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Co-digestion of macroalgae for biogas production: an LCA-based environmental evaluation

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Abstract

Algae represent a favourable and potentially sustainable source of biomass for bioenergy-based industrial pathways in the future. The study, performed on a real pilot plant implemented in Augusta (Italy) within the frame of the BioWALK4Biofuels project, aims to figure out whether seaweed (macroalgae) cultivated in near-shore open ponds could be considered a beneficial aspect as a source of biomass for biogas production within the co-digestion with local agricultural biological waste. The LCA results confirm that the analysed A and B scenarios (namely the algae-based co-digestion scenario and agricultural mix feedstock scenario) present an environmental performance more favourable than that achieved with conventional non-renewable-based technologies (specifically natural gas - Scenario C). Results show that the use of seaweed (Scenario A) represent a feasible solution in order to replace classical biomass used for biofuel production from a land-based feedstock. The improvement of the environmental performances is quantifiable on 10% respect to Scenario B, and 38 times higher than Scenario C.

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Keywords: marine macroalage; LCA; biogas; Anaerobic Co-digestion

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1. Introduction

Research and development on promising cleaner and more efficient technologies is a key issue within a large scale production of biofuel using biomass as the main feedstock [1, 2, 3]. Still research on non-edible biomass for energy purpose, in order to shift toward a second and third generation biofuel, is an important and open point of discussion. This issue is of particular importance within the scientific arena in connection to a more sustainable and viable solution for the exploitation of an alternative biomass.

Seaweed present a very high photosynthetic efficiency compared to terrestrial plants, as well as a higher biomass growing rate and higher absorption rates of carbon, nutrients and heavy metals [4, 5], thus they represent a promising alternative as feedstock for biofuel production [6]. The anaerobic digestion of seaweed has been investigated as a positive energy conversion pathway. In fact, within this aspect macroalgae biomass could contribute to match two important targets: the reduction of the eutrophication effects and the use of renewable sources for the production of energy. The use of the Anaerobic Digestion (AD) digestate as recycled nutrient [7] is also bringing further beneficial impact. Under these perspectives, the proliferation of algae culture technologies has increased within the last decade, creating different types of technological solutions and more advanced controlled systems. Several methods of improvement could lead to a significant decrease of the environmental impact of algae-based bioenergy systems. In light of this, Life Cycle Assessment (LCA) represents an efficient tool for the overall impact quantification.

The present study is specifically devoted to the environmental assessment of the production of biogas from near shore-open pond-cultivated macroalgae feedstock, with data gathered from a real pilot scale biogas plant in Augusta Bay, Italy, within the FP7 project “BioWALK4Biofuels”. The main goal of this study is to evaluate whether the production processes of biogas through an anaerobic co-digestion bioenergy pathway, including a seaweed cultivation system, represents a more environmentally friendly approach to use alternative type of biomass feedstock rather than the use of natural gas. A total of three scenarios have been investigated, namely: i) the biogas production system of the proposed novel production biogas scheme based on algae (scenario A), ii) a conventional biogas plant using an agricultural mix as feedstock (scenario B), iii) a non-renewable production pathway using natural gas instead of biogas as fuel (scenario C).

2. Methodology

According to the ISO Standards 14044 [8], the LCA is defined as an analytical comprehensive tool that evaluates environmental burdens, benefits and performances in connection to the entire supply chain of a product, process or service. The LCA methodology is based on four main stages: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation of the results. The present study is following the guidelines of the consequential LCA principles based on the ISO 14044 Standards [8] and the ILCD Handbook [9]. Within this perspective, the theory of the system expansion, including the identification of specific avoided products, has been proposed.

The system’s processes and technologies have been modelled using marginal inventory data: directly from the plant; whenever not available, data from literature, or background data from Ecoinvent 2.1 database have been used [10].

3. System definition and inventory

3.1. Goal and scope

The main aim of the proposed study is the evaluation of the potential environmental impacts caused by biomethane production from macroalgae and its combustion in a CHP unit with 40 kW_{el} capacity for final production of electrical and thermal energy. In a cradle-to-grave perspective, the selected LCA inventory included all the main steps: from the algal biomass cultivation and harvesting (in open ponds), followed by anaerobic co-digestion with manure and other wastes for biogas production, its combustion within a CHP unit. The construction phase has been taken into account together with the extraction and transportation of resources (but not the dismantling of the facility).

The characterization of environmental impacts is based on the impact assessment methodology Eco-Indicator 99 (hierarchical) [11]; the LCA software Simapro 7.2 has been used for the modelling. The functional unit was defined as the net output of products associated with the reference flow of 1 m^3 of biogas produced. The function of the system comprises the production of heat and electricity. A co-product of the proposed system is organic compost as soil fertilizer. Thus the whole functional unit was defined as: 1.02 kWh of electrical energy, 10.92 MJ of thermal energy, 1.86 kg of compost.

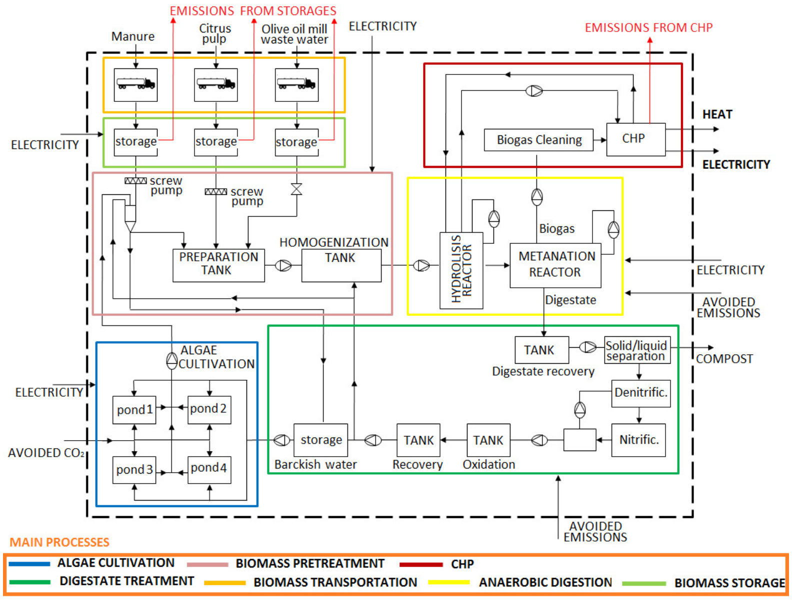

Fig. 1. Detailed LCA scheme of the base scenario (Scenario A) based on the real plant from BioWALK4Biofuels project.

The analyzed process system is referred to a real pilot plant system (see Figure 1) starting from initial seaweed cultivation till the final CHP unit. However, a part of the input data has been selected from literature and directly from the Ecoinvent database.

The algae type selected for the study is *ulva lactuca*, since it was considered the most suitable and sustainable alga-type based on meteorological conditions referring to Augusta Bay. The values of the biomass co-digested together with algae are calculated with reference to a weekly transportation of biomass. The co-digested biomass has been considered to be stored separately in special containers and then sent on a daily basis to subsequent pretreatment.

Due to the main function of the system, an economic allocation was selected. Nevertheless, from a mass allocation perspective, the by-product would be charged with higher environmental burden if compared to biogas.

The pilot plant considered for production of heat and electricity within the CHP, uses biogas deriving from different substrates other than algae, namely: poultry manure, Oil Mill Waste Waters (OMWW) and citrus pulp. All feedstocks implemented within the anaerobic co-digestion are collected weekly and transported (maximum radius of 60 km)to the plant site. Once having arrived at the system, they are stored separately in special tanks. As a daily activity, the required amount of biomass is sent to the preparation tank in order to realize an optimal proportion of nutrients and to improve the mix of chemical and physical parameters required by the bacterial strains involved in the Anaerobic Digestion process. Further, the mixture is homogenized in order to reach the optimal condition prior to being supplied to the two-stage anaerobic digestion conversion processes. The biogas produced is sent to the cleaning (desulphurisation) process and then to the CHP unit for production of electricity and heat.

Anaerobic digestion foresees the management of solid and liquid digestate as a by-product of the conversion processes. Thus a separation of the solid fraction from the liquid is implemented through a helical compression separator that allows to obtain a clarified liquid fraction and a solid fraction (commonly defined: compost) having a high percentage of organic matter partially stabilized. The liquid fraction afterward passes a nitro-denitro biological process for the removal of dissolved ammoniac nitrogen and is further released directly in the environment. The final solid fraction produced (compost) can be used for soil conditioning, since it is still rich in organic matter and nutrients.

For scenarios B and C, the implemented existing schemes from the Ecoinvent database have been selected including an Italian primary energy mix.

3.2. Inventory of the base scenario (Scenario A)

The biogas production system of the present study is referred to as a real demo-plant based system; the overall inventory data set has been selected from technical information directly related to the plant building, and partly from the present knowledge on equivalent process and technology at pre-industrial scale. For the purposes of this study, specific data on the macro algae used within the modelling phase (i.e. *ulva lactuca*) have been gathered by experts within the sector and already presented in previous studies [12, 13].

The phase of the plant construction has been considered within the overall impact, but at this stage of the study the dismantling and landfilling were not included within the study. Within the modelling phase, an average life span of 15 years for all the plant facilities was considered. The main values for the inventory are summarized in Table 1 where the plant components, matter and energy consumption are reported, including all the steps of the whole system. As reported in Figure 1, seven main unit processes within the overall system were identified and discussed afterwards.

Table 1. Life Cycle Inventory.

Process	Input	Output	Avoided	Description	Quantity	Unit	Source
1.Algae cultivation	X			Electrical energy	4 380	kWh/year	Manufactures, calculation
		X		Algae biomass	37	ton/year	Partners, calculation
			X	CO_2 (fossil)	24	ton/year	calculation
2a.Transport poultry manure	X			Transport 3.5-7.5 ton	21 840	tkm/year	calculation
2b-Transport OMWW	X			Transport > 32 ton	2 190	tkm/year	calculation
2c.Transport Citrus pulp	X			Transport 3.5-7.5 ton	16 380	tkm/year	calculation
3a.Poultry manure storage		X		NH_3 (air)	127	kg/year	calculation
3b.OMWW storage	X			Electrical energy	548	kWh/year	Literature, calculation
			X	Polyphenols	1 971	kg/year	Manufactures
			X	COD	10 950	kg/year	Analysis OMWW
3c.Citrus pulp storage		X		CO_2 (biogenic)	20 600	kg/year	Literature, calculation
4.Biomass pretreatment	X			Electrical energy	9 031	kWh/year	Literature, calculation
5.Anaerobic digestion	X			Electrical energy	27 463	kWh/year	Manufactures
	X			Heat	111 370	MJ/year	Manufactures
		X		Biogas	134	ton/year	calculation
		X		Digestate	1 037	ton/year	calculation
			X	CO_2 (biogenic)	57 630	kg/year	calculation
			X	CH_4 (biogenic)	278	kg/year	calculation
6a.Upgrading		X		CO_2 (biogenic)	64 287	kg/year	Data base Simapro
		X		CH_4 (biogenic)	1 653	kg/year	
		X		H_2S	0.26	kg/year	
		X		SO_2	41	kg/year	
	X			Electrical energy (gross)	37	MWh/year	
6b.Cogeneration		X		Electrical energy (gross)	191	MWh/year	
		X		Heat	1 328	GJ/year	Calculation
		X		CO_2 (biogenic)	150	ton/year	
		X		CO (biogenic)	427	kg/year	Data base Simapro
		X		CH_4 (biogenic)	214	kg/year	
		X		NOx	187	kg/year	
		X		NMVOC	27	kg/year	
		X		N_2O	13	kg/year	
		X		SO_2	1.47	kg/year	
			X	Electrical energy (net)	113	MWh/year	Calculation
			X	Heat (net)	1 217	GJ/year	
			X	H_2S	249	kg/year	
7.Digestate treatment	X			Electrical energy	8 946	kWh/year	Manufactures, calculation
		X		Compost	218	ton/year	Data base Simapro
			X	CO (biogenic)	16	kg/year	
			X	CO_2 (biogenic)	33	ton/year	
			X	CH_4 (biogenic)	1 922	kg/year	
			X	NOx	94	kg/year	

The algae cultivation process foresees cultivation, harvesting and collection of algae from 4 open-sea and near-shore ponds located just in front of the biogas plant. The cultivation guarantees strict control of several parameters (pH, nitrogen compounds, phosphates, etc.) avoiding water exchange with the open sea. The data selected for the present study have been previously modeled, deeply analyzed and presented in a publication [12].

As mentioned previously, within this specific case *ulva lactuca* has been used within the cultivation phase, as it is considered the optimal and more sustainable algal species suitable for the local conditions of Augusta Bay. Within the cultivation process, the amount of captured CO_2 was evaluated on the basis of the overall carbon cycle regarding intensive algal cultivations [12, 13].

The values used within the biomass transportation unit process have been evaluated with reference to the weekly transportation of biomass from local suppliers providing the requested plant feedstock.

The main biomass contributing to the co-digestion of algae biomass are poultry manure, Olive Mill Waste Water (OMWW) and citrus pulp. The feedstock is stored separately in special containers and then sent to the next shredding stage prior to the correct evaluation of the required amount. The storage period of approximately 7 days with production of GHG emissions, together with acidification and eutrophication compounds has been evaluated and (conservatively) considered within the modelling phase.

For this case study, emission from the poultry manure storage (principally CH_4 and H_2S)have been considered negligible, due to the limited duration of the storage; while N_2O and ammonia emissions have been considered since they take place in the very first days of storage [13, 14], and the values have been obtained according to biomass composition from analyses performed on biomass used in the plant.

The environmental impact of Olive Mill Waste Water (OMWW) is related to the release in ground waters of polyphenols, and COD (Chemical Oxygen Demand). Polyphenols content from specific analysis on local OMWW have been used. Gaseous emissions for the storage of Citrus Pulp are gathered from literature data [14].

Within the biomass pretreatment process unit, the following steps have been taken into account: collection, dewatering and desalinization of the algae, manure and citrus pulp pre-treatment (chopping and handling), biomass feeding to the preparation tank and residence time in the homogenization tank, where a better homogenization of biomass over time is performed prior submission to the AD processes.

The main steps of the 2-stage anaerobic co-digestion have been considered, including the following processes: biomass injection to the hydrolysis and methanisation reactors, biogas collection and digestate extraction. The conversion process is performed at mesophylic conditions; the amount of the required heat was evaluated as equivalent to 1 MJ per m^3 of biogas produced.

To estimate the annual production of biogas within the installation, the following calculation and assumptions have been performed: evaluation of the carbon content within each feedstock biomass, evaluation of the biogas yields from each feeding biomass, efficiency of bio-degradation activity within the digesters equal to 70%; decrease in carbon content due to volatilization of CO_2 during the storage phase were taken into account.

The positive environmental impact due to the anaerobic digestion process is mainly related to the avoided emissions that would occur if biomass, instead of being used as feedstock, would be composted or spread on land according to conventional methods. With regard to poultry manure and citrus pulp, the overall avoided emissions have been calculated mainly according to IPCC factors [16], specifically in terms of ammonia (NH_3), hydrogen sulphide (H_2S), nitrous oxide (N_2O), biogenic carbon dioxide(CO_2) and biogenic methane (CH_4) (with regard to climate change impacts). Only the avoided emissions of methane and carbon dioxide were allocated to the process of anaerobic digestion while the rest have been associated with nitro-denitro and the biogas upgrading process.

At the basis of this choice, there is the fact that during the digestion step there are neither nitrogen nor sulfide removal dynamics. Avoided methane emissions were calculated using the model proposed by IPCC [16].Within the impact given during the cultivation phase, the results show that nutrient supply and water refilling in the ponds play a crucial role in terms of energy within the unit processes.

4. Comparative analysis: main results

The results of LCA for Scenario A are reported in Figure 2. The figure is referenced to the selected functional unit (namely 1.02 kWh of electrical energy, 10.92 MJ of thermal energy, 1.86 kg of compost). The graph highlights only 6 middle-point impact categories of the *Ecoindicator 99 (H)* with a score larger than 1%, specifically: respiratory inorganics, climate change, ecotoxicity, acidification/eutrophication, land use, mineral and fossil fuel.

Results show that the most beneficial effect on the process considered is related to the avoided impact from the use of a locally produced biofuel. From a quantitative aspect, this represents 74% of the overall beneficial impact on environment (82% of overall balance). While the effects of disposal of poultry manure and OMWW represent 11% of positive impacts (12% of overall balance).

One environmental hot spot of the plant is related to gathering and storage of poultry manure: in fact the weekly transportation represents a relevant impact in terms of fossil fuel consumption and climate change effects. Ammonia emissions in the storage phase are responsible for impacts on respiratory inorganic compound emissions and on acidification and eutrophication effects with a share of 35% in respect to the total negative impacts of the plant (5% of overall balance). The other transport processes and biogas upgrading allocate 31% of the total negative impacts (4% of global result).

In regard to the impact category "respiratory inorganics", the results obtained are connected to emissions of NH_3 in the storage phase of poultry manure and the use of trucks for transportation of biomass. Within the mid-point category, there is an evident effect of the avoided emissions due to the substitution of electrical energy from conventional sources (shares 50% of the total reduction), substitution of compost from conventional composting facility (17 % of total reduction) and avoided emissions of NH_3 due to the treatment of poultry manure and citrus pulp in the plant (30 % of total reduction).

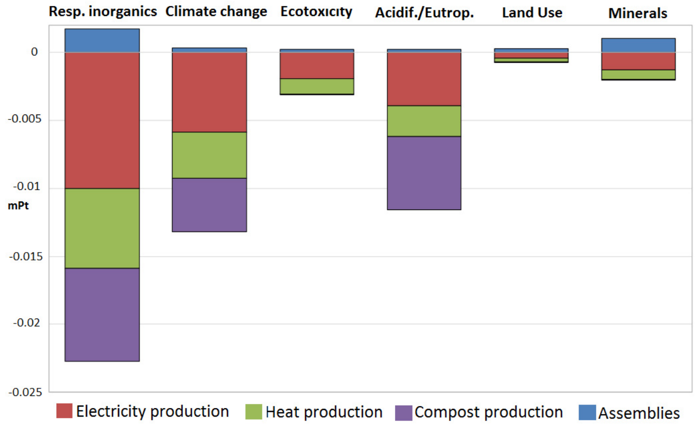

Fig. 2.Ecoprofile scenario A.

The impact due to biomethane production presents a relatively low share of the overall impact.

The substitution method used to evaluate the beneficial effect on the use of AD digestate as a by-product is reflected as a positive impact in terms of avoided production of compost. The overall assembly of the plant facilities, considered with a technical life-span of 15 years, represents the most substantial impact mainly due to the energy consumption and use of fossil fuels necessary for raw material extraction and their treatment for building the main plant components. This affects mostly the impact category of use of non-renewable resources and respiratory inorganics.

The main normalized results among the 3 scenarios are presented in Figure3a in terms of final damage categories. The results confirm that both scenarios A and B present an environmental performance which is much better than that achieved with conventional non-renewable-based technologies (Scenario C). Due to better insight into the results, it has been noticed that the process of cogeneration provides the most evident beneficial contribution to scenarios A and B with regard to the impact category of fossil resource depletion. The reason why scenario A gives the worst result in this category is that, given its pilot scale and pre-industrial development level, the examined system has higher levels of self-consumption.

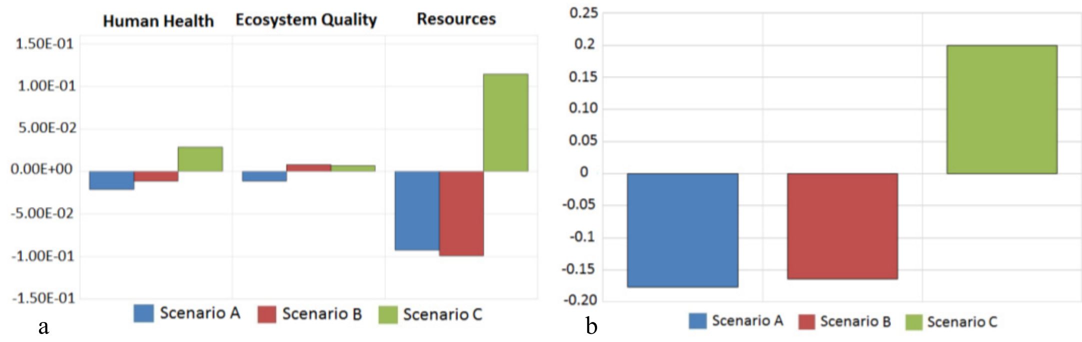

Fig. 3. LCIA: comparative results of the 3 scenarios; fig. 3.a – results by impact category, fig. 3.b – single score results.

Moreover, the production of compost as a by-product is beneficial in terms of decreasing impact. That is mainly relevant to Human Health and Ecosystem quality impact categories, which, specifically for both scenarios A and B, are accounted for a share of approximately 45%.Scenario B presents a higher beneficial effect for depletion of fossil based-source due to a scale effect (Scenario A is based on a pilot scale plant).

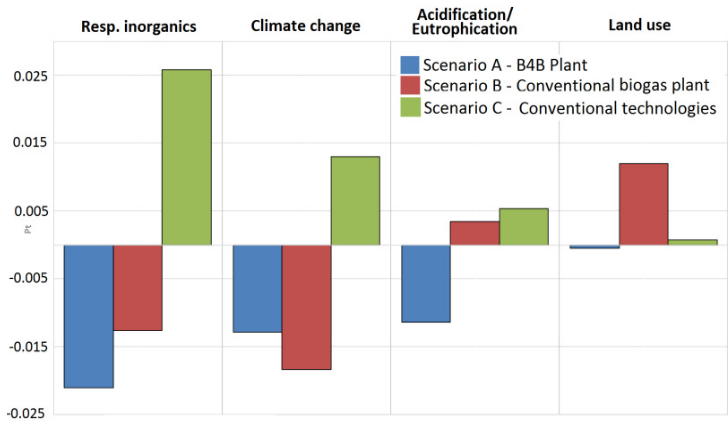

Fig. 4. LCIA: comparative results of the 3 scenarios - specific mid-point categories.

Looking at the overall eco-profile analysis presented in Figure 3b, it is observed that the implementation of algae cultivation, and thus the use of algae biomass, provides an improvement in environmental performance at around 10% with respect to Scenario B and 38 times lower impact than in Scenario C. One important aspect should be devoted to the Land use damage category (see Figure 4).In fact, the results highlight that Scenario B (conventional biogas) results in the worst overall performance: this is mainly due to the higher rate of land occupation needed for dedicated energy crops. This aspect in turn highlights the beneficial effects of having an exploitable biomass, with high photosynthetic efficiency, in the near-shore open ponds. On the other hand, the overall beneficial effect should be evaluated in a comprehensive way; in fact, the use of a Pressure Swing Adsorption (PSA)upgrading unit technology (considered in the analysed system) consumes 29% of the gross electricity produced.

5. Conclusions

The study highlights that biogas production from fresh algae co-digestion with manure and/or agricultural waste seems to be a valuable bioenergy root from an environmental point of view, if compared to the conventional techniques. However, it is evident that important technical improvements within an eco-design phase are needed in order to guarantee a better overall system efficiency with higher benefits to climate change and depletion of fossil sources.

The implementation of a scale-up system of the proposed concept would be beneficial in order to better understand the real environmental hot-spots at a larger scale of production and thus to study the real economic feasibility within an industrial market. A more valuable environmental benefit can be obtained by including more integrated renewable sources in the system. A better evaluation of the final impact based on different allocation will be further evaluated.

Acknowledgements

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