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Environmental assessment of bioenergy production from microalgae based systems

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ABSTRACT

Microalgae have been studied as a potential alternative raw material and various technologies have been proposed to transform the algal biomass into energy products. In this study, two bioenergy production systems of very different complexities were modelled to assess their environmental efficiencies: a biodiesel system and a biogas system. Biodiesel system used supercritical extraction and transesterification as key processes; to the best of authors' knowledge, there is no previous work analysing the environmental performances of such production system. Cumulative energy demand, Life Cycle Assessment (LCA) and dynamic LCA for climate change were used to evaluate the environmental footprint of the production systems. Conventional systems for electricity, heat and diesel production were considered for comparison. Energy balance showed that the supercritical extraction and drying steps were the most energy consuming unit operations in biodiesel production and further developments of technologies might be envisaged. LCA showed that climate change was the main contributor to impacts on human health and ecosystem quality due to energy consumed in production steps. Also, heat from biogas was the only product that proved to have a satisfactory environmental performance with regard to other conventional production systems. Finally, dynamic climate change evaluation (used for the first time for bio-chemical processes) revealed no carbon sequestration in microalgae system.

1. Introduction

Energy production is the main contributor to climate change, accounting for 47% of global greenhouse gas (GHG) emissions in 2010. In addition, the transportation sector is responsible for approximately 14% of the global warming effect as almost all the energy consumed (approximately 95%) in transport systems comes from fossil fuels (IPCC, 2013). To reduce the impact of the use of fossil energy, bioenergy policies have been implemented in Europe. The Renewable Energy Directive (RED) establishes national energy targets for countries in the European Union (EU). In France, a target of 23% of renewable energies in the total energy consumption is envisaged for 2020. Renewable energy production in France in 2013 represented only 14.3% of the total energetic production (Eurostat, 2015) which still shows that important efforts have to be deployed to match the target for 2020. Additionally, the estimated bioenergy consumption in France in 2015 was 1.35×10^5 TJ in biofuels and 6.3×10^5 TJ for heating and cooling. By 2020, an increase of 26.3% is expected for biofuels and 31.1% for heating and cooling (RED, 2009). The feedstock for first and second generation biofuels comes mostly from edible crops. This scenario has raised important questions concerning the competition between food and biofuel production for arable land and also the fact that fuels from crops can lead to a

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Abbreviations: Greenhouse Gases, GHG; Renewable Energy Directive, RED; Intergovernmental Panel on Climate Change, IPCC; Biodiesel scenario, BD; Biogas scenario, BG; Diesel scenario, D; Natural gas scenario, NG; French Market scenario, FM; Energy Balance, EB; Cumulative Energy Demand, CED; Life Cycle Assessment, LCA; Life Cycle Inventory, LCI; Life Cycle Impact Assessment, LCIA; Ecosystem Quality, EQ; Human Health, HH; Resources, R; Dynamic Life Cycle Assessment, DLCA; Global Temperature Change Potential, GTP.

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higher global warming effect than the use of fossil fuel (Collet et al., 2011). In this context, microalgae have been pointed out as an interesting source of energy that does not enter into significant competition with food. Fuels derived from microalgae, which present advantages such as a very rapid growth compared to other oil crops, high photosynthetic yields and high ability to cumulate lipids, are being considered as third generation fuels (Chisti, 2007). The photosynthetic yield for microalgae is about 3–8% of solar energy transformed to biomass whereas, for terrestrial plants, it is about 0.5% (Huntley and Redalje, 2007; Li et al., 2008). Moreover, some studies (Francisco et al., 2010; Pokoo-Aikins et al., 2010) have also claimed that bioenergy production from microalgae results in carbon sequestration (defined as the capture and long-term storage of atmospheric carbon dioxide).

A variety of technologies for biodiesel production have been investigated and others are under study. The key steps of biodiesel production from microalgae are the cultivation of the microorganisms, lipid extraction and transesterification. Conventional lipid extraction usually involves hexane, which is flammable and toxic and is believed to have adverse health and environmental effects (Cheng et al., 2011). Conventional transesterification includes the use of catalysts, which has at least two drawbacks: it is a relatively time consuming process and the product has to be purified to remove catalyst and saponified compounds (Saka and Kusdiana, 2001). Environmental assessments of biodiesel manufacture from microalgae using such processes are available in the literature (Lardon et al., 2009; Sander and Murthy, 2010). Supercritical fluid processes, such as extraction (Cheng et al., 2011; Mendes et al., 1995; Nikitine et al., 2009) and transesterification (Saka and Kusdiana, 2001; Bunyakiat et al., 2006; Demirbas, 2005), have been studied as possible alternatives to the conventional methods as they avoid the drawbacks mentioned above.

Furthermore, microalgae can also be an interesting source of biogas. This process, relatively simple compared to biodiesel production, does not require concentration and oil extraction steps and could thus avoid significant energy consumption (Collet et al., 2011). Studies for the production of biogas from microalgae were performed (Ehimen et al., 2011; Jegede, 2012; Mussgnug et al., 2010; Ras et al., 2011) in order to analyze their feasibility and technical parameters. However, few energetic and environmental studies, such those of Collet et al. (2011), were performed for these systems.

In this context, the present study aims to evaluate the environmental efficiency of two systems for obtaining bioenergy from microalgae, using different and complementary environmental assessment tools and methods. The bioenergy systems chosen were of very different technological complexities: 1) biodiesel (BD) using supercritical extraction/transesterification (an effective but complex, high steps number process) and 2) biogas (BG) for cogeneration (a simple, low steps number process).

The following assessment methods were applied: i) Energy balance analysis of the production process at the process level (EB) and over the process life cycle using a Cumulated Energy Demand (CED) indicator, ii) Life Cycle Assessment (LCA) to evaluate the environmental impacts of the bioenergy over its life cycle (i.e. direct and indirect impacts generated by the bioenergy production and utilization, involving all natural resources consumed and all harmful substances emitted), and iii) Dynamic Life Cycle Assessment (DLCA) to demonstrate the possible existence of carbon sequestration by microalgae-to-fuel systems.

2. Methods

Hereafter the global studied systems are described and the assessment methods used are briefly presented. Then a detailed description of the processes, parameters and data used for mass and energy balance is given along with the calculation hypotheses.

2.1. Bioenergy production systems

The bioenergy production systems investigated in this study were: i) the biodiesel process (BD), in which electricity and heat are also produced, and ii) the biogas process (BG), in which heat and electricity are produced (Fig. 1).

The microalgae culture and harvesting steps were considered to be similar for both systems (Fig. 2). In BD, the harvested biomass is dried and sent to the lipid extraction step, which uses supercritical carbon dioxide as the solvent. The extracted oil is used in supercritical transesterification with methanol as a reactant and, finally, the biodiesel obtained is purified by distillation. The biomass remaining after extraction is sent to anaerobic digestion, in which biogas is produced and transformed into electricity and heat by cogeneration. In BG, the algal biomass is directly used in an anaerobic digester for biogas production and subsequently for electricity and heat production by cogeneration. Details of the processes are presented below.

To the best of authors' knowledge, there are no full scale plants for biodiesel production from microalgae. However, environmental assessment of potential but not yet existent real-scale production paths is a necessary step in order to guide future developments, as mentioned by Collet et al. (2015).

In order to apply the aforementioned assessment methods, a mass and energy balance was calculated on the basis of unit process modelling and available literature data. Unit processes were dimensioned following the chemical engineering principles and process flowsheet was established enabling modelling of mass and energy balance. This scale-up approach ensures coherence of data for all unit processes, at the production real-scale (despite the inexistence of such production unit). This is also one of the originality of the present work when compared with other LCA studies on microalgae-energy production (Collet et al., 2011; Lardon et al., 2009; Sander and Murthy, 2010; Campbell et al., 2011). Most of them only used data collected from different studies, or directly extrapolated from lab-scale experiments, or extrapolated from other systems (other vegetal oil extraction and esterification, organic waste treatments, etc.).

2.2. Energy balance and analysis

As pointed out above, the energy balances of BG and BD were calculated on an industrial scale, and the Energy Return On Investment (EROI) (equation (1)) indicator was used to evaluate the performance of each energy production system.

$$\mathbf{EROI = Energy\ produced/Energy\ invested} \qquad (1)$$

The Cumulated Energy Demand (CED) indicator (Jungbluth et al., 2007) was calculated using the Life Cycle Inventory (see 2.3) in order to show the contribution of natural energy resources to global energy consumption over the whole life cycle of the process.

2.3. Life cycle assessment

The Life Cycle Assessment (LCA) method is defined by ISO 14040 as the “compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle” (ISO 14040, 2006a). LCA is applied following four steps (ISO 14040, 2006a, 2006b): the definition of goal & scope, the building of a Life Cycle Inventory (LCI), the Life Cycle Impact