Energy Balance Of Third Generation Bioethanol

Amina Allouache, Majda Aziza, Toudert Ahmed Zaid, and Mohammed Amouri

Abstract− Global greenhouse gas emissions are constantly increasing, despite the partial replacement of fossil fuels by renewable energies. The transport sector is responsible for almost 24% of direct CO_2 emissions from the combustion of fossil fuels, generating greenhouse gas emissions, highlighting the need for a greater focus of international policies to encourage the production and the use of biofuels. Bioethanol is the most consumed biofuel in the world; it is produced by fermentation from materials rich in sugar (glucose, starch, cellulose). However, the controversy around the use of first and second generation have forced the transition to the third generation based on marine and freshwater algae; the latter have the advantage of being abundant, even invasive, easy to cultivate with good energy potential. This study proposes a life cycle analysis (LCA) of bioethanol production from the macro algae Ulva Lactuca, it was carried out after the introduction of several data into the SimPro8.1 software (e.g. quantity of water, consumed electricity, used chemicals) using the Impact 2002+ methodology. The results show a positive energy balance reflecting high-energy efficiency since the system produces about 1.44 times the energy consumed.

***Keywords*− Bioethanol, 3rd Generation, Macro algae, LCA, Energy balance.**

NOMENCLATURE

LCA	Life Cycle Assessment
kwh	kilowatt hour
CDER	Centre de Développement des Energies Renouvelables

I. INTRODUCTION

After first-generation biofuels derived from food plant materials, and second-generation biofuels produced from lignocellulosic biomass, a third generation is now arousing great enthusiasm. These are biofuels from algae, also called "Algofuels". Algae represent a major reservoir of energy, they have a higher carbon fixation rate than that of terrestrial plants (17.5 t/ha/year against 5 to 10 t/ha/year for sugar cane) and their production price is lower than that of agrarian crops [2]. Algae represent a wide variety of species living by photosynthesis in diverse environments. They can be autotrophic or heterotrophic. Autotrophs exploit sunlight and fix atmospheric CO_2 that is then assimilated in the form of carbohydrates. Heterotrophs are able to use small organic molecules present in the environment, transform them and store them in the form of fat or protein. Thus algae can produce carbohydrates, lipids and proteins quickly, which can be processed to generate biofuels.

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Based on their morphology and size, algae are grouped into two categories - microalgae and macro algae -. As their name suggests, microalgae are microscopic photosynthetic organisms, many of which are single-celled. On the contrary, macro algae are composed of several cells whose structure resembles the roots, stems and leaves of higher plants. [2]

Algofuels can be made from so-called chlorophyceae algae such as *chlamydomonas*, *closterium,* or diatom algae such as *phaeodactylum, melosira* or even macroalgae such as sea lettuce. While the first efforts to produce biofuels from algae were focused on biodiesel as an end product, researchers have begun to explore the production of ethanol from algae. The large investments made in the production of ethanol and the technological innovations as a result could make the production of ethanol from the starch and cellulose of algae a viable alternative via different processes. [1]

Indeed, several major features make algae an excellent candidate for the production of bioethanol. Algae have a high conversion efficiency and are able to synthesize and accumulate large amounts of carbohydrates (14 times more than terrestrial plants); they can also tolerate and use noticeably high levels of CO_2. Therefore, they can use the CO_2 emitted during ethanol production thereby reducing greenhouse gas emissions. In addition, algae are rich in cellulose and poor in lignin or hemicellulose, the main barriers to the production of lignocellulosic ethanol. Furthermore, algal cells can be harvested in a short period compared to terrestrial plant and can therefore meet the increasing demands of ethanol production.

Algae growth is simple; it can reach high densities, and uses light, carbon dioxide, and other inorganic matter efficiently, so it can produce 6,000 gallons of ethanol a year when corn alone produces 400 gallons of ethanol per year [3]. Algae can be easily grown in different aquatic environments such as sewage, salt or municipal water, which would allow for sustainable bioethanol production, as it decreases competition with food crops, which need fresh water for irrigation. In addition, algae can provide sustainable bioremediation of wastewater through the use of polluting molecules as nutrients for their growth such as nitrogen and phosphorus. In addition to the production of bioethanol, algae provide valuable co-products such as protein-rich waste that can be used as animal feed [4].

Many macro alga especies are known to be good candidates for bioethanol production, such as brown algae: *Laminaria*, *Saccorhiza*, *Alaria*, which store laminarin, mannitol, and red algae such as *Gelidium amansii*. The latter store cellulose, glucan and galactan, green algae: *ulva lactuca* and *rigida* characterised by interesting rates in cellulose and the absolute absence or near absence of lignin, which makes enzymatic hydrolysis easier [4].

Life cycle analysis (LCA) is an environmental assessment method that quantifies the impacts of a product (whether it is a good, a service, or even a process) over its entire life cycle, from the extraction of the raw materials that make it up to its disposal at the end of its life, passing through the distribution and use phases.

LCA, a standardized and recognized tool, is the most successful method in terms of overall assessment, it results from the interpretation of the quantified data balance (quantity of water, energy consumed, etc.) linked to each stage of the production cycle (acquisition of raw materials, transport, production, consumption, recycling or disposal). This data will be used to calculate potential environmental impacts [5].

With the aim of quantifying the impacts and avoiding possible problems related to energy consumption or significant greenhouse gas emissions, the application of life cycle analysis is therefore recommended [6].

These analyzes take into account the impacts of the entire production cycle, from the acquisition of raw materials to consumption, including transport and processing and are known as “well to wheel” or “cradle to grave ”LCAs.

This study proposes a quantification of the fossil energy consumption of an algae-based bioethanol. The results obtained made it possible to calculate the energy balance and to evaluate the efficiency of the production system.

II. LIFE CYCLE ASSESSMENT METHODOLOGY

The bioethanol produced in this study is based on a local green macro alga *ulva lacuca*, which is considered as a very promising source for production of liquid biofuels in the future.

The life cycle analysis of this bioethanol was carried out after the introduction of several data into the SimPro8.1 software (quantity of water, consumed electricity, used chemicals used…) using the Impact 2002+ methodology (see Fig.1).

To perform this analysis, the following assumptions were made:

- The reference unit considered in this analysis is 1 liter of bioethanol produced.
- The data are related to the harvesting, pretreatment, saccharification, fermentation and distillation stages. They concern a trial of bioethanol production at a small scale (laboratory scale) extrapolated to a medium scale to allow a comparison with other bioethanol made from other bioenergy resources.
- The processes used to model the manufacture of bioethanol were built from a trial made in Bioenergy an Environment laboratory (CDER) where 3.52 g/L of ethanol was produced after 48 h of fermentation. This was performed using commercial cellulase for saccharification and *Saccharomyces cerevisiae* for fermentation at 30 °C and pH 5, leading to a yield of 0.41 g of ethanol/g of glucose after 96 h of enzymatic hydrolysis at pH 5 and 45 °C [7].
- Macroalgae are not cultivated, the biomass needed for ethanol production is harvested from algal bloom on Algerian costs.
- The bioethanol produced is supposed to contain 5% water, it is therefore a hydrated ethanol, and the dehydration operation is not taken into account due to a lack of data related to the energy needed for this operation.
- The energy consumption related to the transport of bioethanol to the gasoline pumps, as well as the mixture with gasoline (15% of ethanol with 85% of gasoline) are not taken into consideration.
- Distillation energy consumption was taken from literature.

The data collected were entered into the SimaPro software, they allowed us to calculate the amount of fossil energy consumed during the production of algal bioethanol.

III. RESULTS AND DISCUSSIONS

a. TREE STRUCTURE OF THE ENTIRE CYCLE PRODUCTION

After entering the data into the software, we got the tree structure depicted in Fig.2.

The obtained results are shown in Table 1. Thus, the production of 1 liter of bioethanol from algae necessitates 14.719 MJ of nonrenewable energy. Results also show that the fermentation step is the most consuming step of the entire cycle with 6,525 MJ, which corresponds to 44.3 % of total energy consumption.

Indeed, fermentation requires an important intake in electricity and water, high-energy consumption is due to the long period of fermentation (96 h), and the temperature (30°C) needed by saccharomyces cerevisiae to ensure an effective fermentation and a high yield in ethanol.

Saccharification step is responsible of 29.5 % of the total energy consumption, corresponding to 4.34 Mj , it is mainly due to the high temperature (40° C) needed to hydrolyze cellulose into glucose even if the saccharification duration (48 h) is relatively short compared to that of fermentation.

Table 1
Data used for Energy balance of algal bioethanol production

Type of input	Nomenclature	Unit	Quantity
Biomass preparation			
Biomass (Macroalgae)	[7]	Kg	25.5
Energy	Manual Harvest	kwh	0
Transportation	Biomass by car	km	14.5
Water	Tap water	L	12
	(Used water for washing and desalination) [7]		
Energy	Drying	kwh	0
	(air drying)		
Energy	Milling	Kwh	0.08 kwh
	Calculated from grinder electric consumption for 30 min		
Pretreatment			
Chemicals	Sulfuric acid [7]	ml	25
Energy	Autoclaving	Kwh	0.245
	Calculated from autoclave electric consumption 20 min at 120°C		
Saccharification			
Enzymes	Celluclast [7]	ml	55
Energy	Electricity, medium voltage (DZ) natural gas burned in gas turbine	kwh	0.350
	Calculated from shaker electric consumption at 40°C during 48h		
Fermentation			
Microorganism	Saccharomyces cerevisiae [7]	g	50
Water	Tap water [7]	L	14
Chemicals	$(NH_4)2HPO_4$ [7]	g	18.5
Energy	Electricity, medium voltage (DZ) natural gas burned in gas turbine	kwh	0.523
	Calculated from shaker electric consumption at 30° C during 96 h kwh		
Distillation			
Energy	Electricity, medium voltage (DZ) natural gas burned in gas turbine [7]	kwh	0.132

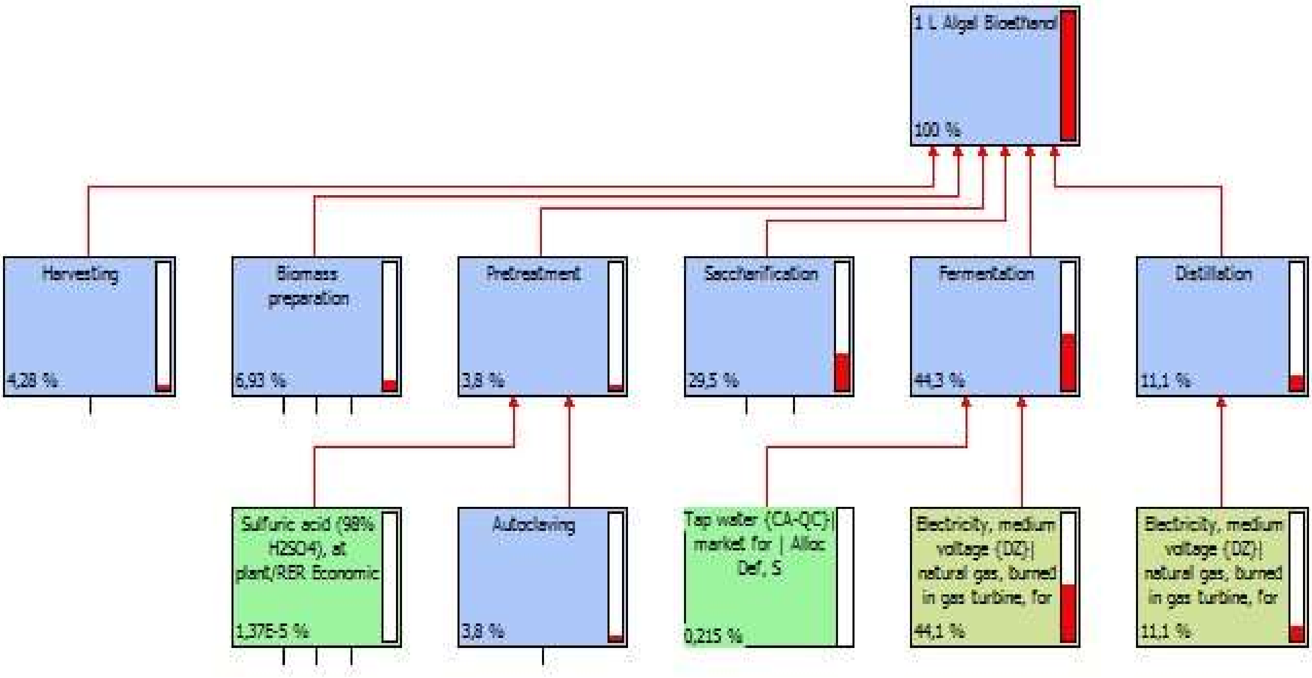

Fig. 1: life cycle steps of third generation bioethanol production

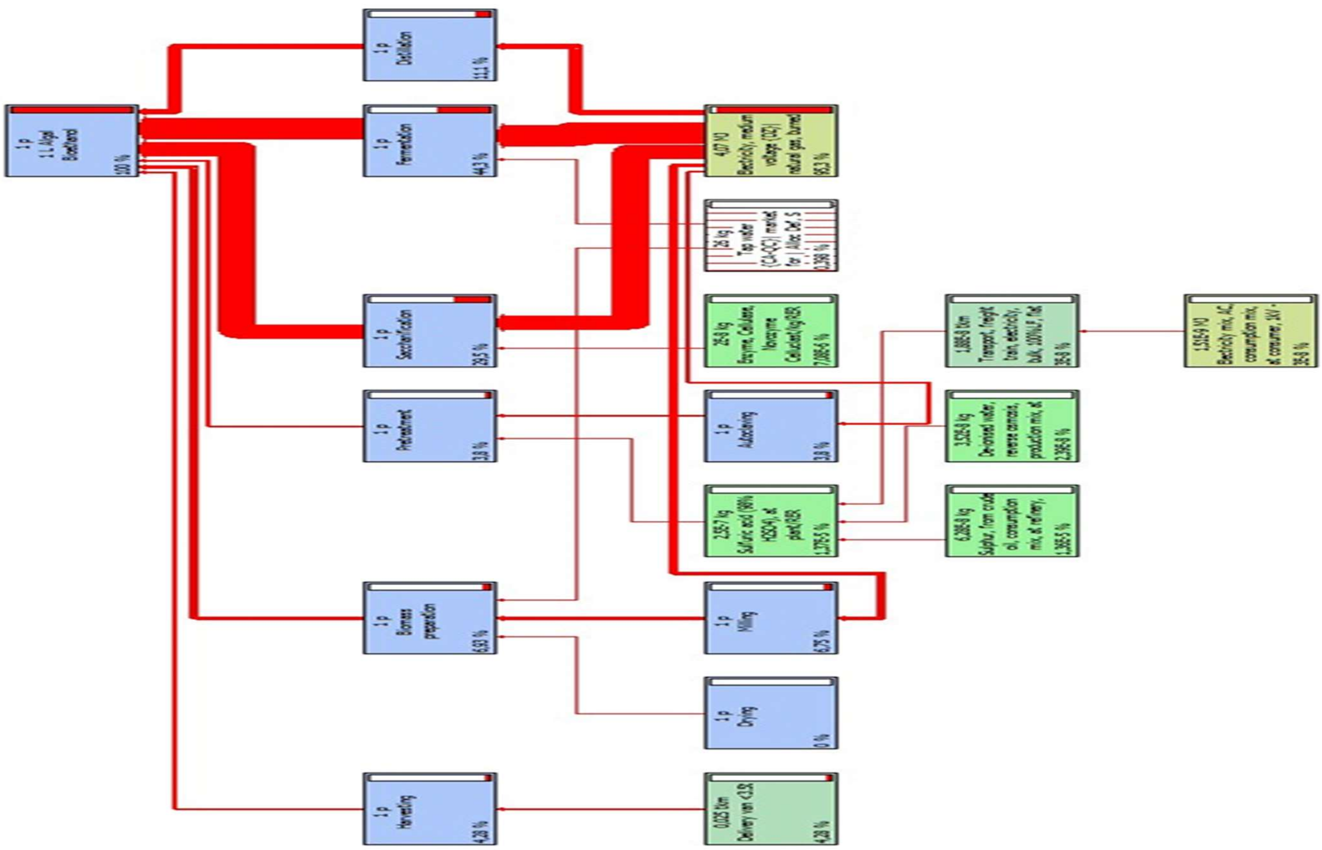

Fig. 2: Tree structure of third generation ethanol production

Table 2
Energy consumption during each algal bioethanol production step

Production steps	Non-renewable energy consumption Mj	Non-renewable energy consumption %
Biomass preparation	1,020	6.93 %
Harvesting	0,629	4.28 %
Pretreatment	0,558	3.5 %
Saccharification	4,346	29.5 %
Fermentation	6,525	44.3 %
Distillation	1,639	11.1 %
Total	14,719	100 %

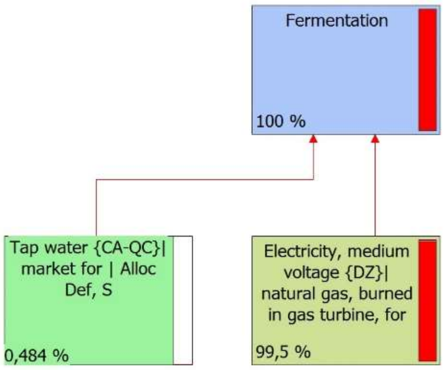

Fig. 3: Nonrenewable energy consumption during fermentation

Distillation is known to be the most consuming step of energy in bioethanol production, it can reach 60% of total consumption, when the dehydration step leading to a concentration of 99.7% ethanol is required. This step was not achieved in this study and the energy consumption was only 11.1 % of the total energy consumption, while a concentration of 95% was achieved which meets the bioethanol specifications as a gasoline fuel additive [9].

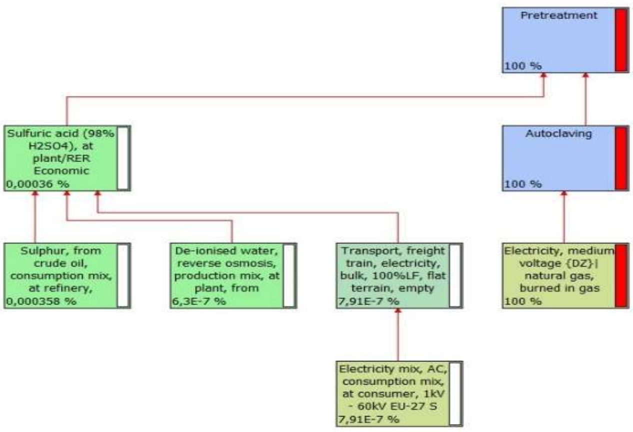

Fig. 4: Nonrenewable energy consumption pretreatment

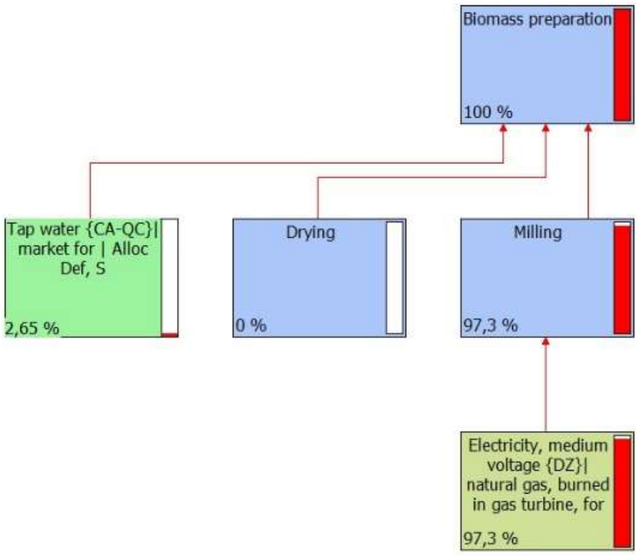

Fig. 5: Nonrenewable energy consumption during biomass preparation

Biomass preparation, harvesting and pretreatment are the less nonrenewable energy consuming steps of the process with 6.93 %, 4.28 %, and 3.5 % of the total energy consumption respectively. Indeed, important amounts of energy were saved by reducing transportation to the minimum, promoting solar drying, reducing the use of acids for pretreatment (acid makes algal sugars more accessible to enzymes) and water for desalination to the lowest possible guaranteeing good results in terms of energy saving.

b. ENERGY BALANCE

The energy balance was calculated according to the following equation:

Energy balance = Energy produced in the form of biofuel/ consumed Energy

- Produced Energy = PCI (lower calorific value of bioethanol) = 21.3 MJ/L[10]
- The energy consumed is equal to 14.719 MJ/L of bioethanol produced (given by the SimaPro 8.1 software)

Thus, the energy balance of algae-based bioethanol is equal to 21.3/ 14.719 = 1.44

The energy balance of algal bioethanol shows a good energy efficiency compared to other types of bioethanol produced from other substrates (Table 3). Indeed, the energy produced is 1.44 times higher than the energy consumed.

▪ Reduction of energy consumption related to the transport of biomass.

▪ Elimination of the dehydration step responsible for 30% of the energy consumption.

▪ The limitation of water supply specially during desalination of algae.

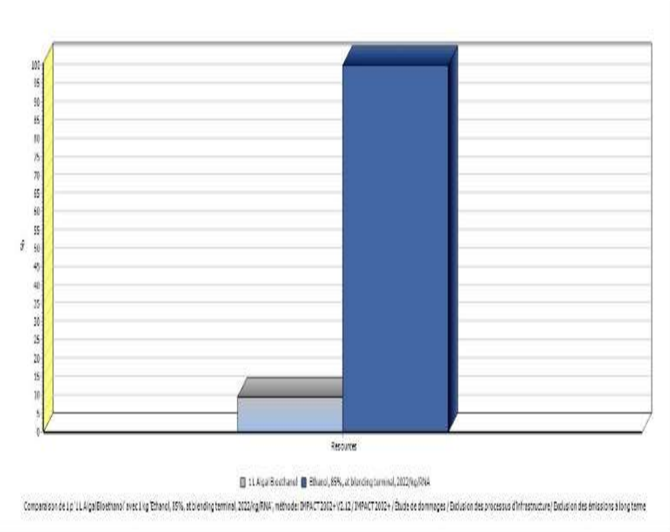

Fig. 6: Energy consumption comparison of algal ethanol and E85 (15 % ethanol, 85% gasoline)

Compared with (15 % ethanol, 85% gasoline), third generation ethanol made from macroalguae present an energy saving of 85 %. [11]

c. Comparison of the energy balance of algal bioethanol with that of other energy crops

SimaPro 8.1 software with its rich database allows us to compare non-renewable energy consumption and energy balance of algal bioethanol with other bioethanol made from other substrate: switchgrass, cornstover, forest residues.

Table 3
Comparison of the energy balances of several bioethanols

Production steps	**Non-renewable energy consumption Mj**	**Energy balance**	**Reference**
Algal bioethanol	14.71	1.44	Present study
Sugar beet ethanol	7.1	3	12
Corn stover bioethanol	14.77	1.44	13
Switchgrass bioethanol	14.37	1.48	14
Forest residues bioethanol	1210.66	0.017	15

Table 3 shows that the energy balance of algal bioethanol is comparable to bioethanols made from conventional substrates such as corn stover or switchgrass, it is lower than that sugarbeet bioethanol and higher than forest residue bioethanol that consumes more energy than it produces.

II. CONCLUSION

Biofuels produce and consume energy, reduce and emit greenhouse gas. Their economic and ecological impacts can be actually measured only by life cycle analyses that allow to establish precise energy and carbon balance. This study removes the uncertainty that hangs over the interest on third generation biofuels specially bioethanol whose production still need to be improved to be competitive, since it demonstrated that algae-based bioethanol produces 1.44 times more energy than its production consumes. Moreover, the main advantages of algae based bioethanol over other alternative bioethanols lie in the fact you do not need arable land to produce it. There is no competition with food and most of all the yields in bioethanol are very much higher, even if, many challenges must be taken up to make large-scale ethanol production possible and economically viable.

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