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Environmental assessment of a biomethane production system from offshore-cultivated macroalgae

Juliette Langlois[1,2*], Arnaud Hélias[1,2], Jean-Philippe Delgenès[2] and Jean-Philippe Steyer[2]

[1] Montpellier SupAgro, 2 place Pierre Viala, F-34060 Montpellier Cedex 2, France

[2] INRA, UR050, Laboratoire de Biotechnologie de l'Environnement, Avenue des Etangs, F-11100, Narbonne, France

*juliette.langlois@supagro.inra.fr

Abstract Biofuels from algal biomass seem to be a promising source of bioenergy for the future. Life Cycle Assessment (LCA) is an efficient tool for quantifying environmental impacts of bio-based materials. To assess if macroalgae is effectively an environmentally friendly feedstock for bioenergy production, a comparative LCA is used in this study. The functional unit used is one MJ consumed in an internal combustion engine. Methane from anaerobic digestion of macroalgae is compared to natural gas as a fossil fuel reference. The study is carried out on the brown seaweed *Laminaria saccharina* cultivated in a coastal environment. The ReCiPe method is used for the impact assessment. The results highlight that one of the key improvements to focus on is electric consumption. A first stage of ecodesign by coupling offshore wind turbines and seaweed production allows enhancements. Interesting levels of impacts by comparison with the fossil fuel reference are reached: reduction of 51.0% of the greenhouse gas emissions and of 72.4% of the fossil depletion. Despite its recent attention, further improvements can be achieved in the near future to make the use of macroalgae for biofuels production competitive compared with terrestrial feedstock from an environmental point of view.

1 Introduction

Biofuels production is worldwide increasing [1]. However, many uncertainties remain about environmental impacts of such bio-based fuels, especially on land use and food crop production competition, but also on pollution transfers. The production of some of them leads to a decrease of the environmental quality, replacing fossil depletion and greenhouse gas emissions by eutrophication [2,3] resource depletion, ecotoxicity, biodiversity loss [2], acidification, ozone depletion and human toxicity [3]. To avoid those impacts and to override technical barriers and cost effectiveness of the second generation biofuels, the use of an algal feedstock for energetic applications appears to be promising [4,5,6]. Microalgae have been particularly studied [7,8] but less attention has been given to macroalgae (seaweeds). However there are assumed to possibly become a new feedstock for bioenergy in the future [4,9,5]. As a macro-organism cultivated in a natural environment, they need neither sophisticated cultivation systems (raceways or photobioreactors) nor harvesting systems (centrifugation or flocculants). Moreover, offshore growth can reduce eutrophication in eutrophic zones [9].

Life Cycle Assessment (LCA) is an efficient tool for quantifying environmental impacts of bio-based materials. Two previous LCA have been carried out on bioenergy from macroalgae [10,11]. The present study focuses on the production of biogas from macroalgae using a dedicated offshore cultivation system, which, to our knowledge has not been performed yet. Anaerobic digestion is a widely used technology for sludge from wastewater treatment and/or biomass treatment. It has been well known for decades, including algae [12,13]. In the present study we focus on the anaerobic processing of applied to the brown seaweed *Laminaria* (kelps), the most important genus of seaweed harvested in the world [14]. More especially, we focus on *Laminaria saccharina*, which naturally grows along the French coast. They are cultivated on long-lines in a coastal environment, after a plantlets production in a nursery. They are then transformed into biogas in an anaerobic digestion plant.

The goal of this study is to assess if biomethane from offshore cultivated macroalgae is more environmentally friendly than natural gas. A theoretical scenario, using basic actual knowledge and technics of production is analyzed by contribution analysis using the ReCiPe midpoint method (hierarchist version). Then several improvement pathways are assessed, changing the nature of the electricity used to heat the digesters and to feed facilities in the nursery, the anaerobic digestion plant and the gas station. A comparative LCA is performed, between biomethane produced by anaerobic digestion of fresh *Laminaria saccharina* and natural gas from EcoInvent database [15] as a fossil fuel reference.

2 Definition and inventory of the system

2.1 Goal and scope definition

To allow a comparison between biomethane from macroalgae and natural gas for fuel, the functional unit is to consume 1MJ of fuel in an internal combustion engine. The Recipe method is used with EcoInvent v2.2 database and SimaPro 7.3 software to carry out the impact assessment. According to the principles of exhaustiveness in LCA [16], the inventory includes all steps of cultivation and harvesting of the biomass, its transformation to biomethane provided at a gas station and its combustion. Facilities construction and dismantling, and extraction and transportation of resources are taken into account. Fig. 1 shows an overview of the whole system, from the seaweed cultivation to the use of biomethane.

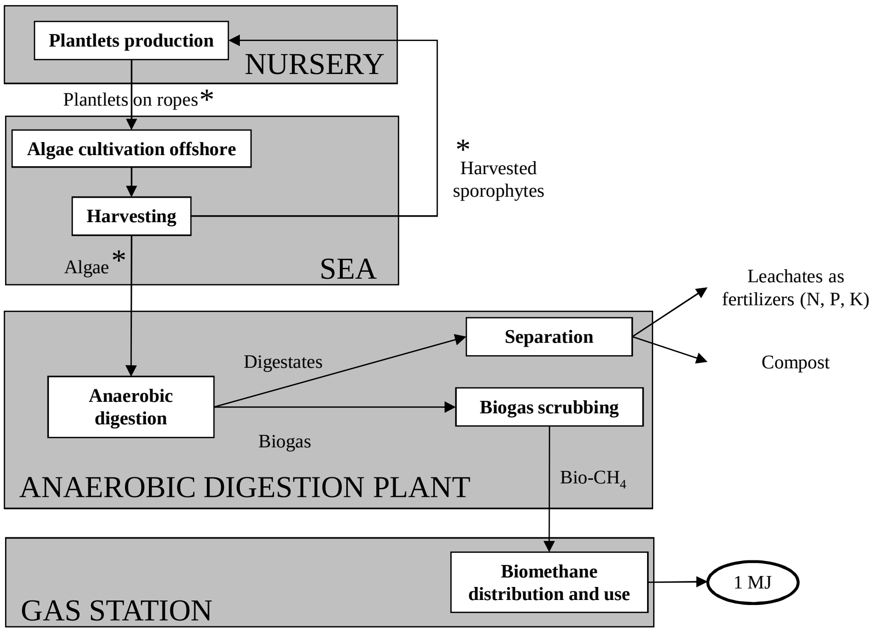

Fig. 1 : Overview of the production system of biomethane from macroalgae cultivated in open ocean (* stands for boat transportation)

The substitution method has been used to take into account anaerobic digestion by-products (phosphate, ammonium and potassium dissolved in the leachates, and compost produced from the solid part of the digestates), used as fertilizers. This is done in accordance with the ISO guidelines, which suggest preferring substitution instead of allocation when it is possible [16].

The analysed process chain refers to a hypothetical system based on extrapolation from semi-industrial production systems for biomass production (Aleor, producer of seaweed). The anaerobic digestion has been scaled up (Naskeo Environment, anaerobic digestion plant designer) on the basis of laboratory experiments (INRA-LBE). Standard rules are considered for materials transportation [17] and substructures replacement (30 years lifespan for the plants and replacement of electrical facilities every 10 years). After building, dismantling and facilities replacement, concrete, mineral wool, polypropylene, polyethylene, polyethylene terephthalate, polyvinylchloride, bricks, cement fibre, steel and iron are recycled. The rest of the materials are landfilled. Electricity comes from the European production mix.

2.2 Process inventory of the reference scenario

2.2.1 Plantlets production onshore

Laminaria saccharina cannot be grown by vegetative propagation. An alternation of generations needs to be done through a reproductive cycle in a nursery [18]. Two main steps occur: spores collection from wild harvested sporophytes and plantlets cultivation in ponds from the collected spores. All data about the nursery come from an algae producer, in accordance with technics described in the literature [19]. Only two cycles of production of *Laminaria saccharina* per year have been taken into account. No drying and consequently no storage are considered. Thus, an annual usage rate for facilities use has been defined: 50% for the nursery and the digestion plant, and 75% for the offshore facilities.

The production of spores lasts for one day, and it requires only a few inputs to be carried out: after the cut of fertile zones on the sporophytes and three washings, fertile pieces of algae are subjected to a hydric stress. Then a solution is recovered from the stressed pieces and can be used to inseminate the cultivation ponds.

The production of plantlets lasts for one month and many inputs are required. For the growth (in concrete ponds), mineral fertilizers, fluorescent lamps, spargers for bubbling, booster and circulation pumps are required. Control of water temperature is not considered. The nursery is a closed building (agricultural shed) to allow control of the photoperiod (18 hours.day^{-1} on average). Pumped seawater is filtered and then treated under ultraviolet lamps before being used for the plantlets cultivation in ponds. Spores production is particularly sensitive to bacterial contamination, so the cleaned up seawater is also treated in an autoclave before its use to induce sporulation.

2.2.2 Open ocean cultivation and harvesting

Macroalgae are cultivated by tying them to anchored floating lines on a coastal environment. One longline raft unit is described on the Fig. 2. It consist in 150 m long culture ropes, tied to 10 m long structural ropes. They are anchored to the bottom by chain cables and concrete blocks at each corner and every 50 m in the length. The culture and structural ropes are kept 2 m below the surface. Ropes are made in polyamide, chain cables in galvanised steel, buoys in polypropylene and blocks in fibrous concrete. Macroalgae are wound on small polyamide ropes, with a ratio of 1.25 m per meter of culture rope.

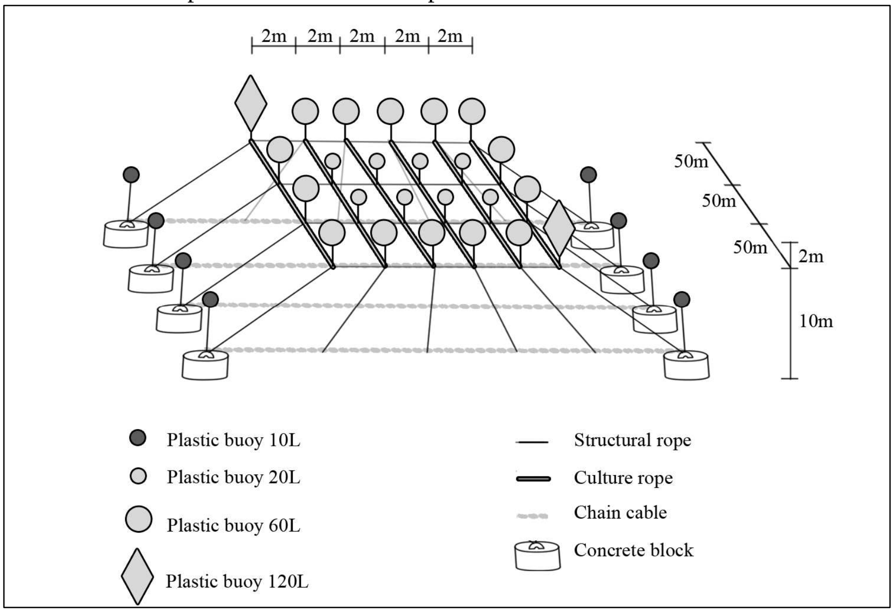

Fig. 2 : Schematic representation of the longline raft

During their growth, the seaweeds capture carbon dioxide, light, and nutrients through photosynthesis, like any other plant. For *Laminaria saccharina*, the uptake reaches 21 g $N.kg^{-1}$ dry weight (dw) and 4.5 g $P.kg^{-1}$ dw [experimental data]. In a context of concern for coastal ecosystems because of eutrophication [20] this uptake consists in a positive impact on the environment [9]. It can be considered as a way to remediate anthropogenic nutrients in excess. The net balance for CO_2 is null, as it is not stored but released in the atmosphere when the algal biomethane is burnt. Only losses of biomethane in the anaerobic digestion plant and in the gas station are taken into account. The productivity of wet biomass on longlines after 4 months in sea is 8.95 $kg.m^{-1}$ [21]. Biomass is harvested by a boat consuming 8.3 $x10^{-2}$ kg $diesel.km^{-1}.t^{-1}$ of fresh biomass harvested. The distance between the coast and the cultivated area is 10 km.

2.2.3 Biomethane and fertilizers production by anaerobic digestion

A description of the anaerobic digestion plant has been performed according to expert knowledge. Anaerobic digestion and biogas purification have been sized up based on state-of-the-art engineering for urban sludge treatment applications. Seven completely stirred tank reactors of 8.17×10^3 m^3 utile volume has been designed, with replications to reach a production capacity of 2MW in total. Home consumption of 26.7% of the produced biogas allows heating the anaerobic digesters to a mesophilic range of temperature.

We consider that all the ammonium, phosphate and potassium oxide contained in the liquid phase of the digestates have the fertilizing value of the equivalent mineral fertilizer: ammonium sulphate for Nitrogen, single superphosphate for Phosphorus, and potassium chloride for Potassium. The compost production has been considered equivalent to terrestrial composting, avoiding collecting waste biomass by private individuals. The hypotheses used to size up the plant and the results of this modelling are written in Table 1.

Table 1 : Performances for anaerobic digestion (measured from BioMethane Potential (BMP) on *Laminaria saccharina* harvested in spring) and sizing of the biomethane production plant

	Parameter	Unit	Value
Anaerobic digestion performances [exp. data INRA]	Methane yield	$Nm^3CH_4.t^{-1}$ DM	147.8
Fertilizing potential (substitution)	Nitrogen	g $N.kg^{-1}$ DM	16.3
	Phosphorus	g $P_2O_5.kg^{-1}$ DM	8.0
	Potassium	g $K_2O.kg^{-1}$ DM	116.2
	Compost	$kg.kg^{-1}$ DM	0.3
Digesters characteristics (industrial design)	Biomass inflow	t $DM.day^{-1}$	128
	Retention time	day	43
	Loading rate	kg $DM.m^{-3}.day^{-1}$	2.3
	Electricity consumption (without heat)	$kWh.day^{-1}$	4.3×10^3
	Raw biomethane yield	m^3 $CH_4.day^{-1}$	1.86×10^4
	Biogas home consumption	%	26.7

DM = Dry Matter

3 Results and discussion

3.1 Contribution analysis in the reference scenario

The results of LCA applied to the scenario of reference for the production of 1MJ of biomethane from macroalgae burnt within an engine are shown on Fig.3.

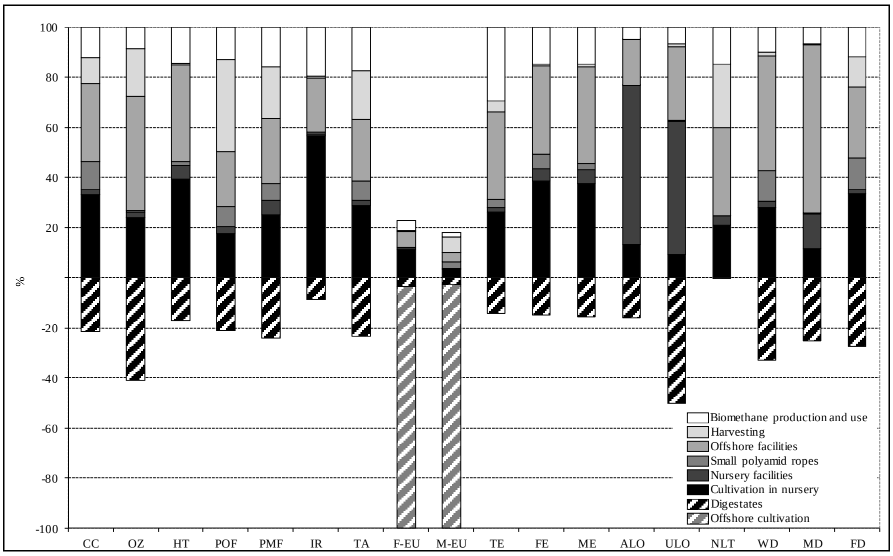

Fig. 3 : Environmental impacts of the production of biomethane by macroalgae (CC=Climate Change, OZ=Ozone Depletion, HT=Human Toxicity, POF=Photochemical Oxidant Formation, PMF=Particulate Matter Formation, IR=Ionising radiation, TA=Terrestrial Acidification, F-EU=Freshwater Eutrophication, M-EU=Marine Eutrophication, TE=Terrestrial Ecotoxicity, FE=Freshwater Ecotoxicity, ME=Marine Ecotoxicity, ALO=Agricultural Land Occupation, ULO=Urban Land Occupation, NLT=Natural Land Transformation, WD=Water Depletion, MD=Metal Depletion, FD=Fossil Depletion)

Results highlight the importance of the macroalgae cultivation technics to ensure the environmental performances of the production system (from 70.3% to 98.1% of the impacts for every impact categories considered). Nevertheless, algae feedstock is used both for fuel production and to heat the digesters. This heating corresponds to 26.7% of the algae production. Thus it is important to note that the same proportion of the pollution due to cultivation is in reality indirectly due to the anaerobic digestion.

Within the cultivation environmental impacts, the analysis highlights the importance of the facilities and substructure, especially offshore facilities. It is mostly due to the steel used for the chain cable and secondly to the concrete blocks anchoring the cultivation system. Even if steel is recycled, its manufacturing is very costly for the environment.

Then the nursery substructure takes an important part of the impacts, especially on land use. This impact should be considered less important than the others because land occupation is still very limited in this system by comparison with terrestrial biofuels.

After facilities and substructure, the operations occurring in the nursery play an important role, mostly because of electricity consumption. The main facilities accounting for this are the fluorescent lamps used to grow the plantlets. The polyamide small ropes wound around the big ropes play a secondary role but their impacts are still significant; they are mainly due to their non-recyclability.

Because seaweed uptake nutrients during their growth, strong positive impacts on the environment are accounted for marine and freshwater eutrophication. A methodological limitation in this analysis is that phosphate catchment is taken into account only in freshwaters within the ReCiPe method. Thus the positive impacts of the phosphate removed offshore are accounted in the “freshwater eutrophication” impact category instead of the “marine eutrophication”. The substitution method used to account anaerobic digestion by-products (phosphate, nitrate and potassium dissolved in the leachates, and compost produced from the solid part of the digestates) also allow to gain positive impacts by avoiding the production of mineral fertilizer and of terrestrial compost.

3.2 Importance of coupling offshore wind farms and macroalgae production

Digesters are usually heated with locally produced biogas. In our case home consumption reaches 26.7% of the total biogas produced. Because losses occur at each step of energy conversions (through photosynthesis, anaerobic digestion, production and transfer of heat) the use of biogas to heat the digester is not the most efficient option. Moreover the main goal of this production system is to produce biogas using a feedstock which is not a waste. Thus the replacement of biogas home consumption by heat from an electrical boiler, supplied by offshore wind farms electricity has been done. Moreover due to the weight of the electric consumption we replaced the European electrical mix by an offshore wind farm to feed the nursery, the anaerobic digesters and the biomethane distribution facilities. For an integrative use of the cultivated area, it is biologically and technically feasible to couple seaweed and electricity from offshore wind turbines production [22]. It is both a renewable and a locally-produced source of energy, allowing significant environmental improvements. The comparison between natural gas and biomethane has been performed with biomethane produced with reference technics, and with biomethane produced by coupling mariculture and offshore wind power. Results are shown on Fig.4.

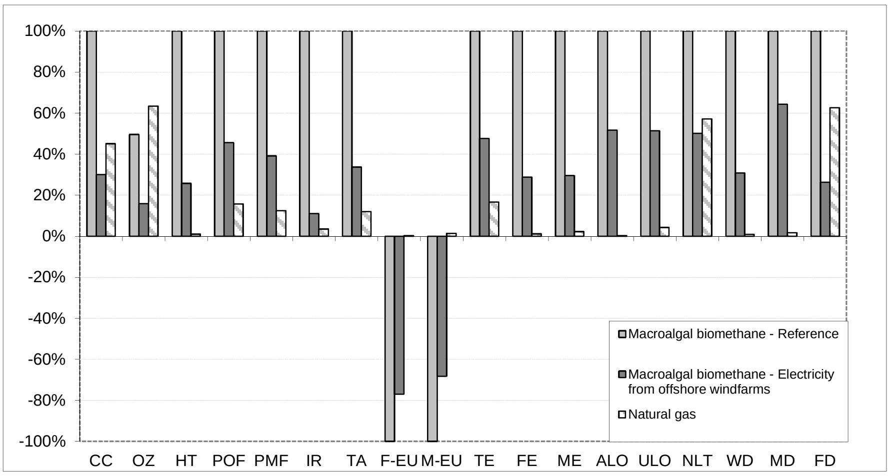

Fig. 4 : Comparison of the environmental impacts of a 1MJ-combustion of algal biomethane and natural gas (abbreviations are listed on Fig.3)

The results highlight that the scenario of reference is not efficient enough to have less environmental impacts than natural gas, except for ozone depletion, marine and freshwater eutrophication. Nevertheless when using electricity from offshore wind farms, algal biofuel allows an important enhancement of environmental performances for ozone depletion (-84.1%), fossil depletion (-72.4%), climate change (-51.0%), natural land transformation (-12.1%) compared with natural gas. Its production even allows gains on the environment for freshwater and marine eutrophication. Nevertheless impacts still remain stronger for metal depletion, land occupation, marine and freshwater ecotoxicity, photochemical oxidant and particulate matter formation, terrestrial acidification and ecotoxicity, water depletion and ionising radiation compared with natural gas.

3.3 Efficiency of the anaerobic digestion process and seasonality management

For the industrial scaling, we considered that it was possible to use the digesters only half of the year. Nevertheless it needs time before becoming stable and efficient right after its setting up. Except if the digestion of terrestrial feedstock is possible for the rest of the year, this could be a hard point to manage in industrial conditions, and seasonality handling could be more important for the anaerobic digester management than a simple question of wear-out of the facilities. This is the next challenge for the ecodesign of the macroalgal bioenergy production chains. Furthermore, macroalgal composition is highly variable along the year, ranging from 220 to 271 $L.kg^{-1}$ volatile solid (VS) for *Laminaria saccharina* [23]. Thus seasonality management during cultivation is another point to focus on to optimize macroalgal biodegradability.

3.4 Limits of the study

No sensitivity analysis appears in this study. Nevertheless some of the parameters chosen for the assessment are strongly influencing the results, as the fuel consumption of the harvesting boat. Harvesting impacts are mainly depending on the fuel consumption of the boat which harvests the offshore biomass. This consumption varies with the distance from the cultivation site to the shore, the boat capacity, the meteorological and maritime conditions, and the biomass productivity on the ropes. Thus the values chosen to model harvest step could be discussed. Another limitation comes from the use of pilot-scale data for biomass cultivation and of literature references for the rest instead of industrial data. Thus the system described is not optimized. Electricity consumption and cultivation facilities impacts would be plenty improved in case of a large scale development of this technology.

4 Conclusion

This study shows the interest of macroalgal biomethane from an environmental point of view. With conventional technics, its impacts are still higher than those of natural gas. Nevertheless considering the possibility to couple productions of seaweed and of electricity from wind farms, this system presents high levels of efficiency, with interesting climate change and fossil depletion decreases. The remaining impacts where efforts have to be made are the offshore infrastructures, mainly because of the quantity of steel used within the cable chains and of concrete. The ability to decrease these impacts will mainly depend on the conditions of harshness on site. Because of pilot-scale data, we can consider that system parameters, and more particularly electricity, would be widely reduced at a large industrial scale.

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