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# Life-cycle assessment of microalgae culture coupled to biogas production

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## ABSTRACT

Due to resource depletion and climate change, lipid-based algal biofuel has been pointed out as an interesting alternative because of the high productivity of algae per hectare and per year and its ability to recycle CO<sub>2</sub> from flue gas. Another option for taking advantage of the energy content of the microalgae is to directly carry out anaerobic digestion of raw algae in order to produce methane and recycle nutrients (N, P and K). In this study, a life-cycle assessment (LCA) of biogas production from the microalgae *Chlorella vulgaris* is performed and the results are compared to algal biodiesel and to first generation biodiesels. These results suggest that the impacts generated by the production of methane from microalgae are strongly correlated with the electric consumption. Progresses can be achieved by decreasing the mixing costs and circulation between different production steps, or by improving the efficiency of the anaerobic process under controlled conditions. This new bioenergy generating process strongly competes with others biofuel productions.

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## 1. Introduction

In a context of climate change and fossil fuel depletion, there is a rising interest of industrial and academic actors in renewable energy sources and especially in energy production based on biomass transformation. The use of agroresources to produce bioethanol and biodiesel generally induces a lower climate change potential, but can create other environmental issues (e.g. eutrophication, resource depletion, ecotoxicity, biodiversity...) and generate competition with foodcrops for the use of arable land (Zah et al., 2007). Furthermore, the global warming effect induced by the production of bioenergy from biomass is also significant and can be sometimes higher than the ones induced by fossil fuel production (Crutzen et al., 2008).

On the other hand, microalgae represent an interesting alternative to the production of first or second generation biofuels (Chisti, 2007; Brennan and Owende, 2004), thanks to a high photosynthetic yield and hence, a lower land competition with food production and a better control of ground emissions. In addition, the ability to use CO<sub>2</sub> directly from industrial emissions as a resource of carbon for the growth of microalgae is a promising feature for fluegas mitigation.

However, as it has been recently shown in life-cycle assessment (LCA) or energy analyses (Lardon et al., 2009; Clarens et al., 2010),

fertilizers consumption, harvesting and oil extraction from algae represent a high energy debt which might jeopardize the overall interest of algal biofuel. According to Molina Grima et al. (2003), the harvesting cost can represent from 20% to 30% of the production cost, and when combined with oil extraction, exceeds 50% (Moheimani, 2005). It is therefore worth to investigate another transformation process by directly carrying out anaerobic digestion of raw algae and hence to use the produced methane as biofuel.

Anaerobic digestion is a well known technology widely used for the treatment of concentrated pollution streams as distillery or piggery effluents. The idea of coupling such a process with algal production was first mentioned by Golueke et al. (1957) and positively commented by others authors since (Sialve et al., 2009). As it by-passes the concentration and oil extraction steps, it could avoid a significant cost and reduce the total energy debt. Moreover by recirculating the liquid fraction of the digestates toward the algal ponds, a significant part of the fertilizers could be recycled.

Most of the time, the biogas produced by anaerobic digesters and landfills is used locally via cogenerators or boilers. However others renewable energy sources with lower impacts (e.g. windmills, solar panels...) can be used for the purpose of heat and electricity production. Biogas can also be enriched to become a fuel used by internal combustion engines (e.g. buses of Lille, France or Linköping, Sweden) (Börjesson and Mattiasson, 2006).

The purpose of this paper is to undertake an environmental assessment of the use of methane from algae as a biofuel and hence compare it to petrol or other biofuels (biodiesel or bioethanol). Environmental and energy analysis will be carried out within the

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methodological framework of the LCA based on a “cradle to grave” inventory of emissions and resources consumption.

The chosen method to assess the potential impacts is CML (Centrum voor Milieukunde Leiden), described in Guinée (2002).

Numerical figures have been suggested in the literature in order to defend this combined production system but such data often over-estimate both the algal productivity and the methane yield production while ignoring inherent difficulties to degrade a particulate substrate with a high protein content. In this study, figures describing the anaerobic digestion of the microalgae *Chlorella vulgaris* are based on experimental data obtained from lab scale processes (Ras et al., this issue). To our knowledge, this is the first time that LCA is used to evaluate the production of biogas from microalgae using experimental data.

## 2. Methodology

### 2.1. Goal and scope definition

The goal of this study is to evaluate the potential environmental impacts of methane production from microalgae and its combustion. The considered functional unit is one MJ produced by combustion in an internal combustion engine. According to the principles of LCA, the inventory will include production, harvesting and concentration of algae, their transformation to methane and its combustion, the facility construction and dismantling, and finally the extraction and shipping of resources.

The substitution method has been used for by-products accounting. It consists in an expansion of the system boundaries in order to take into account the impacts generated by the by-products. This is done in accordance with the ISO guidelines, which suggest to prefer the substitution instead of the allocation when it is possible. Environmental impacts will be evaluated with the CML method (Guinée, 2002).

As stated before, the analysed process chain refers to a hypothetical system based on extrapolation from lab-scale studies. The

inventory is based on figures derived from academic resources, communications with industrial producers, and inventories carried out on similar transformation units and processes described in the Ecoinvent database (Frischknecht et al., 2007). Figures describing the anaerobic digestion of the microalgae *Chlorella vulgaris* are based on experimental data obtained at lab scale (Ras et al., this issue). Standard rules have been used for replacement of infrastructures: buildings have a 30 years lifespan, and are then dismantled, concrete is sent to ultimate landfill whereas steel-based and PVC products are recycled. Electrical engines are changed every 10 years.

The location of the system is in the southern Europe; as a consequence climatic data to determine water loss by evaporation are based on statistics of the south of France (Narbonne), near the Mediterranean area, and the energy mix for electricity is based on the European average.

Fig. 1 shows an overview of the system, from the cultivation of the algae to the use of methane as fuel in a vehicle. Algae are cultivated in open raceways, then concentrated firstly by natural settling and then by spiral plate centrifugation. The concentrated algal stream is injected into anaerobic digesters. A part of the produced biogas (30%) is directly burned in a boiler to heat the anaerobic digestion plant whereas the main part of the gas flow (70%) is processed in a purification plant able to enrich the biogas. The recovered  $\text{CO}_2$  is reinjected into the system dissolved in water and will support algae growth. The methane produced has fuel quality and can be burned in any fitted internal combustion engine.

Daily flows reported on figures and tables are determined for a facility of 100 ha of cultivated area, and 23,000  $\text{m}^3$  of total effective volume for the digesters.

### 2.2. Life-cycle inventory

#### 2.2.1. Microalgae cultivating step

According to Chisti (2007), algae culture in open raceways is more fitted to mass production than photobioreactors, even if the

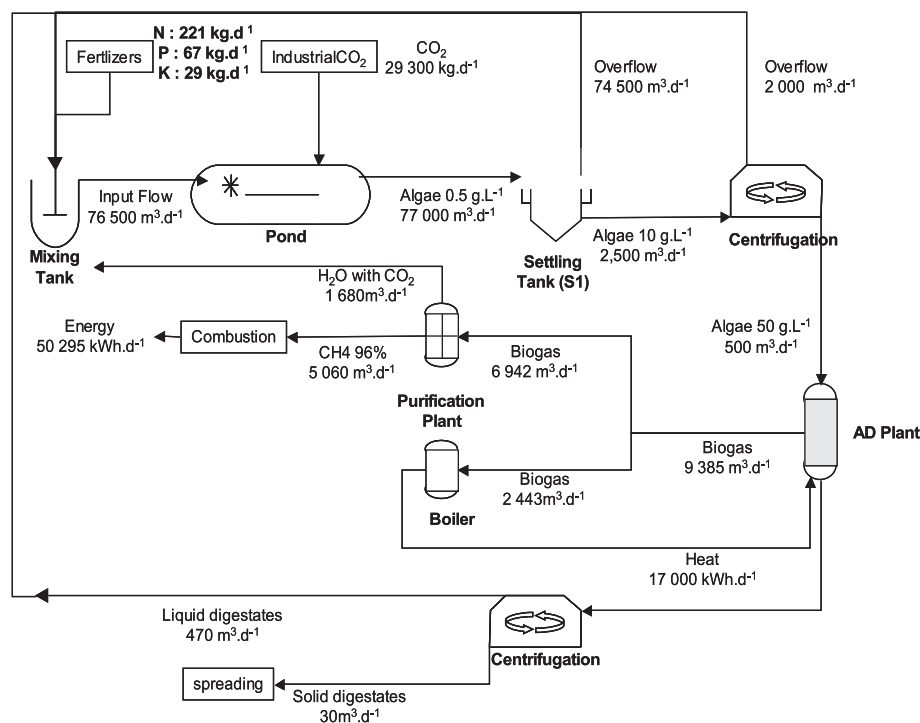


Fig. 1. Overview of the system coupling microalgae production with anaerobic digestion. Values are indicated for a cultivated area of 100 ha in raceways.

growth rate of algae is lower in open ponds than in photobioreactors. Actually the net energy ratio (NER) for total biomass is higher in raceway ponds than in flat-plate photobioreactors (Jorquera et al., 2009). In addition, the economic cost of photobioreactors is almost one order of magnitude higher than the cost of open raceways (Del Campo et al., 2007). Consequently, the culture is performed in open raceways of 1000 m<sup>2</sup> (100 m long and 10 m wide) of useful area and is 30 cm depth (Richmond, 2003; Lardon et al., 2009). The ponds are built out of concrete blocks on a slab of 10 cm of thickness. The pond area and the internal walls are covered with a PVC liner and acrylic varnish. We consider a cultivation system of 1000 ponds, which leads to a cultivated area of 100 ha.

The growth rate of *Chlorella vulgaris* is assumed to be 25 g m<sup>-2</sup> d<sup>-1</sup> (Lardon et al., 2009; Clarens et al., 2010), which leads to a daily productivity of 25,000 kg d<sup>-1</sup>. The algae concentration is 0.5 kg m<sup>-3</sup>. The quantities of carbon dioxide and fertilizers required for growth of the algae are based on the composition of the algae. Experimental data in Ras et al. (this issue) give the following composition for 1 kg of dry algae: 367 gC and 61 gN. The ratios of P and K compared to N in *Chlorella vulgaris* (Lardon et al., 2009) lead to a composition in phosphorus and potassium of 8.1 gP and 6.59 gK per kg of dry algae.

The CO<sub>2</sub> is supplied by three ways: as CO<sub>2</sub> recovered from the purification which is dissolved in water, as dissolved CO<sub>2</sub> in the anaerobic digestion output flow, or as compressed gas injected in the ponds. PVC pipes bring the liquid and gaseous streams to the ponds. It is assumed that the microalgae capture 90% of the gaseous CO<sub>2</sub> injected (Sheehan et al., 1998). The energy cost of the injection is evaluated at 22.2 Wh per kg of CO<sub>2</sub> (Kadam, 2002).

The liquid digestates recirculated from the anaerobic digesters provide a part of the fertilizer requirement of the culture. The remainder is supplied by mineral fertilizers. The choice of the chemical fertilizers is made in order to minimize the environmental effects linked to their life-cycles. Nitrogen is brought by ammonium sulphate, phosphorus is brought by single superphosphate, and potassium is brought by potassium chloride. The distance between storage and production sites is fixed to be 100 km. No supplementary energy consumption is considered for fertilizers mixing as the water has already been pressurized during the purification step.

We assume a total efficiency for the use of the fertilizers, in other words there is no nutrient loss in the system, except the mineral content of the solid digestates. As the supernatant of settling and centrifugation in one hand and the liquid digestates in the other hand are recirculated through the ponds, this assumption is correct on a global balance approach. It only neglects the loss by volatilization of NH<sub>3</sub> which can be controlled by keeping pH lower than 7.

Water movement is provided by a paddlewheel at a velocity of 25 cm s<sup>-1</sup>. The loss of water is estimated to be 600 mm per year. Water losses are compensated by the fresh water used at the purification step and reinjected (at high dissolved inorganic carbon concentration) in the mixing tank.

## 2.2.2. Harvesting step

Biomass harvesting is done in two steps. First a natural settling, and then a second concentration of the algae by centrifugation.

**2.2.2.1. Natural settling step.** Conservative assumptions have been done for the description of the passive sedimentation process, based on data collected by the authors on lab-scale photobioreactors. Experimental data showed good sedimentation properties of *C. vulgaris*, with a sedimentation velocity of 3.575 m d<sup>-1</sup>, allowing the collection of 65% of the algal biomass with a concentration 20 times higher than in the culture stream after one hour (Ras et al., this issue). The overflow is recirculated toward the algal ponds.

Such an harvesting efficiency requires to pump 76,923 m<sup>3</sup> d<sup>-1</sup> for an installation of 100 ha, which means an electrical consumption of 3825 kWh d<sup>-1</sup> for the pumping.

The settlers are cone-shaped concrete structures. The volume of each settler is 1722 m<sup>3</sup>, with 4 m height and a radius of 11.7 m. Fifty settlers are used for the 1000 ponds. (i.e 0.5 settlers per hectare of culture).

**2.2.2.2. Centrifugation step.** The centrifugation is done through the Spiral Plate Technology of Evodos (2010). The concentration factor is 5, which leads to an output flow to the anaerobic digestion step of 500 m<sup>3</sup> d<sup>-1</sup> at an algae concentration of 50 kg m<sup>-3</sup>.

According to constructor details, with a loading rate of 7 kg m<sup>-3</sup>, the energy required in order to obtain an algae paste with 30% of dry matter is 1 MJ kg<sup>-1</sup>. We assume that with a loading rate of 10 kg m<sup>-3</sup>, the energy consumption to obtain an algae paste at 5% of dry matter in the output flow is equal to 0.15 MJ kg<sup>-1</sup>. This energy consumption takes into account the energy required for injecting the algae in the anaerobic digesters. The loading rate of the centrifugation devices is 3 m<sup>3</sup> h<sup>-1</sup>, therefore 34.7 machines are needed to treat the 2500 m<sup>3</sup> d<sup>-1</sup>. We assume that the centrifugation devices are made out of 2000 kg of steel.

## 2.2.3. Anaerobic digestion step

All the data used for the functioning of the anaerobic digestion plant and the biogas purification plant come from industrial data, and are based on state-of-the-art engineering for wastewater treatment applications (Naskeo, internal communication between authors).

From our experimental data, it is necessary to apply a retention time higher than 40 days to obtain a methanisation yield superior to 75% of its maximal biological potential; in this study the anaerobic digester has been designed to offer a hydraulic retention time (HRT) of 46 days. For a production facility of 100 ha, the reactors will have to treat a flow of 500 m<sup>3</sup> d<sup>-1</sup>. It induces that the total effective volume needed for the anaerobic digestion process is 23,000 m<sup>3</sup>. This leads to an organic loading rate (OLR) of 1.4 g<sub>cod</sub> L<sup>-1</sup> d<sup>-1</sup>, which is compatible with the use of a completely stirred tank reactor, the most usual digester technology. We consider seven cylinder-shaped digesters on the site, of 8 m height and 24 m of external diameter.

The tests undertaken in continuous reactors provide the experimental data which are presented in Table 1 (Ras et al., this issue), consistently with other studies (Chen, 1987; Sialve et al., 2009).

The daily production of biogas is 9385 m<sup>3</sup> d<sup>-1</sup>, and its composition is 70% of CH<sub>4</sub> and 30% of CO<sub>2</sub>. The heat required for this plant is 17,000 kWh d<sup>-1</sup>, which is equivalent to a consumption of 2443 m<sup>3</sup> d<sup>-1</sup> of biogas (lower heating value of the biogas is equal to 6.958 kWh m<sup>-3</sup>). This heat necessary for operating the anaerobic digestion plant is provided by burning part of the biogas produced in a boiler. The electric consumption of the anaerobic digestion plant is 2 694.1 kWh d<sup>-1</sup>.

## 2.2.4. Biogas upgrading step

Schematically, upgrading and washing the biogas is achieved by bubbling the biogas in pressurized water. As methane is barely soluble and CO<sub>2</sub> is highly soluble, the remaining gas is mainly composed of CH<sub>4</sub>. Other trace gases (e.g. H<sub>2</sub>S) and dusts are also removed during the process. The energy consumption of this step is 0.301 kWh m<sup>-3</sup> of biogas upgraded. This step leads to a gas with 96% of CH<sub>4</sub>. The daily quantity of biogas to upgrade is 6942 m<sup>3</sup> which leads to 5061.5 m<sup>3</sup> d<sup>-1</sup> of a gas rich at 96% in CH<sub>4</sub>. The water in which the CO<sub>2</sub> has been dissolved is reinjected in the mixing tank.

**Table 1**

Biomass characteristics of *Chlorella vulgaris* and anaerobic digestion performances for a HRT equals to 46 days (Ras et al., this issue).

	Parameters <sup>a</sup>	Value
Biomass characteristics	gVSS/gTSS	0.9
	gCOD/gVSS	1.429
	gTOC/gCOD	0.286
	gTKN/gTOC	0.167
Anaerobic digestion performances	mLCH <sub>4</sub> /gVSS	292
	mLCH <sub>4</sub> /gCOD	204
	%CH <sub>4</sub> in the biogas	70
	Biodegradability	0.56
	Mineralisation rate (own assumption)	0.9

<sup>a</sup> VSS, volatile suspended solids; TSS, total suspended solids; TKN, total kjeldahl nitrogen; TOC, total organic carbon.

### 2.2.5. Liquid digestates recycling step

Anaerobic digestion of the algae leads to the production of digestates composed of organic and mineralized matter. During this step 56% of the carbon fraction of the algae is degraded. Concerning the degradation of the nitrogen, phosphorus and potassium fraction of the algae, the tests undertaken by Ras et al. (this issue) provide mineralisation rates equal to 19% for an HRT of 16 days and to 68% for an HRT of 28 days. We estimate that 90% of the N, P and K is degraded for an HRT of 46 days.

The particulate matter is concentrated by centrifugation up to 30% of dry matter. The electric consumption of this step is 630 kWh d<sup>-1</sup>. These solid digestates are substituted to mineral fertilizers at plant. The solid fraction can be used as a soil conditioner, bringing fertilizers to the soil and increasing its organic content. Even if the availability of the mineral elements is not as high as the one of mineral fertilizers, it is assumed here that the application of the soil conditioner allows to save the equivalent amount of mineral fertilizers for N, P and K. This substitution takes into account the CO<sub>2</sub> emitted during the decomposition of the organic matter, which is here assumed to be complete. This organic fraction corresponds to 33.33 m<sup>3</sup> d<sup>-1</sup>, with a concentration of carbon, nitrogen, phosphorus and potassium by cubic meter equals to 120.01 kgC, 4.5 kgN, 0.607 kgP and 0.495 kgK.

The liquid part of the digestates with mineralised matter is reinjected in the mixing tank and is considered as fertilizers for the algae. It corresponds to 466.67 m<sup>3</sup> d<sup>-1</sup>, with a fertilizer concentration by cubic meter equal to 2.94 kgN, 0.39 kgP and 0.32 kgK.

## 3. Results and discussion

### 3.1. Mass flows and electric consumptions

Table 2 presents the main mass and energy flows which occur during the different steps of methane production from algae. Each step is characterized by significant energy requirements. The highest energy demand comes from heating the digesters. Nevertheless, this heating is provided by burning the collected biogas produced from microalgae digestion. Therefore this energy sink does not appear in the energy ratio. The total electric consumption is 0.640 kWh by kg of algae or 3.2 kWh by cubic meter of methane, which means 16,000 kWh d<sup>-1</sup> for the whole system. The most consuming stages are:

- the paddlewheels: 31.2%
- the pumping between the ponds and the settlers: 23.9%
- the anaerobic digestion plant: 20.8%, with 16.9% for the mixing of the digesters and the pumping, and 3.9% for the centrifugation of the digestates
- the purification plant: 13%
- the centrifugation of the algae: 6.6%
- the CO<sub>2</sub> injection: 4.5%

**Table 2**

Mass and energy flow generated by the production of 1 kg of algae.

Step	Value	Units
<i>Culture and harvesting</i>		
Flow out of the ponds	3.077	m <sup>3</sup>
Nitrogen consumption	8.85E–03	kg
Phosphorus consumption	2.69E–03	kg
Potassium consumption	1.15E–03	kg
CO <sub>2</sub> consumption	1.172	kg
Electricity consumption (CO <sub>2</sub> injection)	0.0289	kWh
Electricity consumption (Paddlewheel)	0.200	kWh
<i>Natural settling</i>		
Flow out of the settlers	0.1	m <sup>3</sup>
Electricity consumption (Pumping)	0.153	kWh
<i>Centrifugation</i>		
Flow out	0.02	m <sup>3</sup>
Electricity consumption	0.042	kWh
<i>Anaerobic digestion</i>		
Biogas production	0.375	m <sup>3</sup>
Electricity consumption (mixing of the digesters)	0.108	kWh
Electricity consumption (centrifugation of the digestates)	0.0252	kWh
Heat consumption (internal biogas) <sup>a</sup>	0.68	kWh
<i>Purification</i>		
Methane, 96 vol%	0.201	m <sup>3</sup>
Electricity consumption	0.083	kWh
Water consumption	0.067	m <sup>3</sup>
<i>Combustion</i>		
Energy (from methane)	2.00	kWh

<sup>a</sup> This value has already been subtracted to the energy production.

It can be noticed that the reinjection of the liquid digestates in the ponds induces very low needs in chemical fertilizers. Without this recycling, the amount in fertilizers would have been increased by a factor 10 in order to fit algae nutrient requirements.

Fig. 2 presents the carbon flows of our system. The carbon lost by combustion or by the spreading of solid digestates is supplied to the system at the pond level in the form of CO<sub>2</sub>.

### 3.2. Processes contribution

The processes implicated in one MJ produced by burning algal fuel through an internal combustion engine are shown in Fig. 3. The CML method (Guinée, 2002) has been used to assess potential environmental impacts. The selected impacts are: *abiotic depletion* (Abd), *potential acidification* (Acid), *eutrophication* (Eutro), *global warming potential* (GWP), *ozone layer depletion* (Ozone), *human toxicity* (Hum Tox), *land competition* (Land), *ionising radiation* (Rad) and *photochemical oxidation* (Photo). The different stages of the whole process chain have been grouped in 4 categories, in order to analyse their contribution towards different impacts:

- Energy: impacts related to the production and the use of the energy (heat and electricity) required on the facility.
- Infrastructures: impacts related to the building and the recycling of infrastructures. This category includes the transport of the materials.
- Combustion: impacts generated by the combustion of biogas in a boiler (heating of the system) and of methane in an internal combustion engine.
- Fertilizers: impacts linked to all the fertilizers, i.e. all substrate compounds required for algal growth (N, P, K, and CO<sub>2</sub>). As the substitution method has been used for by-products accounting, the only impacts of this category are the ones linked to CO<sub>2</sub>.

For most of the impacts, the electric consumption represents the most important contribution. This proportion can reach more than 60% for the ionising radiation (89.8%), abiotic depletion



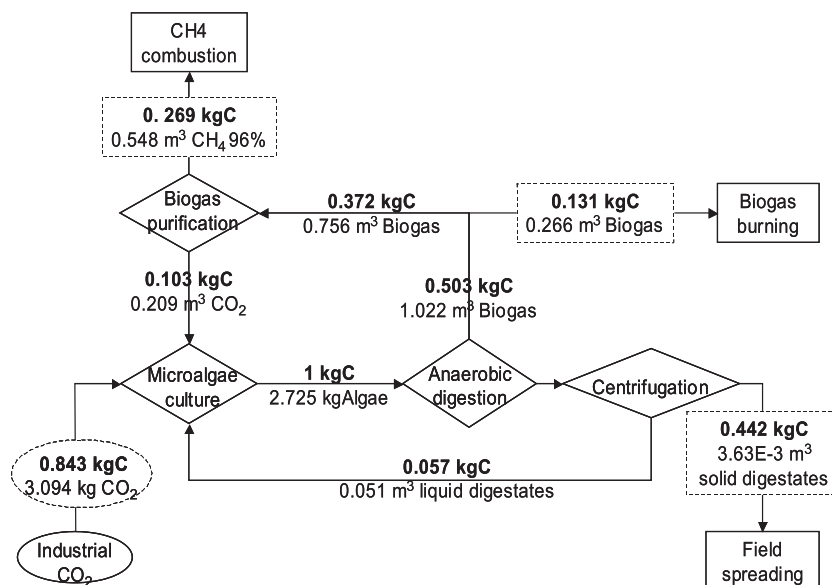


Fig. 2. Carbon balance of the system. The squares correspond to the outputs of the system, and the circle to the input.

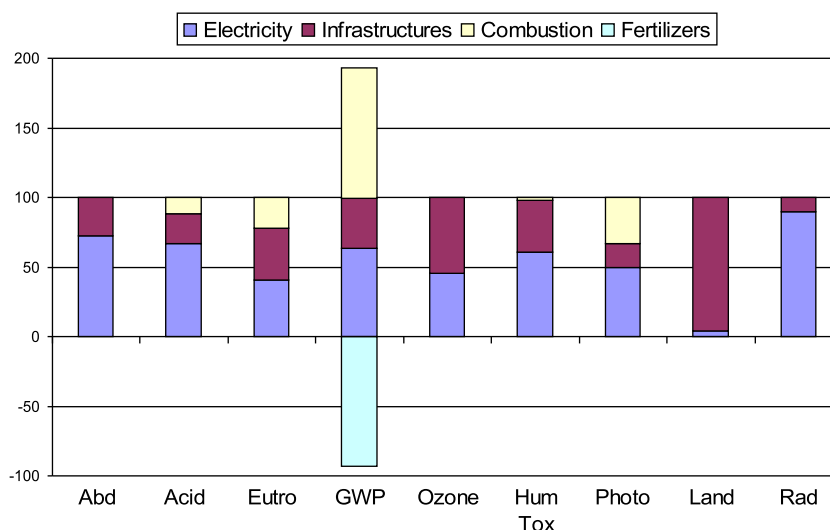


Fig. 3. Processes contribution of the production of 1 MJ by algal methane combustion.

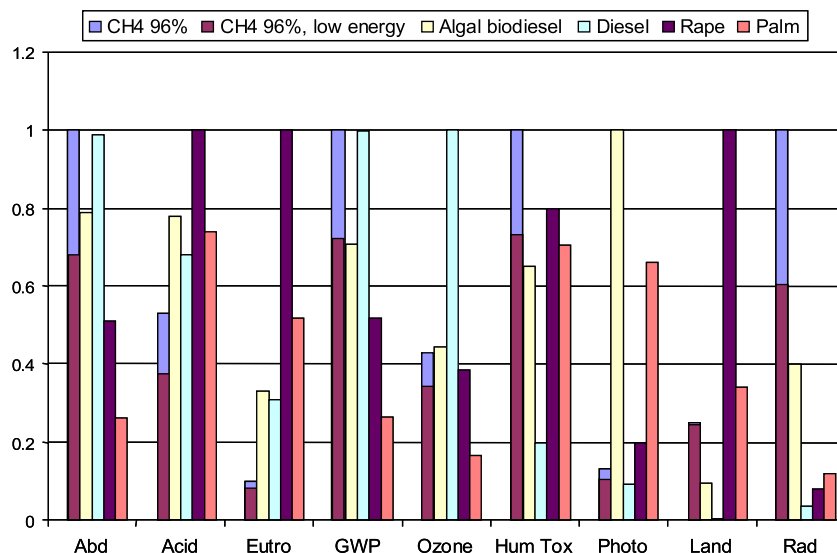
(72.7%), and acidification categories (67%). The impacts related to the building and the recycling of infrastructures are mainly due to the building of ponds as well as the use and transport of concrete. However the high contribution of infrastructure on human toxicity impact category is due to the use of glass fibre plastics to build the paddlewheel. Combustion of biogas and methane contributes marginally to eutrophication (22.8%) and acidification (11.5%) impact categories, and mainly to the photochemical oxidation (32.9%) and the global warming potential (94.3%). The high contribution towards global warming potential by burning biogas and methane is counterbalanced by CO<sub>2</sub> uptake for algal growth at the pond level, which is represented in Fig. 3 as the negative impact in the fertilizers category.

### 3.3. Comparison with algal biodiesel

Fig. 4 compares impacts generated by the production of 1 MJ by burning algal-based methane, algal-based biodiesel (Lardon et al., 2009) and diesel (Frischknecht et al., 2007). The chosen sce-

nario from the ones analysed in Lardon et al. (2009) is a culture with a low nitrogen fertilizer input and a wet extraction of the oil. Each impact is standardised with the value of the worst scenario for this impact. It must be mentioned that the comparison with algal biofuel is not done on exactly the same bases. Actually, the substitution method has been chosen in this study, whereas the impacts of the algal biodiesel are based on the allocation method. Regarding the comparison between algal-based methane and diesel productions, there is no coproduct generated during the production phase, so neither substitution nor allocation is needed.

Results reveal that algal methane is the worst case for abiotic depletion, ionising radiation, human toxicity and global warming potential impacts, mainly because of the strong demand in electricity. For the land use category as well, diesel and algal biodiesel reveal less impacts than algal methane. First of all, the area needed for the construction of the ponds is much higher than the one required for an oil rig. Furthermore, this can be explained by the fact that for biodiesel production, a considerable part of the impacts



**Fig. 4.** Comparison of impacts generated by the combustion of 1 MJ of algal methane and others fuels. The impacts of algal-based methane (CH<sub>4</sub> 96%) and algal-based methane with low energy consumptions (CH<sub>4</sub> 96%, low energy) are surimposed.

has been allocated to oilcakes. Actually the impacts are based on an energy allocation, which implicitly assumes that the total energy content of by-products can be extracted. On the other hand, in the anaerobic digestion scenario, the real extractability of energy is used and the remaining theoretical energy content of by-products (i.e. the soil conditioner) is not added to the balance. It results that the production of 1 MJ of methane-based biofuel requires apparently a higher land surface than the one of 1 MJ of algal oil. In the low nitrogen fertilizer input and wet extraction scenario chosen, 46% of the impacts are attributed to the oil. For instance in terms of land use, only 46% of the impacts generated by the pond construction are counted, while in this present study the total amount of impacts are taken into account (the substitution of fertilizers by solid digestates does not affect the land use). At the energy consumption level, producing algal methane instead of algal biodiesel should avoid high energy demands identified at the dewatering and oil extraction steps. Nevertheless, the high energy demands of paddlewheels as well as pumps make algal methane less competitive compared to algal biodiesel. This is due to how by-products are taken into account. Actually, in the biodiesel scenario, a high proportion of the impacts generated by the electric consumptions has been allocated to oilcakes. In fact both systems (algal methane and algal biodiesel) have very similar energy demands for the paddlewheels and the pumps.

Regarding photochemical oxidation, algal methane and diesel are much lower (respectively 13.3% and 9.3%) than the algal biodiesel, seeing that there is no oil extraction and consequently no use of hexane. Both biofuels coming from algae are preferable to diesel in terms of ozone layer depletion (42.9% for algal methane and 34.3% for algal biodiesel). Finally algal methane is a much better option in terms of acidification and eutrophication (52.9% and 9.9%), principally because the liquid digestates are recirculated into the algal ponds and the substitution scenario is chosen.

#### 3.4. Improvement of the energy consumption and comparison with others biodiesel

As shown in Table 2 and Fig. 3, most of the impacts of the algal-based methane is directly related to the electric consumption. Hence it is clear that any reduction of the electricity consumption will result in a major reduction of the total environmental impact.

In Clarens et al. (2010), authors considered that the energy consumption of the paddlewheel is 0.035 kWh kg Algae<sup>-1</sup>, which is almost six times less than in our study (0.2 kWh kg Algae<sup>-1</sup>). Furthermore, the electric consumption of the pumping of water is evaluated at 0.029 kWh kg Algae<sup>-1</sup> instead of 0.153 kWh kg Algae<sup>-1</sup>. These changes reduce the total energy demand by 44%. The Fig. 4 also includes this alternative in comparison with the algal biodiesel and diesel. This confirms the high sensibility of the impact assessment toward these sole parameters and advocates for further studies to establish reasonable and consensual values.

The first observation is that the algal methane produced under low energy consumption described above is a better option regarding impact categories related to abiotic depletion, acidification, eutrophication, ozone layer depletion and photochemical oxidation compared to algal biodiesel. Moreover the impact on global warming is reduced by using this low energy consumption unit, and is therefore similar to the impact level of algal biodiesel. Even if impacts decrease strongly for human toxicity and ionising radiation categories, it still remains the worst scenario for these two categories as well as for the land use category.

By comparing this second scenario of methane production with rape biodiesel and palm biodiesel (Fig. 4), it appears to be the better option in terms of land use (24.5% of the impacts of the rape biodiesel), photochemical oxidation, eutrophication and acidification. Results are in the same order of magnitude for the ozone layer depletion and the human toxicity categories. Finally, it remains the worst option for abiotic depletion, global warming and ionising radiation.

#### 3.5. Improvement of the environmental performance

It must be underlined that this is a prospective LCA of a non existing process. Consequently the production systems described in this study should not be considered as fixed, and can be subjected to important modifications. Indeed technologies used for growing and harvesting algae are rather immature, and can be liable to improvement in the future. Therefore the aim of this study is to identify the main bottlenecks of a methane production process from algae, and to compare them with the advantages and the drawbacks of mature (first generation biodiesel and diesel) and immature technologies (algal biodiesel).

Even when the consumptions related to algae production (energy demands of paddlewheels and pumps) are drastically re-

duced, the energy requirements of the whole combined process are still high, mainly because of the functioning of the anaerobic digestion plant. As it is shown in Fig. 3, the main part of the impacts is strongly correlated to energy consumptions. Yet the energy demand of the digestion plant is directly linked to the hydraulic retention time (HRT), which will determine the total heat and electricity required for the heating and mixing of the digesters. Several complementary options could be suggested to decrease this HRT with similar or better methane yields.

A higher concentration of microalgae in the input flow would increase the OLR (or symmetrically reduce the HRT if applying a constant OLR) and hence increase the plant productivity (i.e. daily methane production), but would also increase the electric demand at the centrifugation step. An optimization between the concentration of microalgae brought to the digesters and the HRT could be performed and lead to a significant improvement of methane yield.

At this stage, it is worth pointing out that the anaerobic digestion plant designed in this paper is based on state-of-the-art engineering, which is most probably conservative. It is known that, when an advanced control system is associated to the plant, retention times can be decreased down to values in the order of the day for soluble COD (Steyer et al., 2006). With a particulate COD like microalgae, HRT could decrease from several weeks to several days, and so it can lead to both decrease in the electric consumption and increase in overall productivity since a large fraction of the methane which was previously used for the digester heating becomes available.

The choice of the algae could also lead to a significant improvement of the results of the LCA. According to Sialve et al. (2009), the methane yield of *Dunaliella salina* is between 440 and 450 mLCH<sub>4</sub> g<sup>-1</sup> VSS, which corresponds to an increase from 50% to 54% compared to *Chlorella vulgaris*. Furthermore, the HRT is equal to 28 days, that is 18 days less than in our assumptions. These combined effects of an increase of the yield and a decrease of the HRT (i.e. a decrease of the electric consumptions) would induce a strong enhancement of the anaerobic digestion step, and of the LCA results. However, anaerobic digestion of marine algae induces high sodium concentration in the digesters which could possibly have an inhibiting effect on the methane production. This sodium inhibiting effect could be avoided by the use of an adapted marine inoculum (Omil et al., 1995). Additionally a study of Chen et al. (2008) underlines the fact that the sodium is less inhibitory in mesophilic conditions than in thermophilic conditions, which limit the energetic consumptions of this step.

Pretreatments, such as thermic or sonic treatments, are commonly used to increase the reaction speed and the total biodegradability of particulate matter, especially for sewage sludge. However even if they succeed in increasing the methane production, the energy balance can sometimes be jeopardized by too intensive thermal treatments or the chemical additives (most of the time, a strong acid or base) may have a significant environmental impact. Chen and Oswald (1998) investigated different pretreatments (like temperature, substrate concentration and hydroxide sodium addition) and it appears that the temperature has the most important effect. A heating at 100 °C during 8 h generates an increase of the methane production by 33%.

A strategy to increase the performance of a digester is to associate various digestates in order to fit an optimal composition of the influent (Mata-Alvarez et al., 2000). Codigestion with a substrate presenting a high carbon fraction, allows one to increase the global C/N and hence to reach a more favorable range for anaerobic digestion. Yen and Brune (2007) reported a significant enhancement of the methane production with an addition of waste paper to algal sludge feedstock. However the supplementary substrate to treat requires larger reactors and implies to secure the

availability of the co-substrate. Moreover it will probably create new environmental burdens associated to its shipping.

Another option would be to control the C/N ratio of the algae, by controlled nitrogen addition in order to maintain it at a low level which guarantees an improved efficiency of the anaerobic stage and despite a lower retention time (Sialve et al., 2009).

In addition to the energy consumptions, an important part of the impacts is due to the infrastructures, and more precisely to the ponds. The use of concrete for the building of ponds generates on one hand high emissions of CO<sub>2</sub> at the cement works level, and on the other hand an important consumption of fuel for the transport of the blocks. The classical pond architecture could be revisited with an eco-design perspective to reduce its environmental footprint.

Finally as the electricity production is the main environmental burden of the process chain, the algae production facility could also host alternate electricity producers like solar panels or wind turbines. In situ consumption of electricity should reduce the environmental impact and improve the energy ratio of the whole system. For instance in the described system, it should be interesting to replace the digesters heating process, resulting from several conversion steps (solar energy to microalgae by photosynthesis, microalgae to biogas by anaerobic digestion and biogas to heat by combustion) by a more efficient path (solar energy to electricity by solar panel and electricity to heat by electric heating system) without energy storage.

#### 4. Conclusion

The principal aim of this study is to realise the life-cycle assessment of the production of methane from algae. It highlights the main bottlenecks in this production, and compares them with the advantages and the drawbacks of mature and other immature technologies (algal biodiesel). Here we focus on a simplified process where methane was the only recovered product, but the optimum from both environmental and economical points of may consist in a process combining lipid recovery for a fraction of the biomass and methane production from both raw biomass and remaining biomass after lipid extraction.

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