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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_2 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.

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_2 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 "craddle 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 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 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

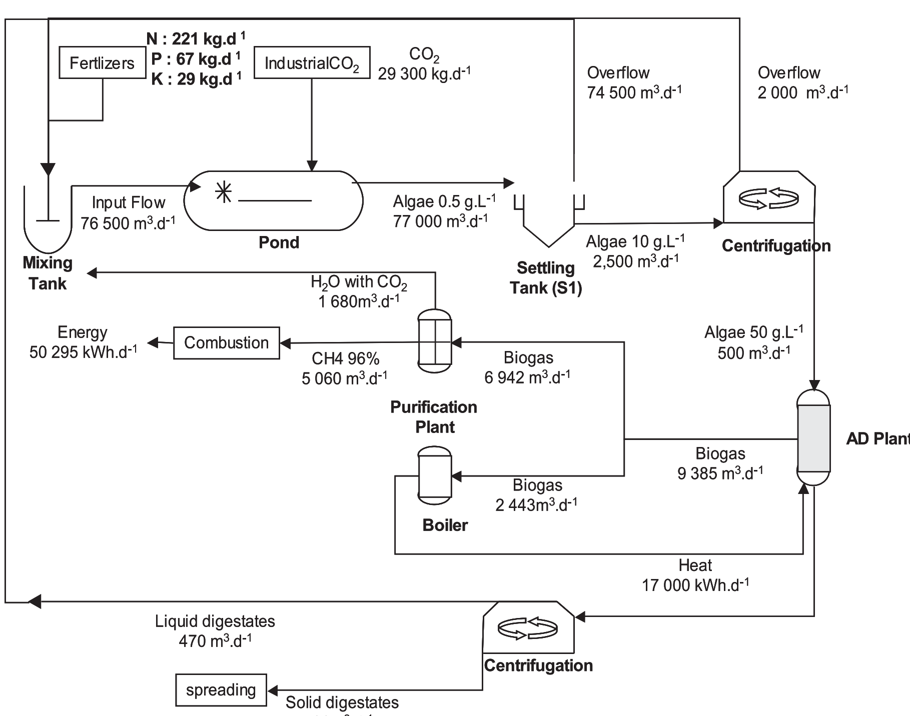

Fig. 1. Overview of the system coupling microalgae production with anaerobic digestion. Values are indicated for a cultivated area of 100 ha in raceways.