the importance of the concentration of algae on GHG emissions and energy consumption.*

Résumé — Analyse de sensibilité des paramètres techniques sur les émissions de gaz à effet de serre et les consommations d'énergie de la production de biocarburant pour l'aviation à partir de microalgues — La prise en compte des effets sur l'environnement de la production de biocarburants est essentielle afin de développer de nouveaux procédés innovants et peu polluants. L'évaluation du bilan de gaz à effet de serre des biocarburants est à ce titre un prérequis obligatoire pour les pays de l'Union Européenne. L'exploitation de nouvelles ressources de biomasse induisant peu de compétition avec les cultures alimentaires est de plus en plus recherchée. Grâce à leur très haut rendement photosynthétique et leur capacité à accumuler les lipides, les microalgues représentent une solution alternative intéressante. Cet article fournit une analyse des impacts environnementaux potentiels de la production de biocarburant pour l'aviation à partir de microalgues à l'aide de l'Analyse de Cycle de Vie (ACV). Les impacts évalués sont les émissions de Gaz à Effet de Serre (GES) et les consommations d'énergie primaire, depuis l'extraction des matières premières jusqu'au traitement ultime des déchets. Cette étude compare deux choix de gestion des tourteaux générés après extraction de l'huile des microalgues. Dans le premier système, ces tourteaux sont traités par allocation énergétique et dans le second par digestion anaérobie. Dans les deux cas, les étapes de culture et de récolte sont les plus impactantes. Des analyses de sensibilité, portant à la fois sur des choix techniques d'exploitation des systèmes (choix du type de nutriments, du mode de récolte, de séchage et d'extraction d'huile) ainsi que sur une analyse de Monte-Carlo des valeurs de paramètres clés pour les émissions de GES (concentration en microalgues dans les bassins, productivité et teneur en huile) ont été réalisées. Elles ont permis de souligner le poids de l'utilisation de fertilisants chimiques et l'importance de la concentration en algues dans les émissions de GES et les consommations en énergie.

DEFINITIONS/ABBREVIATIONS

DAF	Dissolved Air Flotation
GHG	GreenHouse Gas
GWP	Global Warming Potential
HRJ	Hydrotreated Renewable Jet
HVO	Hydrotreated Vegetable Oil
ISO	International Standard Organization
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
NREP	Non Renewable Expended Primary (energy)
PBR	PhotoBioReactor
RED	Renewable Energy Directive
SWAFEA	Sustainable Way for Alternative Fuel and Energy in Aviation
TSS	Total Solid Suspended
WTW	Well to Wake

INTRODUCTION

In a context of climate change and fossil fuel depletion, there is a rising interest in the development of alternative and renewable sources of energy. Renewable energies from wind, sun or geothermal power are promising ways to produce electricity or heat, but these energy forms are hard to store. Consequently, in the transport sector, the development of biomass liquid biofuels in order to power cars and planes is crucial. The use of agroresources to produce biofuels generally induces a lower impact on climate change but can increase other environmental impacts, especially those linked to the consumption of fertilizers (e.*g*. eutrophication, acidification) and to the use of pesticides (*e.g.* toxicity).

Microalgae as feedstock to produce biofuel, often considered as third generation biofuels, can represent an interesting way to produce storable bioenergy [1, 2]. Their high photosynthetic yield, a better control of the ground emissions and the ability to use CO_2 directly from industrial emissions as a source of carbon are promising way to reduce environmental impacts of biofuels. However, this new biofuel production system should be assessed in order to analyze its environmental performances and to identify which processes should be improved.

This paper proposes an environmental assessment of the production of Hydrotreated Vegetable Oil (HVO) from microalgae with a Life Cycle Assessment (LCA) approach and compares it to a petroleum alternative. A sensitivity analysis on technical choices and on parameter values is carried out in order to discuss the variation of the results.

1 LCA METHODOLOGY

1.1 General Presentation of LCA

LCA is a modeling tool to consider and quantify the total environmental effects of a process or service, based on a "cradle to grave" inventory of all the emissions and all the consumed resources. All the different steps, from the production of raw materials to the disposal of waste and products at the "end of life", are therefore included in the scope of a LCA. According to the International Standard Organization (ISO) recommendations [3, 4], LCA is divided into four steps: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and life cycle interpretation. LCA is an environmental tool, so social and economic aspects are not included in the scope of the publication. Nevertheless, decision making must be taken in light of the two other pillars of sustainable development.

Goal and scope definition is the step in which the main objectives of the work are defined. The perimeter of the considered system and the choice of the environmental impacts to be assessed are fixed. The functional unit, which is the reference flow adapted to the function of the assessed product, is determined. All inputs and outputs in the LCI, and consequently all the environmental impacts are related to this functional unit. Many systems lead to the production of several products with different functions. Hence, allocation rules are defined to distribute the environmental burdens between the main product and the coproducts. This is one of the most critical issues in LCA, and the work of Luo *et al.* have highlighted the sensitivity of the results of biofuels production to these allocation rules [5].

The LCI is the step where all the necessary data are collected and treated. This is generally the most time consuming step of the LCA [6], but with relatively few methodological problems.

During the LCIA step, all the environmental flows (consumed resources and emissions to the environment) are converted into a selected number of impacts. Depending on the chosen impact method, midpoint impacts (*e.g.* ozone depletion, acidification) or endpoint impacts (human heath, ecosystem quality) can be selected.

The last step of the ISO recommendations is the interpretation of the results, in which the obtained results are assessed and the limits of the study are set.

1.2 Goal and Scope Definition

This study is based on a previous work carried out for the Sustainable Way for Alternative Fuels and Energy for Aviation (SWAFEA) project. The European project SWAFEA aimed at the assessment of the feasibility and the impacts of introducing alternative fuels in the aviation sector from technical, economical and environmental points of view. A LCA study was conducted in the SWAFEA project to assess the environmental impacts of alternative fuels that were technically selected as promising for the aviation sector. The SWAFEA project selected several types of fuels as promising fuels for the aviation sector. Hydrotreated Renewable Jet fuel (HRJ) from biomass derived oils is one of them as it is a "drop-in" fuel meaning that HRJ is fully compatible with current aircraft engines and fuel supply infrastructures without any additional economic investment. In addition, HRJ production relies on a mature production process and can be blended with conventional jet fuel A1. Numerous flight demonstrations have proven its potential for being an alternative to jet fuel. On the other hand, algae have been selected in the SWAFEA project as a promising biomass feedstock for alternative jet fuel production as they promise higher yields than terrestrial crops and have modest requirements on land quality and avoid a direct competition with food.

TABLE 1
Global Warming Potentials at 100 years time horizon [3]

Flow	IPCC, 2007
CO_2	1 (1 g CO_2 = 1 gCO_2eq)
CH_4	25 (1 g CH_4 = 25 gCO_2eq)
N_2O	298 (1 g N_2O = 298 gCO_2eq)

Hence this study concentrates on the assessment of one pathway of this promising fuel: HVO from microalgae extracted from SWAFEA LCA study [7].

The goal of this LCA study, as defined in the SWAFEA project, is to evaluate the GHG emissions and primary energy consumption related to the production and the consumption of alternative fuels in the aviation sector on a "Well To Wake" (WTW) basis considering the current most promising alternative fuels. A WTW LCA study deals with the assessment of environmental impacts of a fuel all along its life cycle considering the raw material extraction, the fuel production step, the fuel distribution step and the fuel combustion step in a vehicle.

The methodology used is based on LCA principles as defined in the ISO standards [3, 4] and on the recommendations of the Renewable Energy Directive (RED) [8].

Two environmental indicators are assessed in this study: GHG emissions and Non Renewable Expended Primary (NREP) energy, defined as fossil energy by [9]. Non renewable primary energy represents the sum of all the fossil and mineral energy sources directly drawn from natural reserves such as crude oil, natural gas, coal and uranium.

For the GHG emissions indicator, only the 3 main GHG are taken into account – *i.e.* CO_2, CH_4 and N_2O – and converted into a CO_2 equivalent (CO_2eq) using coefficients called Global Warming Potentials (GWP at 100 years time horizon), presented in Table 1, defined and estimated by IPCC [4] (IPCC 2007 values have been chosen for this study). The final results are expressed as CO_2eq.

This study does not include the shorter term impact of aviation on climate (radiative forcing) due to non-CO_2 emissions and effects, which include the emissions of water vapour, particles and nitrogen oxides (NO_x).

A WTW approach has been chosen including algae production, recovery and treatment, extraction of raw material, conversion into fuel, transport and distribution of fuel and fuel use. Infrastructure impacts (and aircraft cycle in particular) are excluded from the scope of study as well as land use impacts.

In this study, the net balance between CO_2 captured for algae growth and CO_2 released to the atmosphere during fuel combustion in the engine is assumed to be equal to zero. Assuming that CO_2 used for algae growth would have been emitted to the atmosphere regardless, calculations take into account neither CO_2 entering the system for algae growth nor CO_2 leaving the system during the combustion step. Cultivating algae using waste CO_2 from industrial plant is a way to recycle those emissions but not to stock them.

All impacts are expressed on the basis of the same functional unit that is the MJ of jet fuel produced.

Calculations are made with a LCA software GABI (v4.3). Data are extracted from literature and the EcoInvent v2.2 database [10].

Methodology for taking into account coproducts in the first pathway has been defined considering the RED recommendations. Impacts are allocated to co-products (excluding waste that has no impact and electricity that is taken into account differently) on the basis of their energy content (Lower Heating Value, LHV). As a consequence this allocation method is used to share the impacts between products and coproducts from hydrotreatment process in all pathways and for biomass residues in the first pathway.

Concerning excess electricity coproduction by cogeneration, we used the avoided impact methodology considering a credit equal to the amount of impacts that would be produced when the same amount of electricity is generated in a power plant using the same feedstock in a cogeneration unit (as recommended in the RED). So excess electricity produced in pathway 2 substitutes to electricity produced by cogeneration from biomass residues. Impacts induced by electricity production from anaerobic digestion of algae biomass residues are taken into account in this second pathway.

2 DEFINED PATHWAYS AND CORRESPONDING DATA

Process chains for jet biofuel production from algae studied in this publication are prospective and extrapolated from lab-scale data since no industrial pathway exists yet. Yields and process choice and process data are extracted from available literature and adapted for each considered pathways in order to minimize burdens (*Tab. 2*).

Two pathways are considered for HVO production from microalgae. Those pathways have similarities and differences in terms of biomass characteristics and in terms of considered processes (*Tab. 3*). The first pathway will be described in detail (*Fig. 1*); the other will be described on the basis of the first only highlighting the differences (*Fig. 2*).

The average European electricity mix provided by the EcoInvent database is considered in the calculation.

2.1 First Pathway: Base Case

Microalgae are grown in open raceways mixed with paddle wheels in a facility covering about 100 ha [11]. Open ponds have been chosen mainly because the alternative technology, PhotoBioReactors (PBR), seems to be too expensive in terms of capital costs [12]. Furthermore energy costs of PBR are claimed to be too high for microalgae biomass production [13]. Ponds are located near a power plant in order to recycle the flue gases with 15% mass of CO_2 [14]. A purification step of flue gases is required in order to extract CO_2 [15] and to inject it in the growth medium. The uptake efficiency of CO_2 is set to 90% according to [16]. Nutrients are supplied by sludge from waste water treatment plant in order to lighten the environmental burden in a best case perspective [17, 18]. The algae culture medium is freshwater that is recycled up to 90% after harvesting, *i.e.* all the water removed from the harvesting process is feeding back to the pond. The remaining 10% is processed in a waste water treatment plant. No N_2O emission at the pond level is taken into account, in accordance with most of the LCA studies on bioenergy production from microalgae. This assumption is confirmed by the experimental data from [19] suggesting that N_2O emissions at pond level are much lower than conventional terrestrial crops.

Microalgae productivity is 25 g/(m^2.day) with an algae concentration in ponds of 0.5 kg/m^3 [16]. The oil content is 34% of dry matter which is the average of values available in the literature.

Microalgae harvesting is carried out by a Dissolved Air Flotation system (DAF) with an addition of hydrophobic polymer to reach a concentration of 20 g/L of dry matter with an efficiency of 95% [14]. Recovered water during harvesting is filtered to remove polystyrene before going back into the ponds.

Microalgae are pretreated before oil extraction. First harvested algae are concentrated up to 200 g/L Total Solid Suspended (TSS) by centrifugation before being dried. The heat used for drying is waste heat from the power plant, assuming that this plant produces enough heat to support algae drying needs and achieve an algal paste concentration of 90% TSS [20].

Oil is then extracted from microalgae by solvent extraction with hexane. This type of extraction process on dried microalgae paste leads to a recovery of 95% of their oil content [14]. This step leads to the production of microalgae oilcakes, which are taken into account with an energetic allocation.

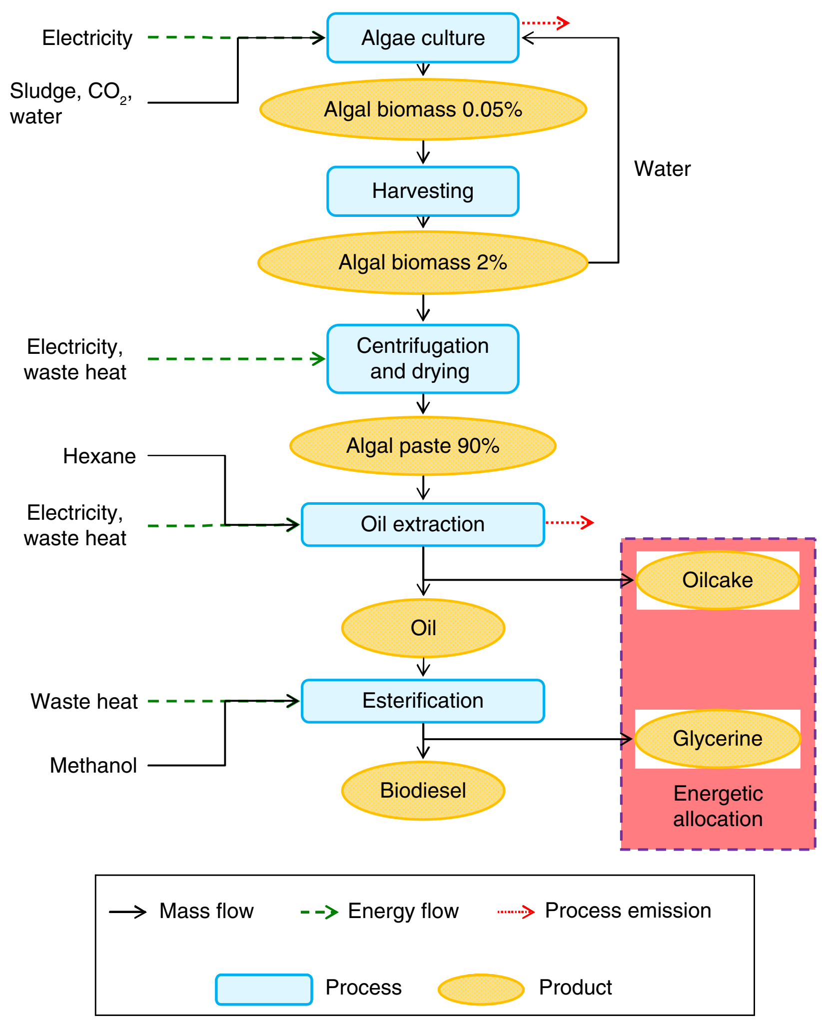

Figure 1

System boundaries of the first pathway.

Algal oil needs to be refined before being hydrotreated. Technical data on oil refining and hydrotreatment processes considered in this study correspond to the NexBTL process commercialized by *Neste Oil*. NexBTL is a HVO process that coproduced biogasoline and fuel gas converted into electricity and steam, part of the electricity production is used as utility for the process [21]. Data are presented for one MJ of HRJ even if others fuels (gasoline, naphtha) are produced *i.e.* an energetic allocation has already been made between fuels leaving processes. Other coproducts are taken into account with an energetic allocation in our calculations.

HRJ is supposed to be transported from the production site to a depot and then to a filling station in a 40 tons truck over a distance of 150 km. The corresponding Diesel oil consumption – including return trip (empty) – is 0.00344 MJ per MJ of HVO. The fuel is then stored in a depot. Corresponding electricity consumption is 0.00084 MJ per MJ of fuel. Electricity consumption associated with fuel distribution in a filling station is supposed to be 0.0034 MJ par MJ of fuel. These assumptions are in line with the ones from JEC 2008 study [22].

2.2 Second Pathway

The second pathway is quite similar to the first one. Main differences are process choices for nutrient supply, harvesting, and algal residues valorisation steps.

Harvesting is done thanks to settling ponds. Algae culture medium is fed into these settlers that allow

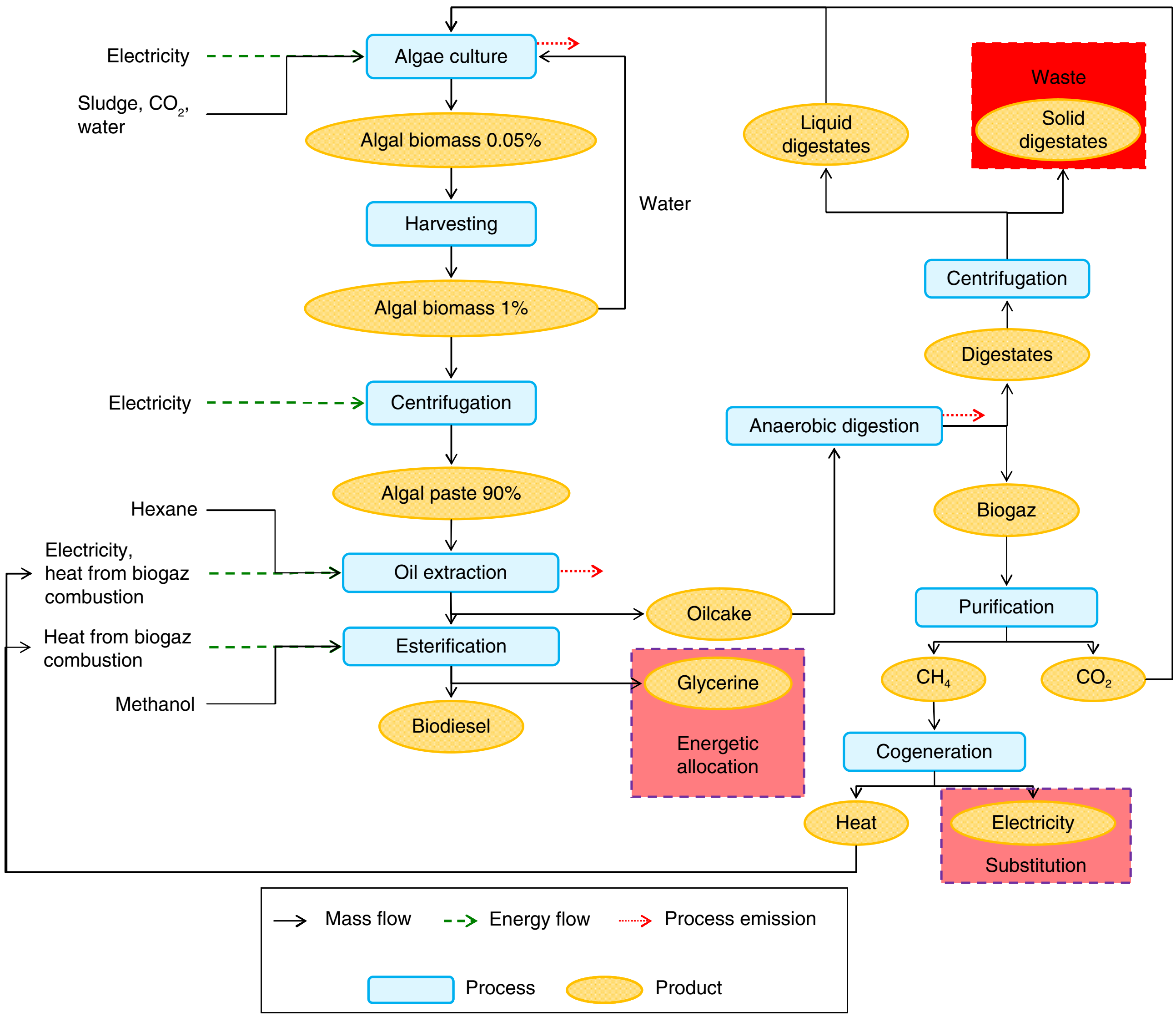

Figure 2

System boundaries of the second pathway.

to recover 65% of microalgae with a concentration of 10 g/L [16]. Electricity consumptions are lower compared to DAF system but final algae concentration is reduced. A rotary press is used to concentrate algae instead of centrifugation. Electric consumption associated to rotary press is smaller than centrifugation for almost the same efficiency [23]. The oil is extracted by press, with a lower efficiency than the hexane extraction (75%).

Algal biomass residues are converted into biogas for electricity and heat production by cogeneration. Algal biomass residues are fed into anaerobic digester for biogas conversion containing 70%vol of methane and 30%vol of carbon dioxide. The methane potential is equal to 209 mL CH_4/gTSS, which is a conservative value in the range of the experimental data of [24]. Heat required for digester operation is provided by steam from cogeneration. Biogas is then purified into methane by using water purification process. It consists in bubbling biogas in pressurized water in order to dissolve CO_2 in it and recover CH_4. Methane is converted into electricity with an efficiency of 32% [14] by cogeneration and electricity is fed into the grid. In this pathway, 1 kg (dry mass) of cultivated algae leads to an electricity production of 2.28 MJ.

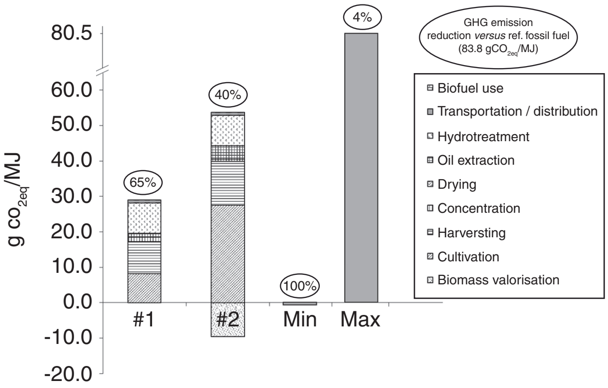

Figure 3

WTW GHG emissions in gCO_{2eq}/MJ of HRJ from microalgae.

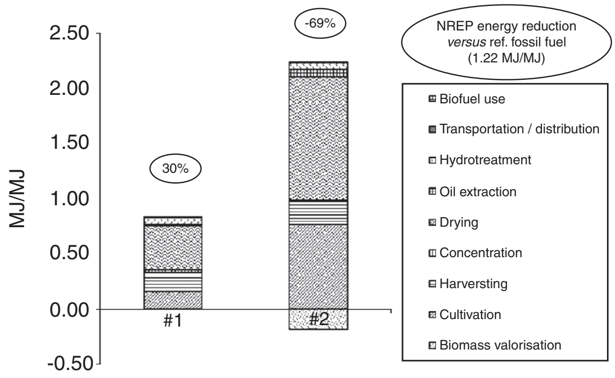

Figure 4

WTW non renewable expended primary energy in MJ/MJ of HRJ from microalgae.

Liquid digestates are recovered and fed into cultivation ponds. It allows to recycle 75% of nitrogen and 50% of phosphorus fed into cultivation ponds and to use it as nutrients for microalgae [25]. An addition of chemical nutrient is necessary to comply with photosynthesis needs. Nitrogen is supplied by urea and phosphorus by single superphosphate. In this pathway, CO_2 is provided by two ways: CO_2 recovered from the purification of the biogas which is dissolved in water and the rest from purified flue gas as in the first pathway. Solid digestates are considered as wastes.

3 RESULTS

3.1 GHG Emissions and Expended Primary Energy for Defined Pathways

Results presented below are relative to the production of HRJ from microalgae for the two pathways defined in the previous section. The two graphs display GHG emissions (*Fig. 3*) and NREP energy (*Fig. 4*) with the relative contribution of every life cycle steps for each pathway.

The GHG emission reduction of the two pathways compared to the RED fossil fuel reference (83.8 gCO_{2eq}/MJ) is mentioned. The minimum [14] and maximum [31] values of literature for similar systems (production of biodiesel in open raceways) have also been added to give some idea about the variability that exists in the literature for this pathway. We could not perform a full Monte-Carlo analysis to estimate uncertainties related to our model as we were not able to estimate a distribution for all parameters. Nevertheless we conduct a Monte-Carlo analysis for 3 main parameters (Sect. 3.2.2).

The NREP energy can be compared with the corresponding for fossil fuel which is equal to 1.22 MJ/MJ of Diesel according to EcoInvent 2.2. Comparison with the references used in Figure 4 [14, 31] was not possible because the results of the energy consumption were not expressed in the same metric. In this section, we also propose to analyse the influence of the coproduct management on the results.

3.1.1 Management of the Coproducts

Following the methodology for LCA of biofuel defined in the RED, an allocation based on energy content is applied in the first pathway to allocate the impacts between algae oil and algal residues. For the second pathway, the avoided impact method is used for taking into account the coproduction of electricity from algal residues by cogeneration as recommended by the RED methodology. In this case, all the impacts are only allocated to the main product (here one MJ of HRJ fuel) and a credit is given to the electricity coproduced from algal residues. This credit is equal to the amount of impacts that would be generated by the production of the same amount of electricity produced in a conventional way. These different methodological choices induce lower impacts in the pathway 1 than in the pathway 2.

Indeed with the energetic allocation in the pathway 1, 45% of the impacts from cultivation to oil extraction are allocated to algae oil. But all these impacts are allocated to the oil when using the avoided impact method in the

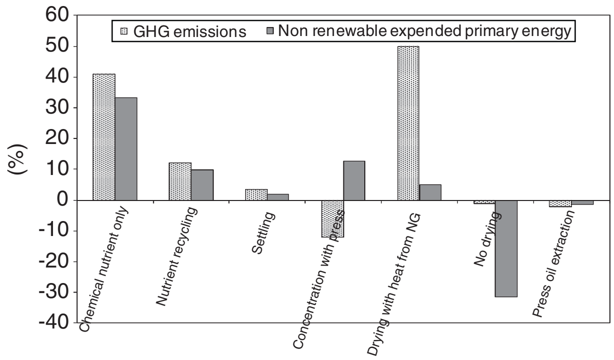

Figure 5

Sensitivity to technical choices compared to base case.

pathway 2. In this pathway, impact credit induced by the production of electricity from biomass residues just offset about 15% of the impacts produced by pathway while 55% of "real" impacts are allocated to biomass residues in pathway 1. This high sensibility of the results to the chosen allocation method is sharpened by the high energy content of the oilcake (21 MJ/kg) contrary to other coproducts with low energy content like straw in other biofuel pathways.

It is important to remind that the choice of a method for taking into account coproduct is determined by technical choice for the valorisation of biomass. Indeed, pathways with electricity coproduction by cogeneration cannot be studied with the same method as pathways coproducing oilcakes for animal feed for instance when following RED recommendations. Therefore both pathways presented here do not have to be compared one to each other but help for the understanding of algae pathway mechanisms.

3.1.2 Climate Change Impact

GHG emissions related to the production of one MJ of HRJ from microalgae are equal to 29.4 and 44.2 gCO_{2eq} for the first and the second pathway. It corresponds to a GHG emission reduction of respectively 65% and 40% compared to the RED fossil fuel reference. Consequently, results for the first pathway comply with the GHG emission reduction threshold of 60% set by the RED from 2017 [8].

For GHG emissions, the most impacting steps are the cultivation step (28% for pathway 1 and 51% for the pathway 2), the harvesting step (respectively 31% and 23%) and the hydrotreatment of algal oil for the first pathway (30% of total GHG emissions). At cultivation step, more than 90% of impacts for this step are due to electricity consumption. This electricity is used for CO_2 supply, water pumping and for water mixing in ponds. GHG emissions for harvesting step are due to electricity consumption for DAF operation in pathway 1 and water pumping for both pathways. GHG emissions associated with hydrotreatment step are linked with the hydrogen supply that comes from on site natural gas steam reforming. In the second pathway, 18% of GHG emissions are compensated by substituting the coproduced electricity. It should be underlined that there is no CO_2 emission linked with the drying step in both pathways. This is due to the use of waste heat with no environmental burden.

3.1.3 Energetic Balance

Focusing on the NREP energy, the first pathway leads to the consumption of less than 1 (0.85) MJ of fossil fuel for the production of 1 MJ of HRJ. In the second pathway, the ratio is higher than one (2.06 MJ/MJ), which underlines the higher dependence to fossil energy consumption of this pathway.

For NREP energy, most impacting steps are cultivation, harvesting and drying steps for the first pathway (respectively 19%, 21% and 47% of the NREP energy), and cultivation and drying steps for the second pathway (34% and 50% of the total NREP energy respectively). As for GHG emissions, NREP energy at cultivation and harvesting steps is due to electricity consumption. Drying step consumes a large amount of heat for drying algae (pathway 1 and 2). Here the heat consumed is waste heat coming from an industrial plant. This wasted heat is assumed to be an elementary flow of primary energy, meaning that the consumption of one MJ of this heat induces the consumption of one MJ of non renewable primary energy. It means that the consumption of this wasted heat does not induce any environmental burden. Hence, non renewable primary energy consumption associated with heat supply for drying algae represents 50% of non renewable primary energy consumption of pathways 1 and 2.

Next sections will analyse different aspects of the model (technical choices and main parameter values) in order to test their sensitivity.

3.2 Sensitivity Analyses

Sensitivity analyses are performed both on technical choices and on main parameters affecting GHG emissions. Technical sensitivity is done through scenarios comparison, and sensitivity analysis on the relevant parameters through Monte-Carlo analysis.

TABLE 2
Process options for each pathway to be assessed in SWAFEA project

Step	Input/process	Available options	Pathway 1	Pathway 2
Cultivation in open pounds	CO_2	From flue gases	x	x (in complement)
		From CO_2 recycling from anaerobic digestion		x
	Nutrients	From chemical only		x (in complement)
		From sludge	x	
		From recycling		x
	Light	Sunlight	x	x
	Water	Freshwater recycling	x	x
Harvesting		Settling		x
		Dissolved Air Flotation (DAF)	x	
Algae pretreatment	Concentration	Centrifugation	x	
		Mechanical press		x
	Drying	Heat from waste heat of industrial plant	x	x
		Heat from natural gas		
		No drying		
Extraction of raw material	Oil extraction	Hexane extraction	x	
		Mechanical press		x
Conversion into fuel	Hydrotreatment of vegetable oil	No propane recycling for utility production	x	x
Transport and distribution of fuel			x	x
Coproduct valorisation	Valorisation of biomass residues	Methanisation for electricity production (substitution with electricity from biomass cogeneration in Europe)		x
		Energetic allocation	x	
	Other fuels from hydrotreatment plant	Energetic allocation	x	x

3.2.1 Technical Sensitivity

A sensitivity analysis on technological choices on various steps of the pathway is done to compare each alternative scenario with the base case, defined as the pathway 1. Every alternative technology is presented below in Table 4.

Sensitivity results are presented below (*Fig. 5*). A positive percentage traduces an increase of the impact compared to the base case.

The use of chemical nutrients for algae cultivation increases by more than 40% the amount of GHG emissions compared to the use of sludge as nutrient (considered as a waste *i.e.* with no impact associated with its supply). The rise of GHG emissions and non renewable primary energy corresponds to the manufacture and the supply of chemical nutrient. In the nutrient recycling scenario, 75% of N and 50% of P are recycled, and the missing part is supplied by chemicals. This supply of

TABLE 3

Main data for pathways 1 and 2. Most of data is extracted from literature [10, 11, 14, 16, 20, 22, 24-30]

Data	Pathway 1	Pathway 2	Unit	Sources
Cultivation	In open pounds			
Productivty	21		g/(m^2.day)	[16]
Algae concentration	0.5		kg/m^3	[16]
Pond area	100		ha	[16]
Water depth	0.3		m	[16]
CO_2 content in flue gas	15%		(mass)	[14]
CO_2 needs	1.35		kg/kg of dry algae	[24]
N needs	0.061		kg/kg of dry algae	[24]
P needs	0.0081		kg/kg of dry algae	[24]
CO_2 recycle rate	-	33%	(mass) of original input	[25]
N recycle rate	-	75%	(mass) of original input	[25]
P recycle rate	-	50%	(mass) of original input	[25]
Electricity for CO_2 transportation	0.022		kWh/kg of injected CO_2	[26]
Electricity for paddle wheel	0.123		kWh/ha of pound	[27]
Electricity for water pumping	0.087		kWh/m^3 of water pumped	[27]
Harvesting	DAF	Settling		
Algae concentration out	20	10	kg/m^3	[14, 16]
Harvesting rate	95%	65%	(mass)	[14, 16]
Electricity	0.205	0.05	kWh/m^3 of input water	[14, 16]
Polystyrene	0.00242	-	kg/kg of dry harvested algae	[14]
Concentration of biomass	Centrifugation	Rotary press		
Algae concentration out	200	200	kg/m^3	[28] Fournier industries
Electricity	1.25	0.1	kWh/m^3 of input wet algae	[28] Fournier industries
Drying	Drying with waste heat from			
Algae concentration out	90		% of dry matter	[11]
Heat	2570		MJ/m^3 of water to be evaporate	[21]

(continued)

TABLE 3 (continued)

Data	Pathway 1	Pathway 2	Unit	Sources
Oil extraction	Hexane extraction	Oil press		
Oil content	34%		(mass) dry matter	Average from literature
LHV algae oil	36		MJ/kg	[29]
LHV algae before oil extraction	25.83		MJ/kg (dry matter)	[26]
Oil capture rate	95%	75%	(mass)	[14] constructor data from algaefuelsystems.com
Hexane losses	1.5	-	kg/t of dry algae	[14]
Heat	729	-	kg/t of dry algae	[14]
Electricity	70.18	125	kWh/kg of dry algae	[14] constructor data from algaefuelsystems.com
Hydrotreatment	NexBtL process			
Vegetable oil input	1.03		MJ/MJ of HRJ	[22]
Hydrogen input	0.09		MJ/MJ of HRJ	[22]
Electricity coproduced	0.002		MJ/MJ of HRJ	[22]
Steam coproduced	0.008		MJ/MJ of HRJ	[22]
LHV of HRJ	44.1		MJ/kg	[30]
Storage, transport and distribution of HRJ	150 km			
Diesel oil	0.00344		MJ/MJ of HRJ	[22]
Electricity	0.0042		MJ/MJ of HRJ	[22]
Valorisation of biomass coproduct	Animal meal	Methane to electricity		
LHV of biomass residues	21		MJ/kg of dry matter	Calculated
Conversion rate of biomass into CH_4	-	16.5	% of dry biomass converted in CH_4	Extrapolated from [22]
Electricity for mixing	-	5 388	kWh/m^3 of input biomass	[24]
Ekectricty for pumping	-	0.301	kWh/m^3 of input biogas	[16]
Autoconsumption of biogas	-	26%	of produced biogas	[16]
Yield of electricity production from CH_4	-	32	% energy	[14]
CO_2 credit for electricity coproduction	-	48	gCO_{2eq}/MJ of electricity	[10]

chemical nutrients explains the increase of the impacts for this scenario compared to scenario with the use of sludge as nutrient.

The choice of process option for the harvesting step impacts both the NREP energy and the GHG emissions. DAF system concentrates the algae to 20 kg/m^3 with a harvesting rate of 95% whereas settling system concentrates algae to 10 kg/m^3 with a harvesting rate of 65%. Consequently, more algae has to be cultivated with settling option in order to produce the same amount of algae harvested because there is no recycling of the overflow in the scope of this study. So these assumptions lead to an increase of the impacts linked with cultivation step for settling scenario.

Choosing a mechanical press instead of centrifugation for algae concentration reduces GHG emissions of the pathway but increases the NREP energy consumption. Indeed electricity consumption of the press is about ten times lower than the one for centrifugation. Even if the output algae concentration is lower, the amount of electricity consumed is smaller so as associated GHG emissions. Nevertheless more heat is consumed at drying step in order to reach the algae concentration of 90% TSS needed for dry hexane extraction. Therefore, NREP energy increases at drying step but GHG emissions do not increase because consumed heat is considered as waste with no CO_2 emissions associated.

Impacts associated with drying step could be significantly different depending on the process option. First the origin of heat used to dry algae is critical. The use of heat from natural gas leads to an increase of GHG emissions and NREP energy compared with the use of waste heat from industrial plant. Then the fact of drying or not algae before oil extraction modifies the energy balance of the system. Oil can be extracted from wet biomass by supercritical CO_2 but it lowers the efficiency of the oil extraction of 33% [32] so the oil recovering rate is equal to 62% instead of 95%. Hence upstream impacts

TABLE 4
Process options for the technical sensitivity

Step	Sensitive parameter	Base case	Alternative scenario
Cultivation	Nutrient supply	Sludge	Chemical nutrient only
Cultivation	Nutrient supply	Sludge	Nutrient recycling
Harvesting	Process option	DAF	Settling
Concentration	Process option	Concentration by centrifugation	Concentration with press
Drying	Process option	Drying with waste heat from industrial plant	Drying with heat from NG
Drying	Process option	Drying with waste heat from industrial plant	No drying
Oil extraction	Process option	Hexane extraction	Press for oil extraction

TABLE 5
Monte-Carlo analysis testing the sensitivity of each main parameter on GHG emission results for the first pathway

	Parameter Unit	Algae concentration kg/m^3	Algae productivity g/(m^2.day)	Oil content %
	Mean	0.76	28.04	0.34
Parameter distribution	Std deviation	65.72%	32.16%	39.70%
	Min	0.13	10.5	0.1
	Max	1.67	48	0.7
	Mean	18.2	19.9	20.1
	Std deviation	32.8%	0.3%	1.9%
GHG emission results distribution (gCO_{2eq}/MJ)	10th percentile	13.3	19.9	19.5
	25th percentile	14.3	19.9	19.8
	Median	16.2	19.9	20.1
	75th percentile	19.7	20.0	20.3
	90th percentile	25.8	20.0	20.6

associated with algae production are higher to produce the same amount of oil. Nevertheless, results for assessed impacts are lower than for the base case, which is in line with [31]. Indeed the amount and the LHV of biomass residues coproduced are higher and it represents 71% of the energy output at extraction step. Consequently the use of the energetic allocation for sharing the impacts between products and coproducts minimises the impacts allocated to the oil because of the high energy content of the oilcakes (see previous section about methodological sensibility).

The choice between an oil press instead of the hexane extraction induces a slight reduction of GHG emissions and NREP energy because no chemical inputs is needed for oil press extraction.

3.2.2 Sensitivity of Main Parameters for GHG Emissions

Several algae parameters are often mentioned as key parameters for algae production in the literature. These parameters are algae productivity and oil content on dry mass of algae [33], and algae concentration in ponds. Here, we conduct a Monte-Carlo analysis testing the distribution of each parameter one by one in order to evaluate its influence on GHG emissions result of the entire system. The same approach has been used by Benoist *et al.* to compare the GHG emissions of three first generation biofuels [34]. Parameter distributions correspond to distributions of the values found in the literature [1, 11, 13, 14, 16-18, 26, 31, 33, 35-43].

The Monte-Carlo analysis results show a weak system sensibility to algae productivity and oil content but a high system sensibility to algae concentration during cultivation that corresponds to a standard deviation of about 33% for the GHG emission results.

The high sensibility of the system to algae concentration value could be due to the amount of water to manage. Indeed the less algae are concentrated in water the higher the amount of water to be pumped, mixed and then to be removed to obtained the desired amount of algae will be. This water management is associated to electrical consumption that represents 45% of the electrical consumption of the culture step. GHG emissions associated with electricity consumption for water management (pumping and mixing at cultivation step and water removal at harvesting step) represent 36% of GHG emissions for the base case. Consequently, the less algae are concentrated the more GHG are emitted for culture and harvesting step.

The oil content influences both in opposite ways the amount of HRJ by kilogram of algae and the LHV of the biomass residues. When algae contain more oil, more biofuel is produced but the LHV of algal residues is lower. As the impacts allocated to HRJ are based on energy content between oil and algal residues, a higher oil content leads to a higher amount of impacts allocated to the production of HRJ. In the end, the sensibility to oil content is weak as indicated by the value of the standard deviation.

In our system, the value of algae productivity hardly affects the GHG emissions. In fact, impacts are expressed for one MJ of fuel produced. This production needs a certain amount of algae. When the productivity of algae increases, this needed amount of algae to produce 1 MJ of biofuel remains the same, as well as cultivation inputs (expressed per kg of algae produced). The only impacted processes are the ones which are independent from the growth rate: electricity for the paddlewheel and building of the infrastructures. However algae productivity strongly influences the land use impact that is not taken into account in our study.

DISCUSSION AND CONCLUSIONS

Since a couple of years LCA method is more and more used to assess the environmental impacts of bioenergy production from microalgae. Most studies are focused on the production of biodiesel, and some of them on biogas. The presented work is focused on the production on a type of biodiesel, the biojetfuel. The production of biogas by anaerobic digestion of the oilcakes and its use have also been analyzed. The main goal of this study is to perform sensitivity analyses on technical choices and on the main parameter values affecting energy consumption and GHG emissions. The sensitivity analysis on technological choices allows us to identify the best system configuration in terms of reduction of energy consumption and GHG emissions. The best scenarios are the ones with the use of nutrients from wastewater, and with extraction of oil from wet biomass by supercritical CO_2. Finally Monte-Carlo approach has been undertaken to link the variations of important parameters (oil content, algae productivity and algae concentration in the ponds) with the variations of GHG emissions. This analysis shows that the main parameter influencing GHG emissions is the algae concentration in the ponds. However, this result is strongly affected by the assumptions of the study, like the allocation rule chosen to account for coproducts impacts. Furthermore, nitrogen deprivation and its implication on productivity and oil content have not been taken into account, and could be the objects of future developments. In fact, given that growth rate and lipid content conflict with each other, a trade-off must be made between these two parameters when producing biofuel. The use of Monte-Carlo analysis allows us to incorporate probabilistic uncertainty analysis into LCA, and therefore to better understand the reliability of the results, even if we were not able to perform it taking into account all parameters distribution. The direct comparison with other studies is most of the time not straightforward, because of the different assumptions, data and system boundary choices set by each microalgae or algae production chain. Nevertheless our results are in line with results from the literature [44, 45], both for energy consumption and GHG emissions.

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REFERENCES

1 Chisti Y. (2007) Biodiesel from microalgae, *Biotechnology Advances* **25**, 3, 294-306. doi:10.1016/j.biotechadv.2007.02.001.

2 Brennan L., Owende P. (2010) Biofuels from microalgae — A review of technologies for production, processing, and extractions of biofuels and co-products, *Renewable and Sustainable Energy Reviews* **14**, 2, 557-577. doi:10.1016/j.rser.2009.10.009.

3 International Organization for Standardization (ISO) (2006) ISO14040:2006 Environmental management-life cycle assessment-principles and framework.

4 International Organization for Standardization (ISO) (2006) ISO14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines

5 Luo L., Voet E., Huppes G., Udo de Haes H.A. (2009) Allocation issues in LCA methodology: a case study of corn stover-based fuel ethanol, *The International Journal of Life Cycle Assessment* **14**, 6, 529-539. doi:10.1007/s11367-009-0112-6.

6 González-García S., Gasol C.M., Gabarrell X., Rieradevall J., Moreira M.T., Feijoo G. (2010) Environmental profile of ethanol from poplar biomass as transport fuel in Southern Europe, *Renewable Energy* **35**, 5, 1014-1023. doi:10.1016/j.renene.2009.10.029.

7 Novelli P., Marizy C., Bringtown S. Tamboer B., Cariolle D., Paoli R., Roetger T., Prieur A., Patouillard L., Thellier L., Bessagnet B., Metz S., Novelli P., Vancassel X., Jongschaap R., Conijn J.G., Rutgers B., Courtet C., Rollin G. (2011) SWAFEA project - Environmental impact analysis report, **Vol. 2**.

8 European Parliament (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, *Official Journal of the European Union* **L 140/16**, 16-62.

9 Arvidsson R., Fransson K., Fröling M., Svanström M., Molander S. (2012) Energy use indicators in energy and life cycle assessments of biofuels: review and recommendations, *Journal of Cleaner Production* **31**, 54-61. doi:10.1016/j.jclepro.2012.03.001.

10 Dones R., Bauer C., Bolliger R., Burger B., Heck T., Röder A., Emmenegger M.F., Frischknecht R., Jungbluth N., Tuchschmid M. (2007) Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries Data v2.0, *Ecoinvent report No. 5*.

11 Lardon L., Hélias A., Sialve B., Steyer J.-P., Bernard O. (2009) Life-Cycle Assessment of Biodiesel Production from Microalgae, *Environmental Science & Technology* **43**, 17, 6475-6481. doi:10.1021/es900705j.

12 Del Campo J.A., García-González M., Guerrero M.G., (2007) Outdoor cultivation of microalgae for carotenoid production: current state and perspectives, *Applied Microbiology and Biotechnology* **74**, 6, 1163-1174. doi:10.1007/s00253-007-0844-9.

13 Jorquera O., Kiperstok A., Sales E.A., Embiruçu M., Ghirardi M.L. (2010) Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors, *Bioresource Technology* **101**, 4, 1406-1413. doi:10.1016/j.biortech.2009.09.038.

14 Campbell P.K., Beer T., Batten D. (2010) Life cycle assessment of biodiesel production from microalgae in ponds, *Bioresource Technology* **102**, 1, 50-56. doi:10.1016/j.biortech.2010.06.048.

15 Singhal A.K., Mehrotra R.K. (2000) *Environmental Issues and Management of Waste in Energy and Mineral Production*, A.A.Balkema.

16 Collet P., Hélias A., Lardon L., Ras M., Goy R.-A., Steyer J.-P. (2011) Life-cycle assessment of microalgae culture coupled to biogas production, *Bioresource Technology* **102**, 1, 207-214. doi:10.1016/j.biortech.2010.06.154.

17 Sander K., Murthy G.S. (2010) Life cycle analysis of algae biodiesel, *The International Journal of Life Cycle Assessment* **15**, 7, 704-714. doi:10.1007/s11367-010-0194-1.

18 Clarens A.F., Resurreccion E.P., White M.A., Colosi L.M. (2010) Environmental life cycle comparison of algae to other bioenergy feedstocks, *Environmental Science & Technology* **44**, 5, 1813-1819. doi:10.1021/es902838n.

19 Fagerstone K.D., Quinn J.C., Bradley T.H., De Long S.K., Marchese A.J. (2011) Quantitative measurement of direct nitrous oxide emissions from microalgae cultivation, *Environmental Science & Technology* **45**, 21, 9449-9456. doi:10.1021/es202573f.

20 Reinhardt G., Gärtner S., Helms H., Rettenmaier N. (2006) An assessment of energy and greenhouse gases of NExBTL, *Ifeu - Inst. Energy Environ. Res Heidelb.*

21 Stasta P., Boran J., Bebar L., Stehlik P., Oral J. (2006) Thermal processing of sewage sludge, *Applied Thermal Engineering* **26**, 13, 1420-1426. doi:10.1016/j.applthermaleng.2005.05.030.

22 JEC - Joint Research Centre-EUCAR-CONCAWE collaboration (2008) Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context (Version 3) (p. 88) *JRC/EUCAR/CONCAWE European Commission Joint Research Center*. doi:10.2788/79018.

23 Earle J.K.J. (2005) Wheels of Progress: Rotary Press Selection for Plum Island, *Florida Water Resources Journal*, April, 48-52. http://www.fwrj.com/techarticle05/0405%20fwrj%20tech%202.pdf.

24 Ras M., Lardon L., Bruno S., Bernet N., Steyer J.-P. (2011) Experimental study on a coupled process of production and anaerobic digestion of Chlorella vulgaris, *Bioresource Technology* **102**, 1, 200-206. doi:10.1016/j.biortech.2010.06.146.

25 Weissman J.C., Goebel P.R. (1987) *Design and Analysis of Microalgal Open Pond Systems for the Purpose of Producing Fuels*, Golden, Colorado. http://www.nrel.gov/docs/legosti/old/2840.pdf.

26 Kadam K.L. (2002) Environmental implications of power generation *via* coal-microalgae cofiring, *Energy* **27**, 10, 905-922. doi:10.1016/S0360-5442(02)00025-7.

27 Sazdanoff N. (2006) *Modeling and Simulation of the Algae to Biodiesel Fuel Cycle*, The Ohio State University. https://kb.osu.edu/dspace/bitstream/handle/1811/5981/?sequence=1.

28 Fournier Industries at http://www.rotary-press.com/ (n.d). Retrieved from http://www.rotary-press.com/.

29 Minowa T., Yokoyama S., Kishimoto M., Okakura T. (1995) Oil production from algal cells of Dunaliella tertiolecta by direct thermochemical liquefaction, *Fuel* **74**, 12, 1735-1738. doi:10.1016/0016-2361(95)80001-X.

30 Hileman J.I., Stratton R.W., Donohoo P.E. (2010) Energy Content and Alternative Jet Fuel Viability, *Journal of propulsion and Power* **26**, 6, 1184-1195. American Institute of Aeronautics and Astronautics. Retrieved from http://cat.inist.fr/?aModele=afficheN&cpsidt=23434811.

31 Brentner L.B., Eckelman M.J., Zimmerman J.B. (2011) Combinatorial life cycle assessment to inform process design of industrial production of algal biodiesel, *Environmental Science & Technology* **45**, 16, 7060-7067. doi:10.1021/es2006995.

32 Halim R., Gladman B., Danquah M.K., Webley P.A. (2011) Oil extraction from microalgae for biodiesel production, *Bioresource Technology* **102**, 1, 178-185. doi:10.1016/j.biortech.2010.06.136.

33 Hou J., Zhang P., Yuan X., Zheng Y. (2011) Life cycle assessment of biodiesel from soybean, jatropha and microalgae in China conditions, *Renewable and Sustainable Energy Reviews* **15**, 9, 5081-5091. doi:10.1016/j.rser.2011.07.048.

34 Benoist A., Dron D., Zoughaib A. (2012) Origins of the debate on the life-cycle greenhouse gas emissions and energy consumption of first-generation biofuels – A sensitivity analysis approach, *Biomass and Bioenergy* **40**, 133-142. doi:10.1016/j.biombioe.2012.02.011.

35 Vera-morales M., Schäfer A. (2009) *Final Report: Fuel-Cycle Assessment of Alternative Aviation Fuels*, pp. 1-39, http://www.cate.mmu.ac.uk/wp-content/uploads/2012/06/10-Final-Report-Sustainable-Fuels.pdf.

36 Stephenson A.L., Dupree P., Scott S.A., Dennis J.S. (2010) The environmental and economic sustainability of potential bioethanol from willow in the UK, *Bioresource Technology* **101**, 24, 9612-9623. doi:10.1016/j.biortech.2010.07.104.

37 Stratton R.W., Wong H.M., Hileman J.I. (2010) *Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels, PARTNER Project 28 report Version 1.1.*, Cambridge, Massachusetts, http://web.mit.edu/aeroastro/partner/reports/proj28/partner-proj28-2010-001.pdf.

38 Khoo H.H., Sharratt P.N., Das P., Balasubramanian R.K., Naraharisetti P.K., Shaik S. (2011) Life cycle energy and CO_2 analysis of microalgae-to-biodiesel: preliminary results and comparisons, *Bioresource Technology* **102**, 10, 5800-5807. doi:10.1016/j.biortech.2011.02.055.

39 Razon L.F., Tan R.R. (2011) Net energy analysis of the production of biodiesel and biogas from the microalgae: Haematococcus pluvialis and Nannochloropsis, *Applied Energy* **88**, 10, 3507-3514. doi:10.1016/j.apenergy.2010.12.052.

40 Batan L., Quinn J., Willson B., Bradley T. (2010) Net energy and greenhouse gas emission evaluation of biodiesel derived from microalgae, *Environmental Science & Technology* **44**, 20, 7975-7980. doi:10.1021/es102052y.

41 Clarens A.F., Nassau H., Resurreccion E.P., White M.A., Colosi L.M. (2011) Environmental impacts of algae-derived biodiesel and bioelectricity for transportation, *Environmental Science & Technology* **45**, 17, 7554-7560. doi:10.1021/es200760n.

42 Yang J., Xu M., Zhang X., Hu Q., Sommerfeld M., Chen Y. (2011) Life-cycle analysis on biodiesel production from microalgae: water footprint and nutrients balance, *Bioresource Technology* **102**, 1, 159-165. doi:10.1016/j.biortech.2010.07.017.

43 Sturm B.S.M., Lamer S.L. (2011) An energy evaluation of coupling nutrient removal from wastewater with algal biomass production, *Applied Energy* **88**, 10, 3499-3506. doi:10.1016/j.apenergy.2010.12.056.

44 Sills D.L., Paramita V., Franke M.J., Johnson M.C., Akabas T.M., Greene C.H., Tester J.W. (2013) Quantitative uncertainty analysis of Life Cycle Assessment for algal biofuel production, *Environmental Science & Technology* **47**, 2, 687-694. doi:10.1021/es3029236.

45 Slade R., Bauen A. (2013) Micro-algae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects, *Biomass and Bioenergy* **53**, 0, 29-38. doi:10.1016/j.biombioe.2012.12.019.

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