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Life cycle assessment of biofuel production from brown seaweed in Nordic conditions

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HIGHLIGHTS

- ▶ LCA showed that seaweed biogas was more sustainable compared to ethanol scenario.
- ▶ 961 kg of CO_2 per functional unit are removed during seaweed production.
- ▶ 555 kW h of electricity per functional unit are recovered.
- ▶ Energy analysis showed that seaweed production was the most energy intensive step.
- ▶ Grow-out phase accounted for 95% of the total energy during seaweed production.

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ABSTRACT

The use of algae for biofuel production is expected to play an important role in securing energy supply in the next decades. A consequential life cycle assessment (LCA) and an energy analysis of seaweed-based biofuel production were carried out in Nordic conditions to document and improve the sustainability of the process. Two scenarios were analyzed for the brown seaweed (*Laminaria digitata*), namely, biogas production (scenario 1) and bioethanol + biogas production (scenario 2). Potential environmental impact categories under investigation were Global Warming, Acidification and Terrestrial Eutrophication. The production of seaweed was identified to be the most energy intensive step. Scenario 1 showed better performance compared to scenario 2 for all impact categories, partly because of the energy intensive bioethanol separation process and the consequently lower overall efficiency of the system. For improved environmental performance, focus should be on optimization of seaweed production, bioethanol distillation, and management of digestate on land.

1. Introduction

Biomass, either terrestrial or aquatic, is considered a potential renewable energy source for biofuel production. Biomass resources include wood and their wood wastes, energy crops, aquatic plants, agricultural crops and their waste by-products, animal wastes and certain fractions of municipal wastes. Among these, either microalgae or seaweed are considered superior compared to terrestrial plants – in terms of solar energy storage, nutrient assimilation and potential for biofuel production – due to their higher photosynthetic efficiency, higher biomass yield and rates (Lardon et al., 2009). Recently, the EU adopted a binding target of 20% renewable energy from final energy consumption by 2020 (RES Directive, 2009). Energy from biomass (biological, incl. biofuels and non-biological processes incl. gasification, combustion, etc.) is expected to provide more than half to achieve the desired target (EREC, 2008). To this respect the use of seaweed biomass to produce biofuels appears to be a promising process to supplement and secure energy supply and reduce the dependence on fossil fuels in coherence with the target of the EU. However, before new energy policies are implemented and industrial plants are established, the sustainability of algae-based production chain should be documented to prevent burden shifting. To this respect, life cycle assessment (LCA) can be used to holistically analyze and assess potential environmental impacts that new technologies and/or processes may create. Numerous studies have been conducted on the production of biodiesel from microalgae (Lardon et al., 2009; Luo et al., 2010; Campbell et al., 2011; Yang et al., 2011). LCA studies of seaweed-based fuels are sparse in the published literature, and the few

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existing studies only provide generic overview of the energy requirements for the main processing steps involved in the life cycle. For example, both micro and macro algae were included in the software package COMPUBIO, developed by Aresta et al. (2005), for evaluating the energy balance of various biofuels pathways. Energy consumption values for the different processing steps of the life cycle were estimated, but different emissions (e.g. GHGs) were not included in their study. Aizawa et al. (2007) performed an analysis of the life cycle stages of cultivation and harvest of seaweed in coastal or offshore zones with techniques already used in Japan for ethanol production. This seaweed feedstock would be processed into ethanol by means of highly efficient fermentation technologies. In addition, consumption of resources throughout the life cycle was estimated. An energy and emissions analysis was performed by Pietrak and St. Peter (2011) for a hypothetical macro-algal based organic acid production process of an integrated multi-trophic aquaculture farm. The results showed that relevant burdens are associated with emissions of CO_2, phosphorous and nitrogen. The land based growth of juveniles, the grow-out phase and distillation were identified as the most energy consuming processes being electricity the primary form of energy consumed for the processes studied. Therefore, the purpose of this study was to provide an assessment of the environmental consequences of implementing seaweed-based biofuel production in Denmark focusing on two scenarios, namely biogas (scenario 1) and bioethanol + biogas (scenario 2). This was done by (1) establishing the necessary inventory data describing the biofuel processes, (2) carrying out detailed mass and energy balances for each scenario, and (3) performing an LCA to quantify the potential environmental impacts related to the two scenarios.

2. Methods

Life cycle assessment (LCA) is a systematic, comprehensive and international standard framework for analyzing the environmental performance over the entire life cycle of a product and/or service. Material and energy balances are used to inventory all relevant emissions, resource depletion, and energy consumption of all processes comprised in the life cycle, from the conversion of raw materials into useful products to the final disposal of all products and by-products. The inventory is then used to evaluate the potential environmental impacts of the process so that efforts can be focused on mitigating possible effects. The present study follows consequential LCA principles and covers all four interrelated phases of a LCA – goal and scope definition, inventory analysis, impact assessment, and interpretation – according to ISO 14040 (ISO, 2006) and the ILCD Handbook (EU-JRC-IES, 2010). Within consequential approach, system expansion was performed to include within the system boundaries the effects/consequences that the change under assessment (i.e. increased production of biofuels from algae) have on both the background system and other systems. The affected processes and technologies were modeled using marginal inventory data, whenever these were available.

2.1. Functional unit

The service provided by the system under study in LCA is unequivocally defined in the functional unit whose primary purpose is to provide a reference to which all inputs and outputs are related, meaning that, after its definition, all the energy and mass flows in the inventory are normalized with respect to the functional unit. In this study, the functional unit was defined as "cultivation and processing of one tonne of dry seaweed biomass (*Laminaria digitata*) produced in Denmark for biofuels production". The composition of the seaweed species and the biofuels utilization pathways are defined in the following sections.

2.2. Goal and scope definition

The goals of the study were to assess the potential environmental impacts and to perform an energy analysis of seaweed-based biofuels, as well as to identify hotspots in the life cycle where the environmental performance of the system can be improved. In addition, results of the study can potentially support decision-making concerning biofuels policies in countries with climatic conditions similar to Denmark; because consequential approach is used (i.e. the consequences of increased biofuels production are analyzed). The scope of seaweed-based biofuels considers two scenarios: S1-biogas production (scenario 1) and S2-bioethanol + biogas production (scenario 2) (see Fig. 1a). The impact assessment was performed based on the EDIP2003 method (Hauschild and Potting, 2003), for a time horizon of 100 years. The results are presented as characterized potential environmental impacts for the following impact categories: Global Warming, Acidification and Terrestrial Eutrophication. The investigated algal processing system was assumed to be located along the coastline in Denmark. The seaweed cultivation site was situated at the open sea, preferably associated to a fish farm, while the biofuels production facility was situated at the seaside on land.

2.3. Biofuel process system description

The biofuel process system starts with seaweed production, which includes production of seaweed biomass on long line (string) systems at open sea and harvesting of the biomass. The seaweed production involves several intermediate processing steps (see Fig. 1b), which are described in the following sections. The harvest is then followed by mechanical pretreatment (milling and grinding), biofuels conversion (anaerobic digestion and/or fermentation) to the end-use of the biofuels (energy production or fuel additive) and co-products (fertilizer), as shown in Fig. 1a.

2.3.1. Scenario 1: biogas production

The seaweed slurry is used to produce biogas through anaerobic digestion (AD) process in scenario 1. The biogas generated during AD is used for energy production. It is assumed that the biogas produced is combusted in a gas engine, with an electricity efficiency of 42% (Møller et al., 2009). Data on biogas combustion were obtained from EASEWASTE database (EASEWASTE, 2008). Heat is also co-generated in the gas engine, but used internally in the biogas plant. The electricity generated is delivered to the grid and assumed to substitute coal-based marginal electricity (Fruergaard et al., 2009; Fruergaard and Astrup, 2011), modelled using the ECOINVENT process "Electricity, hard coal, at power plant/NORDEL S" (Dones et al., 2007). An alternative to direct use in a gas engine – could be combustion of the biogas in gas-fired power plants, thereby replacing the natural gas otherwise used. This is, however, from a system perspective equivalent to direct use in a gas engine provided the energy efficiencies are the similar which is the case in most Danish facilities. The digestate generated during AD process can be used as fertilizer on agricultural land, thus displacing the industrial production of organic fertilizer.

2.3.2. Scenario 2: bioethanol and biogas production

The seaweed slurry is used to produce bioethanol through simultaneous saccharification and fermentation (SSF) process in scenario 2. The bioethanol produced is upgraded and blended with conventional gasoline, substituting fossil gasoline on a 1:1 energy basis. The 5 vol.% bioethanol is assumed blended with 95 vol.% gasoline, as allowed in the European standard for gasoline EN-228. To

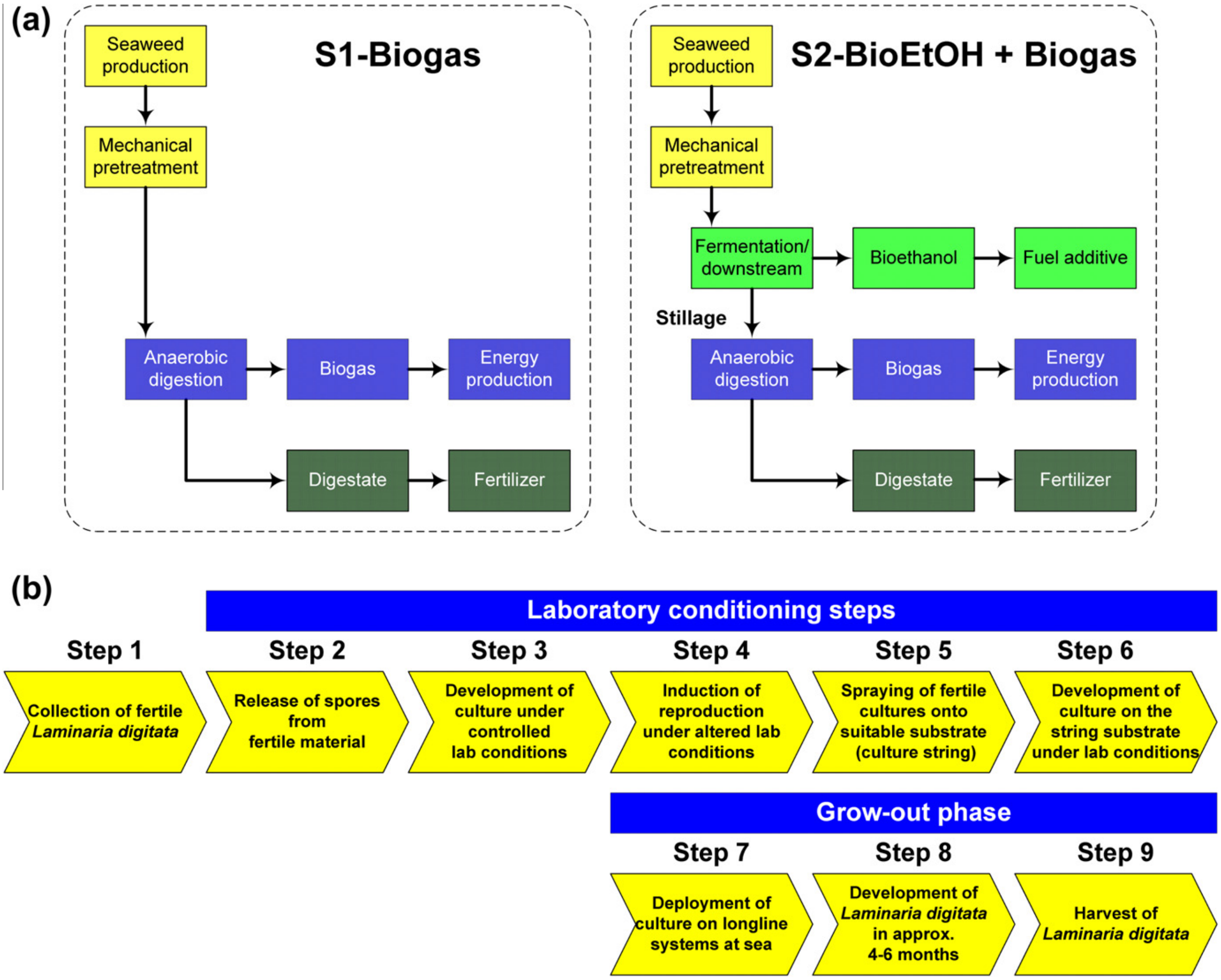

Fig. 1. (a) Biofuel process system outline (S1 and S2 abbreviate scenarios 1 and 2, respectively) and (b) overview of the cultivation of *Laminaria digitata* (based on Edwards and Watson, 2011).

model the substitution, data on exhaust gas emissions of the ethanol–petrol blend and fossil petrol were taken from Pelkmans et al. (2010) and used along with the ECOINVENT process "Operation, passenger car, ethanol 5%/CH" (Jungbluth et al., 2007). Stillage from fermentation/downstream processes is used for biogas production. Assumptions regarding biogas production and digestate were identical to scenario 1.

2.4. Data collection and modelling

The LCA modelling was facilitated in SimaPro 7.2.4 LCA software (Pré, 2010). Inventory data were collected from different sources, including published literature, databases (i.e. ECOINVENT 2.0), unpublished experimental data and personal contacts with professionals with expertise on the topic. When process data were not available, assumptions were made and/or process engineering calculations were performed and data obtained.

2.5. Experimental data generation

Data on total solids (TS) and volatile solids (VS) content of *L. digitata* were generated based on experimental work. Samples of *L. digitata* were collected in late March 2011 at Ømo, Denmark for TS and VS determination. The TS and VS contents were determined as described in Standard Methods (APHA, 2005). Similarly, data on methane potential were generated through batch experiments. Samples of 0.8 g VS (≈8 g of wet seaweed, ≈1.2 g TS) *L. digitata* were distributed in 547 mL serum bottles. The bottles were supplemented with water to reach a total volume of 40 mL and inoculated with 160 g of digested manure. Then, all bottles were flushed with nitrogen to obtain anaerobic conditions, closed with butyl rubber stoppers and aluminium crimps and incubated at 52 °C for 30 days. Methane production was measured by gas chromatography. All the experiments were performed at least in triplicates.

2.6. Life cycle inventory

2.6.1. Seaweed production

Data collection and assumptions for the life cycle inventory for the seaweed production modelled in this study were considered starting from step 3 and primarily retrieved from Arbona and Molla (2006) and Edwards and Watson (2011) unless otherwise stated (see Supplementary data S.1). Seaweed production begins with the collection of fertile *L. digitata* which can be found during October to March around Denmark (step 1). Then, fresh mature

Table 1
Inventory data for the production and processing of one tonne of dry seaweed into biofuels.

Resource consumption	Unit	SWP[a]	MP[b]	AD[c]		F[d]/DS[e]	Main use
				S1	S2		
Diesel	L	30					Transportation (barge)[a]
Petrol	L	30					Transportation (skiff)[a]
Electricity	kW h	30	38	50	45	97	Illumination/pumping[a] grinding/milling[b] stirring[c,d] compression work[e]
Heat	kW h (GJ)			512 (1.84)	138 (0.50)	121 (0.43)	Heating[c,e]
Water	L	2380	3439				
Stock nutrients solution	L	0.03					
Plantlet nutrients	g	189					
Celluclast 1.5 L	kg					5.11	
β-glucosidase	kg					2.32	
Laminarinase	kg					13.4	

[a] SWP: seaweed production.
[b] MP: mechanical pretreatment.
[c] AD: anaerobic digestion.
[d] F: ethanol fermentation.
[e] DS: downstream separation.

sporophylls are prepared for spore release under controlled laboratory conditions (step 2). Development of culture under controlled laboratory conditions (step 3) consists of inoculating flasks containing strain nutrients and seawater with the spore solution filtrate from step 2. Strain nutrients consumption was estimated to be 0.03 L per one tonne of dry seaweed. Energy consumption was estimated to be 10.8 kW h per one tonne of dry seaweed. In step 4, reproduction is induced under altered laboratory conditions by manipulating temperature, irradiance and photoperiod for about 8 days, until sporophytes are developed. Energy consumption was estimated to be 1.75 kW h per one tonne of dry seaweed. Once reproduction is concluded, the small developing sporophytes of *L. digitata* are sprayed onto the culture string collectors (step 5). Collectors need to be placed immediately into culture/nursery tanks once sprayed (step 6), where the collectors are suspended vertically for optimal light conditions. The water must be renewed (50% volume) every third day and new nutrients added. Starting from day 5, water is agitated using very gentle aeration. Aeration must be progressively increased until the end of the operation. Plantlet nutrients consumption was estimated to be 189 g per one tonne of dry seaweed. Energy consumption was estimated to be 17.5 kW h per one tonne of dry seaweed. Nursery plantlets on string of 0.1–0.5 cm in length are ideal to be deployed at sea (step 7). Once collectors are delivered to the coast, transportation at sea is assumed to be by diesel powered work barge with a crane transporting and deploying the collectors in a single day. Diesel consumption was estimated to be 15 L of diesel per one tonne of dry seaweed per day. The cultivation site shall be visited approximately once a month (4–6 days for total grow out period) for maintenance and monitoring the biomass growth. These operations are accomplished with a small skiff using a 25 hp outboard engine consuming approximately 5 L of petrol per one tonne of dry seaweed per day. Maximum yield per site is expected to occur after 4–6 months of growth (step 8). Therefore, 5 months of growth at sea was considered to be enough. The resulting petrol consumption was estimated to be 25 L of petrol per one tonne of dry seaweed. Harvest (step 9) of the seaweed biomass is carried out around April–May and is accomplished by skiff similar in size and petrol consumption as for maintenance and monitoring. Removal of the ropes from the sea is performed with a barge similar to the one used for ropes deployment, thus an equal diesel consumption is assumed. Finally, the harvested seaweed can be transported by road to a facility for further processing. Inventory results for the seaweed production are summarized in Table 1.

2.6.2. *Mechanical pretreatment*

Mechanical pretreatment consists of the milling and grinding of harvested seaweed blades into slurry with a content of solids of approximately 10% (w/w). Inputs to the pretreatment process include the wet seaweed biomass and water, while the main output is seaweed slurry. Through mass balance the total amount of material processed by milling was determined to be 10,000 kg wet which serves as input for further processing steps. The equipment used was assumed to be a circulating wet grinding attritor production mill and the energy consumption was estimated to be 38 kW h per one tonne of dry seaweed (see Supplementary data S.2). The inventory results for the pretreatment process are shown in Table 1.

2.6.3. *Anaerobic digestion (AD) process*

The seaweed slurry is processed in a thermophilic (52 °C) anaerobic digester where biogas is produced after pretreatment process in scenario 1. The only input to AD process is the seaweed slurry, while outputs include biogas and digestate, the latter consisting of undigested seaweed biomass and inorganic material (ash) contained in the raw seaweed. From experimental results methane yield, contents of volatile solids (VS) and ash in *L. digitata* were determined to be 0.20 LCH$_4$/g VS, 66.3% (w/w), and 33.7% (w/w) respectively. Mass balance calculations were performed to estimate the outputs from the AD process. Based on the VS content and the methane yield experimentally determined, the content of TS in digestate was estimated to be 702 kg per one tonne of dry seaweed treated. The gross methane production was estimated to be 133 m^3 per one tonne of dry seaweed, corresponding to a gross biogas production of 221 m^3 per one tonne of dry seaweed with the following v/v composition: CH$_4$: 60%; CO$_2$: 38%; NH$_3$: 0.51%; H$_2$S: 1.21%; H$_2$O: 0.28%. The energy consumption during the AD process was attributed mainly to heating up of the slurry from 8 °C (average annual temperature in Denmark according to the Danish Meteorological Institute) to the desired temperature of 52 °C. The consumption of heat was estimated to be 512 kW h per one tonne of dry seaweed (see Supplementary data S.3), supplied by combustion of part of the biogas produced. Besides heating requirements, electrical power for pumping and mixing the slurry was also considered. Based on AD treatments for manure, a typical value of 50 kW h per one tonne of TS was considered (personal communication). The inventory results for AD process are shown in Table 1.

2.6.4. Fermentation/downstream processes

After mechanical pretreatment seaweed slurry is used for bioethanol production in a SSF reactor at 32 °C in scenario 2. Inputs to SSF include the seaweed slurry and enzymes. The only polysaccharides hydrolyzable were assumed to be cellulose and laminarin, meaning that the commercial enzymes Celluclast 1.5 L, Novozyme 188, and Laminarinase are used for enzymatic hydrolysis (see Supplementary data S.4), while *Saccharomyces cerevisiae* is used as fermenting microorganism. Outflows from the fermentation/downstream separation processes were estimated based on mass balance calculations. Following SSF, the resulting ethanol broth is collected and sent to the downstream processing step. Data collection and assumptions for the downstream process were primarily retrieved from Luo et al. (2010) unless otherwise stated. Downstream separation consists of a vapour compression steam stripping (VCSS) unit operation with a heat exchange efficiency of 80% concentrating the ethanol to a value in the range 5–30% (w/w) depending on the ethanol concentration in the fermentor effluent. After this, a vapour compression distillation (VCD) unit operation is used to concentrate the ethanol up to 94% (w/w) (near the azeotrope – 95.6% (w/w)). A molecular sieve (MS) adsorption process unit is used for the final purification step to fuel grade ethanol ($\geqslant$99.7% (w/w)). The downstream separation process was assumed to recover 98% of ethanol from the effluent of the fermentor. The fuel grade bioethanol production was estimated to be 75 kg per one tonne of dry seaweed based on the carbohydrate content (cellulose and laminarin) in the seaweed (see Supplementary data S.4). The energy consumption during the fermentation process was mainly due to electricity consumption for stirring the fermentor and was retrieved from literature to be 0.056 MJ/MJ_{EtOH}. The energy demand for downstream processing was attributed to heat (steam) and electricity consumption. Heat consumption for VCSS and MS was assumed to be 0.161 and 0.056 MJ/MJ_{EtOH} respectively, while electricity use for VCSS and VCD was 0.051 and 0.067 MJ/MJ_{EtOH} respectively, resulting in an overall energy consumption for downstream separation process of 0.334 MJ/MJ_{EtOH}. Table 1 shows the inventory results for the fermentation/downstream processes.

2.6.5. By-products

2.6.5.1. Scenario 1 – digestate from AD. The fertilizing potential of the digestate with respect to N was estimated based on mass balance calculations for scenario 1. The fertilizing potential with respect to P and K were estimated based on ash composition of *L. digitata* (Ross et al., 2008). The nutrients recovered in the digestate were thus estimated to be 7.98, 8.75 and 36.6 kg of N, P, and K, respectively per one tonne of dry seaweed biomass.

2.6.5.2. Scenario 2 – anaerobic digestion of stillage (biogas + digestate). Based on mass balance calculations, the TS content in the stillage was estimated to be 891 kg per one tonne of dry seaweed for scenario 2. The gross methane production was estimated to be 86 m^3 per one tonne of dry seaweed using a methane yield of 0.15 LCH_4/g VS (Kerner et al., 1991). This results in a gross biogas production of 143 m^3 per one tonne of dry seaweed. Assumptions regarding biogas composition were identical to scenario 1. The energy consumption during the AD process was attributed mainly for heating the system at the desired temperature of 52 °C by burning part of the biogas produced. It was estimated through simulation that the stillage leaves the downstream separation process at around 40–50 °C after heat recovery, so that little energy input would be necessary to run the thermophilic fermentation. The feedstock is heated up from 40 to 52 °C, resulting in a heat consumption of 138 kW h per one tonne of dry seaweed. Electrical power consumption was considered as in scenario 1. The fertilizing potential of the digestate was estimated as in scenario 1 resulting in a nutrients recovery of 8.08, 8.75 and 36.6 kg of N, P, and K per one tonne of dry seaweed, respectively.

2.6.6. Biogas and bioethanol combustion

The gross energy production for scenario 1 was estimated to be 1320 kW h with an electricity production of 555 kW h while for scenario 2 the energy production from biogas combustion was estimated to be 855 kW h with an electricity production of 359 kW h per one tonne of dry seaweed, respectively. Data on air emissions from biogas combustion and exhaust emissions of the ethanol–petrol blend (E5) and fossil petrol were retrieved from EASEWASTE database (EASEWASTE, 2008) and Pelkmans et al. (2010), respectively (see Supplementary data S.5).

3. Results and discussion

3.1. Energy consumption

To optimize the process efficiency, the overall energy consumption can be disaggregated into different sub-processes to identify the energy intensive ones. The contribution of processing steps and energy sources to the total energy consumption reveal that mechanical pretreatment makes use of less than 5% of the total energy for each scenario (Fig. 2a). This is solely due to the electricity used for the milling/grinding equipment. The consumption of energy in the fermentation/downstream processes accounts for 21% (0.78 GJ) of the total energy consumption for scenario 2. Fermentation requires electrical energy for mixing the fermentors, while the downstream separation process makes use of steam for the VCSS and MSA as well as electricity for running the compressors for VCSS and VCD unit operations. Energy consumption for VCSS and MSA unit operations (in form of steam) corresponds to 0.43 GJ (0.216 MJ/MJ_{EtOH}), while the electricity consumption for VCSS and VCD corresponds to 0.24 GJ (0.118 MJ/MJ_{EtOH}) per one tonne of dry seaweed. With regards to energy sources, Fig. 3a shows that for both scenarios most of the energy is supplied through petrol, diesel and electricity. Petrol and diesel are used in grow-out phase steps during the seaweed production which accounts for 50–57% of the total energy demand (see Fig. 2a). This is in accordance to Pietrak and St. Peter (2011) who also showed that the most energy consuming step is seaweed production, accounting for 63% of the total energy consumption. Contributions of sub-processes to energy consumption during seaweed production are shown in Fig. 2b. Laboratory conditioning steps account for 5% of the total energy consumption, because these processes only involve the use of electricity for illumination and air pumping for approximately two months, while grow-out phase steps account for 95% of the total energy consumption due to diesel and petrol consumption as mentioned. Similarly, Pietrak and St. Peter (2011) concluded that the most energy intensive processes during the seaweed production are the land based-grow-out phase of the *Porphyra* – because of the significant electricity demand – and marine grow-out phase – because of the considerable maintenance needed. Table 2 summarizes the energy balance for analyzed scenarios. The total energy consumption was estimated to be approximately 4.28 and 3.70 GJ per one tonne of dry seaweed for scenarios 1 and 2 respectively. Part of this energy (1.84 and 0.50 GJ) is in form of heat recovered from the gas engine and recirculated back to heat the AD reactor. Therefore, the net energy consumption was 2.26 and 3.04 GJ per one tonne of dry seaweed for scenarios 1 and 2 respectively. The energy produced from scenario

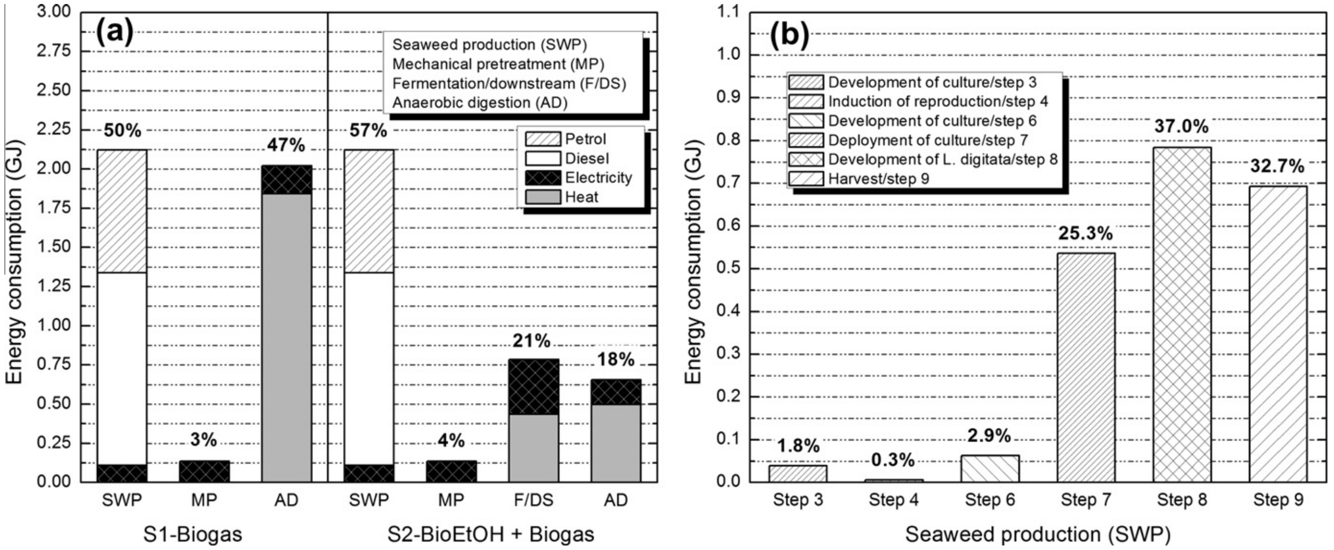

Fig. 2. Process contribution (absolute values in GJ, relative contributions in %) to energy consumption (a) for the analyzed scenarios and (b) during seaweed production.

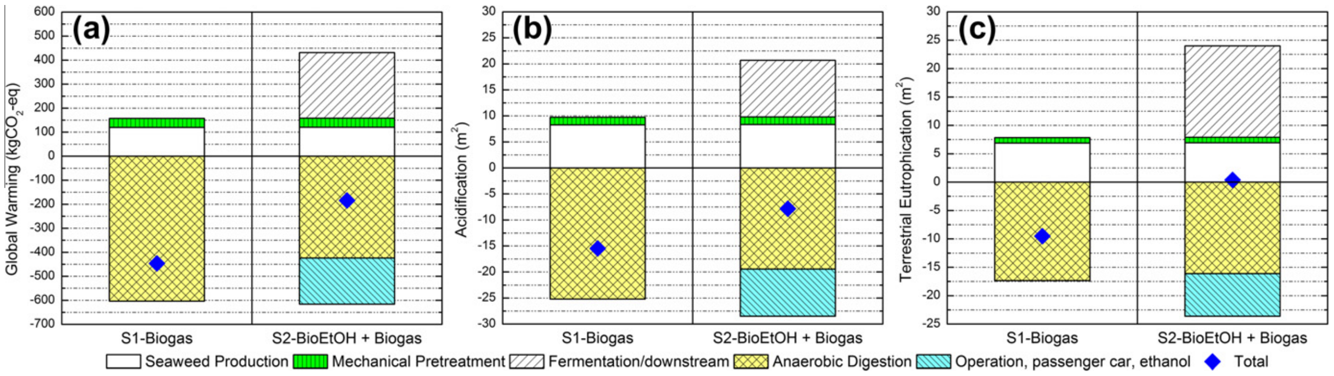

Fig. 3. Potential environmental impact on (a) Global Warming (kg CO_2-eq.), (b) Acidification (m^2) and (c) Terrestrial Eutrophication (m^2) for the baseline scenarios (one tonne of dry seaweed).

1 corresponded to production of 555 kW h (2.00 GJ) of electricity per one tonne of dry seaweed, because no heat from the gas engine was sold on the market. This amount of electricity delivered to the grid is lower than the energy consumption, making the energy balance negative. However, it should be noted that while energy input is mainly in form of liquid fuels, the output is electricity, which is an energy carrier of higher quality because of its higher exergy. This can be seen later in the CO_2 balance being negative. Similarly, the energy produced in scenario 2 was estimated to be 2.01 GJ per 75 kg of produced ethanol and 359 kW h (1.29 GJ) of electricity per one tonne of dry seaweed. This resulted in a total energy production of 3.30 GJ per one tonne of dry seaweed. Aizawa et al. (2007) estimated that the energy balance for seaweed-based ethanol was comparable with corn-based ethanol, with an overall 30% reduction of energy consumption compared to conventional gasoline. However, sufficient data were not provided by the authors to draw a thorough comparison with this study. In addition, it should be mentioned that the baseline scenarios defined in this study are based on the relative conservative assumption that heat is not utilized and no credits due to the sale of heat are considered. Nevertheless, in Denmark the heat produced from biogas combustion is often sold to local district networks or industries. The effect of this assumption is discussed in more detail in the sensitivity analysis section.

Table 2
Energy process balance for baseline scenarios referring to one tonne of dry seaweed.

		kW h	GJ
S1-biogas			
Consumption	Total energy	1189	4.28
Production	CH_4 (133 m^3)	1320	4.75
	Electricity from gas engine	555	2.00
	Heat from gas engine to AD reactor	512	1.84
	Total energy from gas engine	1067	3.84
	Net energy (electricity) to market	555	2.00
S2-bioethanol + biogas			
Consumption	Total energy	1027	3.70
Production	EtOH (75 kg)	557	2.01
	CH_4 (86 m^3)	855	3.08
	Electricity from gas engine	359	1.29
	Heat from gas engine to AD reactor	368	1.32
	Total energy from gas engine	727	2.62
	Net electricity to market	359	1.29
	Net energy to market (EtOH credits + electricity)	916	3.30

3.2. Environmental impact assessment

The following sections present results of the impact assessment as characterised potential impacts for three impact categories: Global Warming, Acidification and Terrestrial Eutrophication.

3.2.1. Global Warming

Seaweed production represents an important burden to Global Warming for both scenarios, while in the bioethanol scenario fermentation/downstream processes results in a larger contribution (Fig. 3a). Mechanical pretreatment has a minor role in both scenarios. As also indicated by the energy analysis, the large contribution from the seaweed production phase is related to consumption of fossil fuels for conducting operations, which results in CO_2 emissions. If only the seaweed production is considered including transportation and maintenance, approximately 176 kg of CO_2 are emitted to the environment due to the consumption of fossil fuels and electricity for conducting operations. Based on the average chemical composition of seaweed, one tonne of dry seaweed absorbs approximately 1137 kg of CO_2, during growth thus delivering a net total removal of 961 kg of CO_2 from the atmosphere (see Supplementary data S.6). On the other hand, production of biogas through anaerobic digestion (scenario 1) has important benefits for the Global Warming impact category, due to large savings linked to both the avoided fertilizer and energy production. In fact, 555 kW h of electricity per functional unit are recovered and delivered to the grid, thereby displacing coal-based marginal electricity production somewhere else in the energy system. In scenario 2, important benefits are seen from both the energy recovered from the stillage in AD and the use of seaweed-based bioethanol in fuel blend. Overall, Fig. 3a shows that scenario 1 has a better performance than scenario 2 with regards to Global Warming. The main factor seems to be the energy consumption for bioethanol downstream and purification process, which basically represents the difference between the overall net savings seen for scenarios 1 and 2 in Fig. 3a. This would suggest that further research may focus on improving this process. The downstream separation and purification was modelled considering a highly heat integrated process, meaning that improvements could be reached with higher concentrations of ethanol in the culture broth. Strategies to achieve this are, for example, related to design of novel microorganism capable of fermenting the sugar mix (five and six carbon sugars) in the culture broth and at the same time tolerate high ethanol concentrations.

3.2.2. Acidification

Fig. 3b presents contributions of different process steps to the Acidification impact category. Both scenarios result in a net savings in terms of environment impacts, mainly because of reduced NO_x and SO_x emissions delivered by the downstream processes. In both scenarios, the direct emissions are connected to the combustion of diesel and petrol during seaweed production and combustion of produced biogas, while in scenario 2 emissions are also associated with energy provision to the fermentation and downstream processes. Conversely, both electricity recovery from biogas and use of bioethanol in gasoline blend have important benefits, due to the emissions saved for coal-based electricity production and gasoline combustion respectively. The latter is due to the fact that combustion of gasoline generates larger emissions of NO_x compared to ethanol blend. Overall, scenario 1 seems to perform better than scenario 2, the difference being mainly due to the electricity and heat (steam) consumption for upgrading of bioethanol in the downstream processing step.

3.2.3. Terrestrial Eutrophication

Fig. 3c presents contributions of different process steps to the Terrestrial Eutrophication impact category. While scenario 1 resulted in a net saving, scenario 2 shows a net burden for the environment. The results are largely determined by the NO_x balance among upstream (e.g. electricity provision), direct (e.g. biogas combustion), and downstream (e.g. avoided energy production) emissions, as well as emissions of N and P from digestate applications, as also reported by Pietrak and St. Peter (2011). In spite of scenario 2 showing a net burden (Fig. 3c) due to the reasons mentioned, the use of seaweed could have other several benefits here not completely accounted for. Firstly, seaweed could potentially remove eutrophying elements (N and P) from the surrounding seawater during the growth phase. Based on the average composition of seaweed (see Supplementary data S.6), 21 kg of N and 8.75 kg of P will be removed from the seawater with every tonne of dry seaweed harvested. If N is taken as example, 3.15 kg of N will be removed from water with every tonne of wet seaweed harvested. The other benefit is related to the application of the digestate (N and P fixed in the seaweed) on land as fertilizer (scenario 1). There is, therefore, a great potential for the seaweed to function as a nutrient remover in the sea and as organic fertilizer supplier on land, meaning that at least a part of the P fertilizer lost to the sea could be potentially cycled back to land, with obvious benefits in term of environmental impacts and resource conservation. Overall, when comparing results for Eutrophication (Fig. 3c) with those for Acidification (Fig. 3b) and Global Warming (Fig. 3a), it can be seen that application of digestate represents a trade-off among the impact categories. While avoiding inorganic fertilizer production result in savings when considering Global Warming and Acidification, the application of digestate on land represent a burden to the environment in Terrestrial Eutrophication for scenario 2. This suggests that further research should aim at optimizing digestate application.

3.2.4. Sensitivity analysis

The purpose of the sensitivity analysis was to test the robustness of the results. Biofuel production from macroalgae is still at its initial stage, meaning that the presented results are based on data regarding processes still sub-optimized and/or under research. The following sensitivity tests were thus performed:

- The consumption of energy (both fuels and electricity) during the seaweed production phase was decreased by 10% in both scenarios to simulate more optimized operations.
- In scenario 1, the methane yield was increased by 10% and 42% compared to the baseline scenario, to assess the effect of improved AD process. In fact, Vivekanand et al. (2011) showed that when seaweed undergoes steam explosion (130 °C, 10 min) higher methane yields (0.285 L/g VS) can be achieved.
- The heat exchange efficiency of VCSS unit operation in scenario 2 is increased by 10%, again representing an improved process.
- The possibility of heat recovery and external heat sale is considered for the AD process in both scenarios. This was modelled using the ECOINVENT process "Heat, unspecific, in chemical plant/RER S" (Althaus et al., 2007).

The results of the sensitivity test are shown in Table 3. The decreased energy consumption during seaweed production improved the energy balance of both scenarios 1 and 2 by 10% and 7% respectively. All impact categories were affected by the change, as a consequence of decreased emissions of CO_2, NO_x and SO_2 especially during diesel and petrol combustion. The increased methane yield had large consequences on all impact categories, because of the increased savings in coal-based electricity production. By increasing the VCSS efficiency in the downstream separation for scenario 2, the energy balance was improved by 6%, because of decreasing use of steam for the downstream process (0.072 vs. 0.161 MJ/MJ_{EtOH}). Credits due to the sale of heat improved the energy balance of both scenarios 1 and 2 by 10% and 25% respectively. The total heat produced in scenario 1 corresponds to 568 kW h (2.04 GJ). Part of this heat 512 kW h (1.85 GJ) is used for heating requirements in the AD and the remaining 56 kW h (0.56 GJ) is assumed to be sold to a local industry. For scenario 2 the total heat

Table 3
Results of the sensitivity analysis.

Impact category	Baseline		Energy consumption in SWP		CH_4 yield		VCSS efficiency	Credits for selling heat	
			−10%	−10%	+10%	+42%	+10%		
	S1	S2	S1	S2	S1	S1	S2	S1	S2
Global Warming (kg CO_2-eq.)	−446	−184	−450	−188	−498	−667	−199	−466	−266
Acidification (m^2)	−15.45	−7.82	−16.00	−08.36	−17.10	−22.60	−08.38	−16.30	−11.50
Terrestrial Eutrop. (m^2)	−09.50	+0.39	−09.83	00.06	−09.88	−11.10	0.062	−10.01	−01.91

produced corresponds to 368 kW h (1.32 GJ) out of which 138 kW h (0.50 GJ) are to fulfill heat requirements in the AD and the excess 230 kW h (0.83 GJ) is sold to a local industry. The results of the sensitivity analysis confirm that the environmental footprint of the seaweed-based biofuels can be largely improved, especially considering that several processes could be optimized at the same time. The methane yield during AD seems to have especially high potential for improvements by pre-treating the seaweed prior to digestion. In alternative, selecting seaweed feedstock with high content of carbohydrate for biofuel production may also be desirable. This could be achieved by optimizing the cultivation procedure to increase the carbohydrate content or by harvesting the feedstock when it reaches the maximum carbohydrate content – late May–early July (Adams et al., 2011).

4. Conclusions

An LCA and an energy analysis to analyze two seaweed-based biofuel scenarios under development in Denmark were performed. For both scenarios, seaweed production was identified as the most energy intensive processing step throughout the life cycle (50–57%). Energy production delivered large savings (603 and 616 kg CO_2-eq. per one tonne of dry seaweed for S1 and S2, respectively) to the assessed systems. Results suggest that a production system prioritizing biogas production (S1) seems to be more favourable from an environmental point of view. Finally, the sensitivity analysis showed that the system has potential for technological development and consequently significant improvements.

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