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Energy performance and greenhouse gas emissions of kelp cultivation for biogas and fertilizer recovery in Sweden

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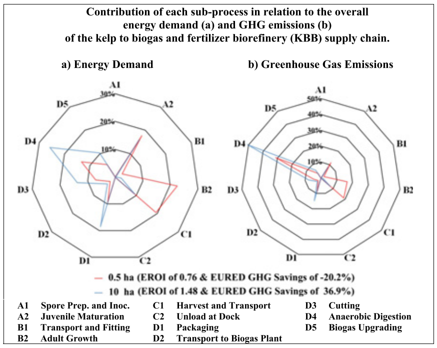
HIGHLIGHTS

- Analysis of Energy and GHG was conducted for a Swedish macroalgae supply chain.
- The effects of upscaling on the energy and GHG emissions performances are studied.
- Energy analysis was used to also identify potentials for economies of scale.
- At Sea processes were found to have the highest potential for economies of scale.
- Upscaled system surpassed break even energy return on investment and GHG savings.

GRAPHICAL ABSTRACT



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ABSTRACT

The cultivation of seaweed as a feedstock for third generation biofuels is gathering interest in Europe, however, many questions remain unanswered in practise, notably regarding scales of operation, energy returns on investment (EROI) and greenhouse gas (GHG) emissions, all of which are crucial to determine commercial viability. This study performed an energy and GHG emissions analysis, using EROI and GHG savings potential respectively, as indicators of commercial viability for two systems: the Swedish Seafarm project's seaweed cultivation (0.5 ha), biogas and fertilizer biorefinery, and an estimation of the same system scaled up and adjusted to a cultivation of 10 ha. Based on a conservative estimate of biogas yield, neither the 0.5 ha case nor the up-scaled 10 ha estimates met the (commercial viability) target EROI of 3, nor the European Union Renewable Energy Directive GHG savings target of 60% for biofuels, however the potential for commercial viability was substantially improved by scaling up operations: GHG emissions and energy demand, per unit of biogas, was almost halved by scaling operations up by a factor of twenty, thereby approaching the EROI and GHG savings targets set, under beneficial biogas production conditions. Further analysis identified processes whose optimisations would have a large impact on energy use and emissions (such as anaerobic digestion) as well as others embodying potential for further economies of scale (such as harvesting), both of which would be of interest for future developments of kelp to biogas and fertilizer biorefineries.

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1. Introduction

Third generation biofuels, from algae biomass, are now firmly considered one of the necessary contributors to a sustainable mix to meet future energy demands (Demirbas and Demirbas, 2010). The crucial advantage presented by third generation biofuels lies in the production of their feedstocks, principally microalgae, macroalgae or cyanobacteria (Rowbotham et al., 2012; Singh et al., 2011), e.g. through aquaculture, which does not add to competition for arable land nor to the demand for fresh water, fertilizers or pesticides for agriculture (Budarin et al., 2011; John et al., 2011; Singh et al., 2011), as opposed to first generation feedstocks (Giampietro and Mayumi, 2009). However in practice, the challenges associated with large-scale macroalgae cultivations at sea coupled with the challenges of handling large volumes of marine biomass have lead to questions being raised on its viability as a feedstock at commercial scales (Aitken et al., 2014).

Aquaculture of aquatic plants is a well-established industry and one of the fastest growing production sectors, with a global average growth of 7.7% annually since 1970 (FAO, 2011), however in the EU it has remained more or less stagnant. As a result from the European Union Commission's call to develop bioeconomy strategies for Europe (EC, 2012), the Swedish Research Council (FORMAS) funded Seafarm project set out in 2014 to foster research around a cultivated *Saccharina latissima* (henceforth *S. latissima*) biorefinery supply-chain to develop and assess the viability of marine biomass based socio-economic utilization strategies for Sweden, or as the EU Commission refers to it, the viability of blue growth strategies (EC, 2014). The potential for seaweed aquaculture to participate toward blue growth strategies are now regarded as significant for coastal communities and the European bioeconomy (Rebours et al., 2014).

Previous viability studies on marine biomass utilization for bioenergy include, Blaas and Kroeze (2014); Budarin et al. (2011); Gao and McKinley (1994); Rebours et al. (2014); Ross et al. (2008) and within the Baltic area, Risén et al. (2013) and Seghetta et al. (2014), who specifically looked at the viability of biofuels by conducting energy analyses in light of GHG savings and using energy input-output based indicators, such as energy return on investment (EROI). The study of Seghetta et al. (2014) investigated the production of bioethanol from wild kelps harvested in eutrophic waters, by accounting for direct and indirect energy outputs (bioethanol yield) and inputs (harvesting & bioethanol production processes), using an energy systems diagram (Odum, 1972) and EROI (Murphy and Hall, 2010) as an indicator of energy performance. Rather than focus on the harvesting of kelps for biofuels, Risén et al. (2013) looked at the harvest of wild reeds in shoreline areas of the Baltic Sea and investigated the bioenergy production and GHG savings from such a venture. However, while both of these papers focused more on the potential of eutrophication countermeasures of these bioenergy production systems from the harvest of *wild* stocks, neither considered the *cultivation* of marine biomass.

This study aimed to perform a systems analysis of a cultivated kelp to biogas and fertilizer biorefinery (hereafter KBB) based on the Seafarm supply chain in the perspective of energy and GHG emission performances, in support of future decision making and to shed light on the viability of scaled up kelp cultivations and third generation biofuel biorefineries in a Swedish context. Specific objectives were to:

- Produce an energy systems diagram of the KBB supply chain;
- Establish the viability of the 0.5 ha case and of an explorative 10 ha scale-up, both from an energy input-output and GHG emissions savings perspectives; and
- Identify the specific processes and system inputs that hinder commercial viability (EROI of 3), from an energy and GHG perspective.

2. Methodology

2.1. Study site

At the crossroads between the salty, nutrient rich waters of the North Sea and the shallow brackish Baltic Sea, the West Coast ecotone is amongst the most biodiverse marine habitats in Sweden (Garpe, 2008). There is a long tradition of marine research in the Skagerrak that, amongst other things, has shown that of all Swedish waters the Skagerrak has the highest prevalence and diversity of macroalgae (as summarized by Blidberg et al., 2012). In 1996 it was estimated that as much as 10% of this population was *S. latissima* (Karlsson, 2007), which is the cultivated species in this study.

The Seafarm pilot cultivation site employed in this study is located on the Swedish West Coast (Fig. 1), approximately 20 km from the Norwegian border. Sheltered from storms, with adequate currents, salinity and suitable water depths for the cultivation infrastructure, the area meets all the basic requirements for aquaculture following the criteria laid out by Lindahl et al. (2005). The cultivation sites are within 5 km of the University of Gothenburg's Sven Lovén Centre for Marine Sciences, Tjärnö, where much of the practical aspects of seaweed production - juvenile hatchery, cultivation preparation, monitoring and harvesting - are undertaken by the Seafarm project. The flows of biomass through the planned Seafarm process/supply chain are outlined in Fig. 2.

Following several deployments of longlines over an area of 0.5 ha, the first successful harvest of cultivated seaweed biomass was made in the early summer of 2015 (to reduce fouling by bryozoans). A gradual expansion of this pilot cultivation is scheduled over the coming years to continue paving the way for this new industry in Sweden, but also to shed light on questions surrounding cultivation spatial/temporal scales, notably about environmental impacts, practical aspects, economies of scale and to identify the principle hurdles for commercialisation. The authors of the present study estimate that a 10 ha cultivation would be representative of a basic commercial scale. As such, a hypothetical 10 ha exploratory scale-up (here after “10 ha estimates”) of the Seafarm system is used in this study to shed light on the commercialization of KBB systems on the Swedish West Coast. Where system processes of the 0.5 ha Seafarm system were neither realistic nor feasible at a 10 ha scale or where economies of scale would be achieved (shaded processes in Fig. 2), processes in the 0.5 ha case were adapted to suit the larger scale (see Section 3.1 for the resulting adaptations to processes). For example, while a 0.5 ha harvest may be loaded onto a small tugged barge with a 30 ton loading capacity, 10 ha worth of harvest would overload this capacity or require ten return trips, thus a much larger 120 ton barge was proposed for the 10 ha estimates. On the other hand, in the case of scalable processes, these were simply multiplied by a factor of twenty to account for the larger 10 ha estimates. For example, the cultivation longlines for the 0.5 ha configuration total 1000 m in length, thus 20,000 m of longline was necessary for the 10 ha estimates.

2.2. System description

To perform the systems analysis, the authors followed the standardized energy systems language (Brown, 2004; Brown and Ulgiati, 2004; Odum, 1972). The Seafarm 0.5 ha case was inventoried using case data (e.g. measurements, invoices and technical specifications) from Seafarm partners and industrial contacts; the 10 ha estimates were constructed therefrom. As defined by the European Union Renewable Energy Directive or EURED (EC, 2010) and exemplified by Alberici and Hamelinck (2010), the permanent infrastructure of the KBB system was excluded both from the GHG savings and energy analyses in this study.

The timeframe for the study was over one cultivation season. Both the 0.5 ha case and 10 ha estimates were analysed as cradle to gate systems (see supplementary material B & C), including biogas and fertilizer production from the cultivated biomass described in Section 2.1 (see

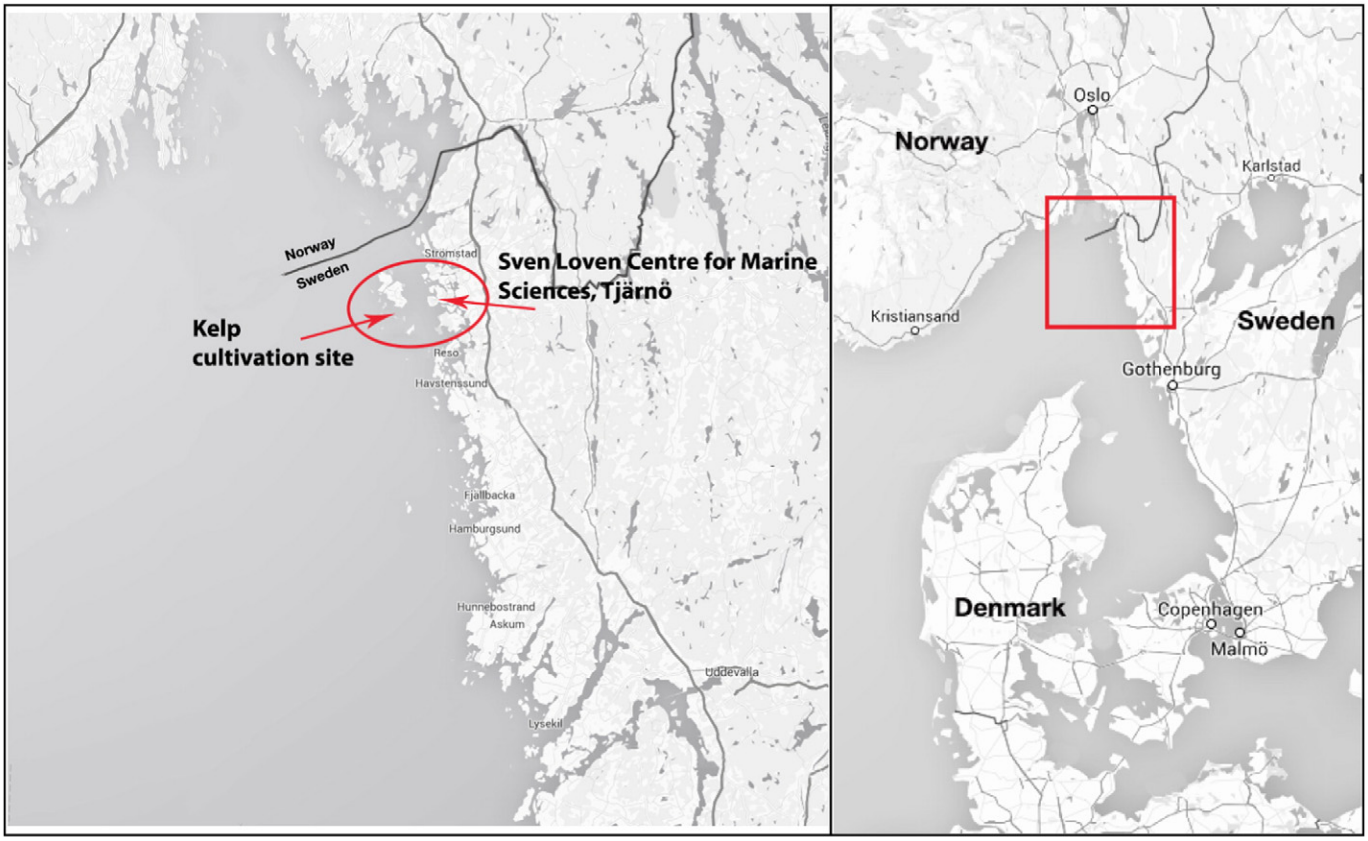

Fig. 1. Location of the 0.5 ha kelp cultivation site currently operated within the Seafarm project.

Supplementary material C & D). The biogas production facility was assumed to be located 10 km from the dock based on their location on the Swedish West Coast (Biogasportalen, 2015; Statens Jordbruksverk, 2011) and given that transport is not considered a sensitive parameter in energy balance calculations of biogas production systems (e.g. Berglund and Börjesson, 2006; Pöschl et al., 2010; Risén et al., 2014). Further definition of system boundaries relating specifically to the energy analysis or GHG savings analysis, are addressed in their relevant following Sections 2.3 and 2.4.

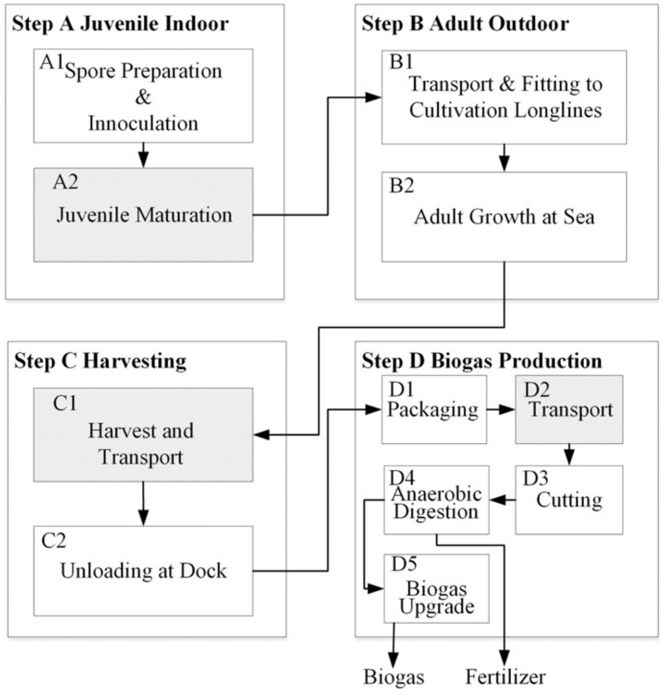

Fig. 2. An overview of the kelp to biogas and fertilizer biorefinery (KBB) process/supply chain with the arrows demonstrating the flow of the biomass within the system. Shaded boxes represent processes that are modified from the 0.5 ha to 10 ha scale systems.

Moreover, as suggested by Carlsson and Schnürer (2011) a realistic scaled up co-digestion only yields approximately 35–90% of the yields achieved in flask experiments under laboratory conditions. Based on this, coupled with the known minimum biogas yield achieved during the experiments, the authors opted for a conservative 40% of the maximum biogas yield obtained in the preliminary lab experiments for the base case. Sensitivity analysis was also conducted across the range from 10 to 100% of the biogas yield obtained in the experiments. The digestate yield from the anaerobic digestion process was estimated as 80% of the volume of the feedstock material (Risén et al., 2013) where the volume reduction is caused by formation of CO_2 and CH_4.

2.3. Energy analysis

This study employs an energy analysis as defined by the International Federation of Institutes for Advanced Study (IFIAS), which is the procedure to calculate the primary energy input to a system for the production of goods and services. Following IFIAS (1978), primary energy was determined from the total direct and indirect energy demand of a given process or system, where direct energy refers to *direct energy inputs*, such as fuel to power processes, and where indirect energy encompassed all required *energy to produce inputs* to the processes. In this study, the primary energy input was calculated by coupling each input of the system with a specific primary energy conversion factor identified in literature. For instance, in the Seafarm supply chain, the spore inoculation process requires paper towels. Thus, the energy used to produce that paper (Klugman, 2008) was included in the energy analyses as an indirect energy input. All other energy and material inputs of the system were handled in the same manner (Supplementary material C and D).

Following the accounting of all direct and indirect energy inputs to the system, the output side of the balance was determined from the biogas and the biofertiliser products. Anaerobic digestion of wild kelp from the same location as the Seafarm was undertaken in biomethane potential experiments (BMP). The amount of biogas produced and its methane content was measured. The BMP experiments were performed to evaluate the total methane potential of the substrate.

However, while biogas is an energy product in itself, biofertiliser is not and a method was required to allow the embodiment of its energy value in the calculation. As exemplified by Risén et al. (2013) systems expansion was applied instead of allocating energy output between end products, where the biofertiliser energy content was calculated from the indirect energy content of Nitrogen (N) and Phosphorus (P) in artificial fertilizer, following e.g. Berglund and Börjesson (2006); Börjesson and Berglund (2006), and Ahlgren et al. (2012), that would *not* be used due to its replacement by the digestate (biofertiliser).

Using all the collected input data (see Table 1 and the Supplementary material), the energy performance was evaluated following IFIAS (1978) to shed light on the viability of the KBB supply chain from an energy perspective. Three separate aspects of the energy performance were investigated: the energy return on investment (EROI), reliance on direct fossil fuel inputs, and identification of the most energy intensive processes in the KBB supply chain. EROI was defined by Murphy and Hall (2010) as shown in Eq. (1).

$$EROI = \frac{\text{Total Energy Output of the System}}{\text{Total Direct and Indirect Energy Input to the System}} \tag{1}$$

EROI studies in the past have yielded conflicting results (Bardi et al., 2011; Mulder and Hagens, 2008) and as a result the EROI standard framework (Atlason and Unnthorsson, 2014; Hall et al., 2014; Mulder and Hagens, 2008; Murphy et al., 2011) is now commonly applied, in line with IFIAS primary energy input standards. Thus, this framework was applied in this study, similarly to Seghetta et al. (2014).

The output from any EROI study is the ratio of all output energy to all primary input energy. Thus, an EROI >1 means that the system "produces" more energy than it "consumes" (see Eq. (1)). Wider debates have been initiated in the literature regarding the minimum acceptable EROI values for fuels to be considered useful by society at large (Hall et al., 2009). The most commonly accepted EROI is 3, as established by Hall et al. (2009).

Table 1
Case specific data obtained from the Seafarm project and industry for the 0.5 ha case.

Value	Unit	Description	Facility
4	Weeks	Indoor cultivation period	Indoor kelp farm
0.00167[a]	m^3/s	Iwaki MX400 magnetic water pump velocity	
0.324[a]	MJ/h	Hailea HAP120 air pump power	
1500[a,k]	m	Polypropylene string for seeding of kelp	
0.0014[b]	kg/m	Weight of polypropylene string	
15[a,g]	coils	Number of seeded polypropylene string coils	
0.3[a]	kg	1 roll of paper towel for spore preparation	
0.1[a]	m^3	Seawater for spore preparation and inoculation	
0.077[a]	m^3/week	Weekly seawater used per tank for juvenile growth	
2[a]	Tanks	Number of tanks used for juvenile growth	
16[a,g]	Bulbs	Total Osram T12 fluorescent bulbs required	
0.027[a]	MJ/h	1 Osram T12 model LSA65W/640 electrical demand	
504[a]	Hours	Total number of hours of artificial lighting	
1.5[c]	MJ/h	Electricity needed to keep 10 m^2 room at 10 °C	
1[a,h]	Room	Number of rooms needed for indoor cultivation	
0.0005[a,i]	ton N/m^3	Nutrient requirement	
0.00005[a,i]	ton P/m^3	Nutrient requirement	
8	Months	Outdoor cultivation period	Outdoor kelp farm
0.015[a]	m^3/return trip	Gasoline required for a small outboard boat	
0.09[d]	m^3/h	Diesel consumption of a small tug boat	
18.5[d]	km/h	Maximum speed of tug boat with barge	
10[a]	km	Distance between indoor and outdoor farm	
11.3–13.8[a,j]	wwt ton	Biomass harvested from 1 cultivation season	
1[e]	wwt ton/m^3	Density of harvested kelp biomass	
22[e]	% dwt kelp	Percentage dry weight of harvested kelp	
55[f]	MJ/m^3	Electricity demand per m^3 wet biomass	Biogas plant
123[f]	MJ/m^3	Heat demand per m^3 wet biomass	
1.33[f]	MJ/m^3	Upgrade electricity demand per m^3 crude biogas	
21.3	kg N/ton dwt	Approximate amount of Nitrogen in biomass[k]	
7.9	kg P/ton dwt	Approximate amount of Phosphorus in biomass[k]	
77[b]	% VS	% volatile solids of *Saccharina latissima* (wild)	
180[b]	Nm^3 CH_4/ton VS	Approx. biogas yield of *Saccharina latissima* (wild)	

Information source:
[a] Authors operated a 4-week indoor and an 8-month 0.5 ha outdoor kelp cultivation farm.
[b] Author's measurements. Regarding the biogas, experience has shown 35–90% of the total methane potential obtained in BMP experiments to be realistic in full-scale (Carlsson and Schnürer, 2011). Therefore, a conservative 40% of the measured methane potential 440 Nl CH_4/kg VS was used in the calculations.
[c] Pers. comm. Francks Kylindustri which specializes in industrial cooling.
[d] Pers. comm. Jenkins Marine which specializes and provides coastal workboats and barges.
[e] Pers. comm. Joakim Olsson of Chalmers University of Tech. (kelp pretreatment under the SEAFARM project).
[f] Pers. comm. Västerviks Miljö & Energi AB producing biogas from Swedish fish waste.
Additional information:
[g] 10 coils of seeded string and 8 fluorescent bulbs per tank (Flavin et al., 2013; Redmond et al., 2014).
[h] A 10 °C maintained 10 m^2 room can hold at least 6 tanks.[a]
[i] Following Provasoli's medium formulation (Flavin et al., 2013; Redmond et al., 2014).
[j] Biomass yield was between 11.25 and 13.75 kg wwt biomass per 1 m polyester longline where 1 m polyester longline requires 1.5 m polypropylene string seeded (0.5 ha cultivation requires 1000 m polyester longlines).[a]
[k] N and P measured by Kjehldahl method and ICP-AES respectively.

2.4. Greenhouse gas emission estimates

For a biofuel to be considered as a viable alternative to fossil fuels in the European Union, certain requirements must be fulfilled amongst which are specific GHG emission saving targets (EC, 2010; Rana et al., 2016). Specifically, the EURED requires GHG emission savings of 60% by January 2018 for new plants, relative to a gasoline fossil reference, f_{ref}, comparator with 83.8 g CO2eq/MJ, following the procedure exemplified by Alberici and Hamelinck (2010). This study included calculations to determine the emission savings of the KBB system, and thus to establish the viability of kelp biogas as an alternative to fossil fuels and to identify the emission intensive parts of the supply chain.

The primary data inputs for the GHG calculations were predominantly supplied by the Seafarm project. The system boundaries extend using the same framework as that used for the energy analysis: to cover material and energy inputs of the supply chain processes, and their embodied emissions, following Alberici and Hamelinck (2010). Emissions of supply chain processes were also included, such as the methane leakage during biogas upgrading. The allocation for bio-fertilizer emission savings were handled in the same way as during the energy analysis: emissions from the production of artificial fertilizers that are *not* used are subtracted from the total emissions.

EURED proposes two methods for the conversion of GHG emissions into CO2 equivalents: the use of standardized EURED *default* conversion values; and *actual* conversion values as provided by literature or measurement (EC, 2010). In this paper, the actual conversion values were applied. For example, the heating requirements for the anaerobic digestion phase were provided by district heating (pers. comm. Västervik AB) and converted to CO2 equivalents using the conversion values (see Supplementary material) from the actual Swedish case (Gode et al., 2011).

With the total emissions accounted for in CO2 equivalents according to the EURED, the emissions savings as specified in Alberici and Hamelinck (2010) were calculated as follows:

$$GHG_{savings} = \frac{f_{ref} - (Net\ GHG\ Emissions\ in\ gCO2eq/MJ\ Energy\ Ouput)}{f_{ref}} \times 100 \tag{2}$$

In addition to the EURED GHG savings, the estimated GHG emissions of the KBB system pinpointed the emission intensive processes in the supply chain, which is also of particular value to future supply chain optimization.

3. Results and discussion

3.1. Systems analysis of the kelp to biogas and fertilizer biorefinery (KBB)

All process data for the Seafarm KBB supply chain (0.5 ha case) was collected from Seafarm partners and industry contacts (see Table 1) and is presented in Fig. 3 using the standard energy systems language (Brown, 2004; Odum, 1972; Odum and Peterson, 1996), where all material inputs are positioned to the left, all energy/fuel inputs are positioned on top, and the output products are to the right. Step A1 involves the sexual reproduction of the kelps and the attachment of the juveniles to plastic seeding lines, comprising preparation of kelp spores and inoculation in a nutrient rich, saline solution. A2 is distinguished as the phase of indoor maturation of juvenile kelps until they reach 1 to a few mm in length. A2 lasts 4 weeks and requires the maintenance of optimal growth conditions through the pumping of air, artificial lighting, cooling, addition of nutrients, and the pumping/filtering of sea water.

Step B1 involves the transport of the juveniles out to sea and their deployment on the cultivation infrastructure; B2 is the adult growth phase, which lasts from the end of autumn until early summer and requires regular monitoring. Step C1 comprises the harvest of the adult kelp using a tugged barge and subsequent transportation back to land (see Table 1 for specific characteristics of the harvested biomass); while C2 involves the unloading of the biomass at a dock. Step D encompasses the energy intensive biogas and fertilizer production: the packaging in plastic (D1), 10 km of transport by truck (D2), cutting (D3) of the biomass, the thermophilic anaerobic digestion (D4), and biogas upgrading (D5), which includes the transport to nearby farms (10 km) and spreading onto a field using agricultural machinery.

As mentioned in Section 2.1, where system processes of the 0.5 ha case were neither realistic nor feasible at a 10 ha scale, or where economy of scale was expected, large scale processes were adapted to suit the larger scale. Table 2 presents a comparison at both scales of the adapted process elements that did not scale up proportionally. All other material or energy inputs to the 10 ha case are multiplied by a factor of 20 from the 0.5 ha case input data. One of the main differences to be observed

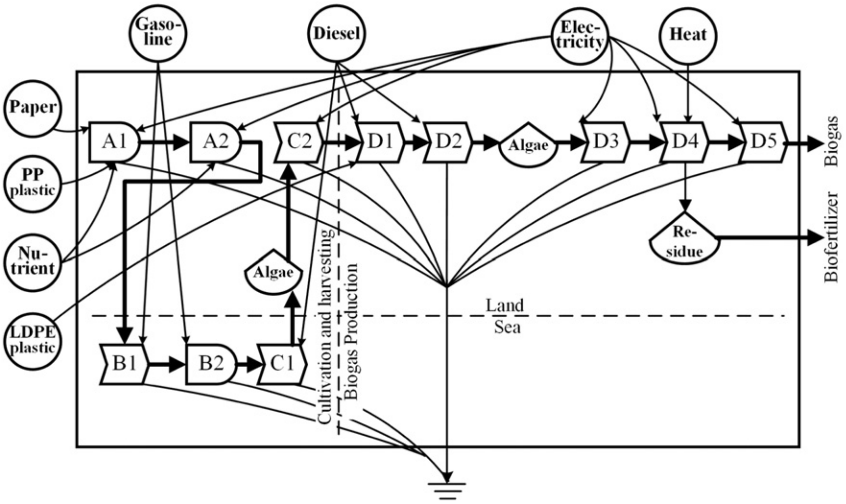

Fig. 3. Energy systems diagram of the kelp to biogas and fertilizer biorefinery (KBB) supply chain, where steps A, B, C and D refer to the processes demonstrated in Fig. 2. The horizontal dotted line differentiate the processes conducted on land and at sea. The vertical dotted line differentiate the biogas production processes and the cultivation and harvesting processes.

from Table 2 regards the differences in barges and tugboat fuel consumption: much less energy per kilo of harvested biomass is consumed at the large scale when compared with the smaller 0.5 ha scale.

3.2. Energy analysis and greenhouse gas emissions

3.2.1. Energy return on investment

As can be seen from Table 3 and following a conservative 40% of the laboratory maximum biogas yield (see Section 2.2), the EROI value for the 0.5 ha case is below 1 meaning that more energy is consumed than is produced by the system, while the 10 ha estimates EROI value is above 1 meaning that somewhat less energy is consumed than is produced by the system. An EROI > 1 for the 0.5 ha case is only attainable if at least 60% of the maximum laboratory biogas yield is achieved. Neither the Seafarm case nor the scale up estimates achieved the value of 3 (even at 100% biogas yield) recommended as a benchmark in the "Law of minimum EROI" Hall et al. (2009), however economies of scale seem to be raising the EROI as the system is scaled up.

3.2.2. Greenhouse gas emissions

The estimated CO_2 emissions for both the 0.5 ha and 10 ha systems are presented in Table 3. For the 0.5 ha case, the KBB system performs worse than the EURED gasoline with a mean savings of −25% relative to this reference. However, in the 10 ha estimates, the mean savings are 33% relative to the EURED gasoline, which is a considerable improvement. However, at 33% GHG savings, the 10 ha estimates still does not meet the 60% GHG savings target set in this study, and as required by the EURED for new biofuel plants by January 2018.

3.3. Implications for commercialization

3.3.1. Energy efficiency

Fig. 4a presents the shares of energy input as a percentage of the total for each step (A1-D5) in the KBB supply chain, both for the 0.5 ha case and 10 ha estimates. For the 0.5 ha case (experimental scale, red line in Fig. 4a), the main energy demand is associated with Step B2 (adult growth), followed by C1 (harvest and transport) and A2 (juvenile maturation). However, as revealed by comparing the red (0.5 ha case) and blue (10 ha estimate) curves in Fig. 4a, key differences emerge between the two scales; specifically, these differences occurred in Step B2, monitoring of the adult growth (22% share at 0.5 ha versus 2% share at 10 ha) and Step C1, the mature kelp harvest (19% share at 0.5 ha versus 9% share at 10 ha).

The substantial difference in the shares of total input energy for Step B2 between the scales is due to the fact that while total energy inputs increase significantly with the scale up, this particular process remains almost identical at both scales, with the same number of 20 km return trips (and thus fuel use) to monitor the kelp farms. The differences in the shares of total input energy for Step C1 result from process adjustments in the scale up of operations: the small harvest vessel of the 0.5 ha case was not suitable to handle the estimated 10 ha biomass yield, thus a larger vessel configuration was required.

Table 2
Specific information used for energy analysis of the 0.5 ha case and 10 ha estimates.

Process elements that do not scale proportionately	Step	0.5 ha case	10 ha estimate	Units
Number of 20-gal aquariums	A	2	30	Tanks
Weekly water volume	A	0.15	2.3	m^3
Light bulb quantities	A	16	240	Bulbs
Number of chilled rooms	A	1[a]	5[a]	Rooms
Fuel consumption of tugboats	C	0.09[b]	0.18[c]	m^3/h
Number of return trips for harvest	C	1[d]	2–3[d]	Trips
Number of transporting trucks[e] (from packaging to biogas plant)	D	1	14–18	Trucks

[a] 1 room can fit 6 twenty-gallon aquariums, each holding 10 coils (each coil has 100 m seed-string) and is air pumped using Hailea HAP120.

[b] 14.7 m Length-overall tugboat (without crane) pulling a barge (pers. comm. Jenkins Marine).

[c] 19.8 m Length-overall tugboat (with crane) pulling a barge (pers. comm. Jenkins Marine).

[d] Barge loading capacity of 120 tons. However the loading capacity for the 0.5 ha case is reduced due to the limited power of the smaller tugboat (pers. comm. Jenkins Marine).

[e] Or number of return trips if only 1 truck is available.

Table 3
Energy consumption and production of GHG emissions per one cultivation season and the associated biomass storage and utilization in the KBB supply chain.

	Energy demand (GJ)		GHG emissions (ton CO_2eq)	
	0.5 ha case	10 ha estimate	0.5 ha case	10 ha estimate
[A1] spore prep. & inoc.	0.01	0.01	1×10^{-5}	1×10^{-5}
[A2] juvenile maturation	3.5	32	0.2	1.9
[B1] transport & fitting	0.6	0.6	0.04	0.04
[B2] adult growth	4.5	4.5	0.3	0.3
[C1] harvest & transport	3.9	20	0.4	1.8
[C2] unloading at dock	0.01	0.1	3×10^{-4}	0.006
[D1] packaging	1.9	38	0.2	3.4
[D2] transport	0.5	7.7	0.04	0.7
[D3] cutting	1.4	28	0.09	1.8
[D4] anaerobic digestion	2.7	53	0.6	12
[D5] biogas upgrading	1.1	21	0.06	0.9
Total Energy inputs	20.1	206	–	–
GHG emissions	–	–	1.9	23
Energy output	15	306	–	–
Fertilizer[a]	2.2	44	0.3	6.5
EROI	0.76	1.48	–	–
GHG savings (%)[b]	–	–	−20	37

[a] The digestate is used as fertilizer and therefore substitutes commercial fertilizer.

[b] Relative to the EURED's GHG-emissions-for-gasoline reference value.

As Fig. 4a portrays the percentage energy consumption, the steps that show less economy of scale than e.g., B2 and C1, become more predominant for the larger scale. Thus, for the 10 ha estimate, step D4 (anaerobic digestion) followed by D1 (packaging) and A2 (juvenile maturation) were predicted to be the dominant energy consumers. Hence, our model indicates that overall step D is the most energy intensive at the large scale, and thus further research should aim to improvements to step D.

A step with relatively large shares of energy input at both scales is the indoor maturation phase (A2). The relatively high-energy use at both scales is partly due to the need for continuous lighting, cooling, pumping and water filtration, but also that this process takes 4 weeks to nurture the juveniles. This highlights the need to explore energy reduction strategies in A2. As also suggested by Philippsen et al. (2014), a reduction in energy investments of the aforementioned processes, for instance by using LED lights or efficient water coolers, could lead to improvements in the EROI.

Our results suggest that spore preparation and inoculation (A1), transport and deployment to longlines (B1), unloading at dock (C2), transport by truck (D2), cutting of algae (D3), and biogas upgrading (D5) are marginal (below 5%) energy consumers at both scales.

3.3.2. GHG emissions efficiency

Fig. 4b visualizes the relative GHG emissions of each step (A1-D5) of the KBB supply chain as a percentage, both for the 0.5 ha case (red curve) and 10 ha estimate (blue curve). The thermophilic anaerobic digestion step (D4) is by far the most intensive in terms of emissions at both scales. This is a result of the large volumes of biomass being heated for anaerobic digestion by district heating, which on average in Sweden is produced from approximately 61% non-renewable sources, including coal, oil, natural gas, wood and peat, amongst others (Gode et al., 2011). Less carbon rich sources for the district heating, the use of low-carbon electricity to heat the biomass, or heat recirculation following e.g.,

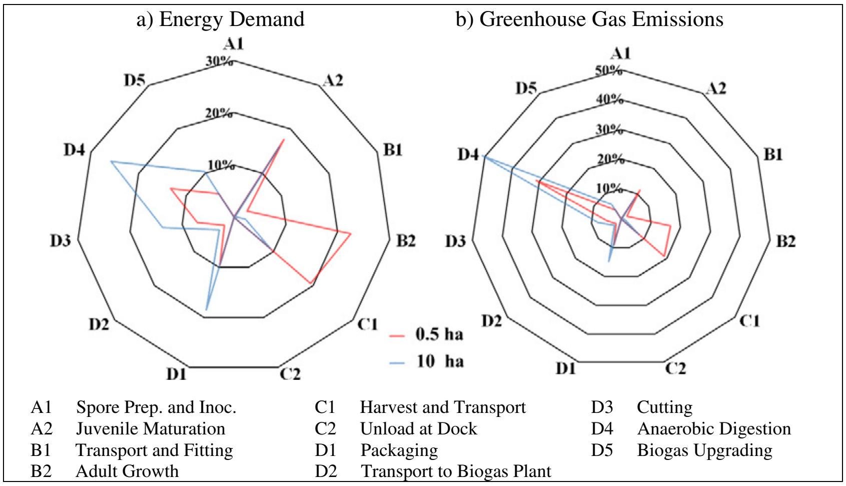

Fig. 4. Contribution of each sub-process in relation to the overall energy demand (a) and GHG emissions (b) of the kelp to biogas and fertilizer biorefinery (KBB) supply chain.

Risén et al. (2013) could reduce the emissions of D4 and therefore have a positive impact on the overall emissions.

Another pattern with important implications for commercialisation is the packaging step (D1), which shows a substantial increase in its share of emissions, from 9% at 0.5 ha to 14% at 10 ha. Coupled with a similar increase in energy demand with the scale-up, this relative increase in emissions in packaging highlights the need to use lower emission and energy demand alternatives, particularly at larger scales.

Similarly to in Fig. 4a, key differences emerge between the two systems in Fig. 4b in the steps that occur at sea, specifically B2 and C1, also due to differences in harvesting vessel configurations and the similarity of the monitoring processes at both scales. Finally, Fig. 4b also highlights the marginal relative emissions (below 5%) of a majority of the steps - A1, B1, C2, D2, D3, and D5 in the 0.5 ha case and A1, B1, B2, C2, D2 and D5 in the 10 ha estimates – which are dwarfed by the anaerobic digestion (D4) at both scales. However, perhaps the most important implication for commercialisation is that both “per kg of harvested biomass” and “per Nm^3 of biogas”, upscaling from a 0.5 ha to a 10 ha cultivation halves both the energy demand and GHG emissions of the KBB supply chain (Table 4).

In other words, a KBB supply chain capable of handling more biomass to produce more product (scaled up) will potentially have lower emissions and energy demand, per product unit, than a smaller KBB supply chain. This finding supports the notion that upscaling operations pushes the system in the direction of commercial viability, as defined by EROI and the EURED GHG savings requirements for biofuels.

The results presented up to here were based on a conservative estimate of 40% biogas yield at full scale digestion as compared to small scale laboratory experiments (see Section 2.2). Alternatively considering an optimistic biogas yield value of 90% (Fig. 5a and b), rather than 40%, resulted in an EROI of c.a. 1.5 for the 0.5 ha and c.a. 2.7 for the 10 ha, and CO2 emissions reduction potentials of c.a. 38% for the 0.5 ha and c.a. 66% for the 10 ha. These results are not only an indication of the high sensitivity of the model output to uncertainties in this particular input number, but also an indication of the potential for a 10 ha cultivation feeding into a KBB supply chain to be commercially viable, both in terms of EROI and in terms of EURED regulations, given an effective biogas production process. This highlights the need for large scale digestion and co-digestion studies with seaweed biomass, to more accurately discern just how much biogas can be produced.

3.4. Comparison to literature values

Energy analysis using EROI as an indicator can provide a holistic impression of viability (Hall et al., 2009) but only a few studies of this nature have been conducted for marine bioenergy production systems. As discussed by Risén et al. (2013), comparison between similar studies remain difficult due to differences in system design, boundaries and methodological approaches; See Table 5 which presents these differences relative to this work.

Particular strengths of the present study relative to other studies in Table 5 are that the majority of input data comes directly from the Seafarm project, that the scaled up supply chain is modelled directly from case data, and that the selected methodologies align with official standards and regulations in Sweden. While the use of case data for Sweden provides quality inputs for the calculations, it also reduces the relevance of the results for other locations: for instance, the Swedish energy mix is different to that in Scotland or in France, and so replicating this study using case data from different locations may substantially affect results.

4. Conclusions

This study represents the first assessment of commercial viability, in terms of energy return on investment and emissions savings potential, of a kelp to biogas and fertilizer biorefinery supply chain located on

Table 4
Overview of the total energy demand and GHG emissions for the kelp to biogas and fertilizer biorefinery supply chain for the 0.5 ha case and the scaled up 10 ha estimates.

	Per ton biomass harvested		Per Nm^3 biogas produced	
	Energy demand (GJ)	GHG emissions (ton CO_2eq)	Energy demand (GJ)	GHG emissions (ton CO_2eq)
0.5 ha case results	1.7	0.15	0.06	0.005
10 ha estimates results	0.9	0.09	0.03	0.003
Limits to achieve targets[a]	0.4[b]	0.04[b]	0.01[b]	0.001[b]

[a] The energy demand and GHG emissions should not be higher than these limits if EROI > 3 and GHG savings of 60% were to be achieved. These limits are relative to the known energy outputs of the system.

[b] At this limit, EROI = 3, and GHG savings = 60%.

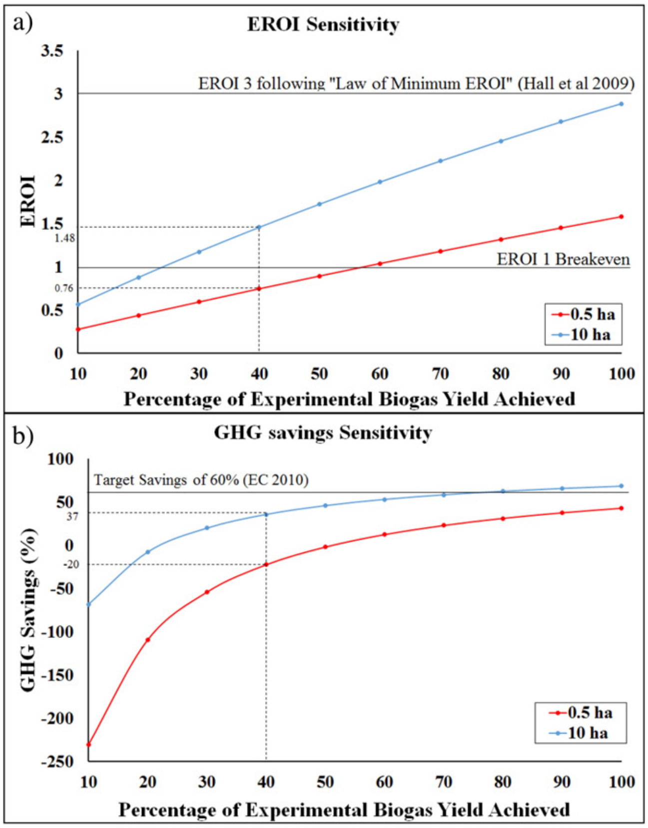

Fig. 5. Sensitivity results for EROI (a) and GHG Savings (b) based on the varying achievable biogas yield (10%–100%). Pre-set EROI and GHG savings targets applied (solid black lines) are also presented along with the 40% biogas yield (dotted black lines) used in the evaluation of EROI and GHG savings for this study are presented.

the Swedish West Coast. Commercial viability was defined as reaching an energy return on investment value of 3 (Hall et al., 2009) and achieving the GHG savings potential required under the European Union Renewable Energies Directive (EC, 2010), or EURED. Two scales of operation were considered: the existing 0.5 ha Seafarm project longline cultivation of *S.latissima* and a set of estimates for a 10 ha scale-up, to shed light on economies of scale and to identify specific processes in need of further development.

Using a conservative estimate for the biogas yield (40% of experimental yield), neither the 0.5 ha case nor the 10 ha estimates reached the target minimum EROI of 3. The EROI value for the 0.5 ha case was below 1, meaning that more energy was consumed than produced by the system, while the 10 ha estimate EROI value was slightly above 1, meaning that only a little less energy was consumed than produced by the system. An optimistic biogas yield (90% of experimental yield) however, at 10 ha revealed an EROI of 2.6 and GHG savings potential above the 60% target. Analysis of the scale up identified processes in need of improvements, such as anaerobic digestion and potential for economies of scale, such as in the at sea processes, both worthy of further investigation.

In terms of GHG emissions savings potential, both the 0.5 ha case and 10 ha estimates fell short of the 60% savings target set by the EURED (EC, 2010) under the conservative estimate of biogas yield. While the 0.5 ha case performed worse than the EURED fossil reference, the 10 ha estimate performed 30% better. Analysis of the scale up also indicated clear improvements and potential for economies of scale worthy of further investigation; based on this model, a 10 ha cultivation of kelp for a biogas and fertilizer biorefinery would approached the emissions savings targets defined in the EURED under beneficial biogas production (digestion/co-digestion) conditions.

Finally, regarding commercialisation, the results of this study confirm that upscaling of operations shifts the kelp to biogas and fertilizer biorefinery system in the direction of viability, as defined by EROI and the EURED GHG savings requirements for biofuels. Specifically, scale up of the system from 0.5 ha to 10 ha cultivation configurations lead to a halving of net energy requirements and GHG emissions.

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Table 5
Literature results for EROI and GHG savings from studies of bio-energy production (and co-products) from some sea-based biomasses.

	This Study		Risén et al. (2013)[a]	Risén et al. (2014)	Seghetta et al. (2014)	Aitken et al. (2014)	Philippsen et al. (2014)
	0.5 ha	10 ha					
Type of analysis	Energy, ghg savings, scale-up model		Energy, GHG savings, N&P recovery	Energy, exergy, scenario	Energy, emergy, growth model	Life cycle analysis[b]	Energy, GHG emissions, cost analysis
Location	Swedish west coast (Skagerrak)		Swedish east coast (Baltic Sea)	Swedish south coast (Baltic Sea)	Danish Koge Bay (Baltic Sea)	Chilean coast (Pacific)	Canadian coast (Gulf of Alaska)
Biomass type	Brown algae		Reed	Red algae	Brown algae	Brown algae	Brown algae
Species	*Saccharina latissima*		*Phragmites australis*	*Polysiphonia fucoides*	*Pylaiella sp. & Ectocarpus sp.*	*Macrocystis pyrifera*	*Saccharina latissima*
Biomass source	Cultivated		Wild[a]	Wild[a]	Wild[a]	Cultivated	Cultivated
Scale	0.5 ha	10 ha	–[a]	–[a]	–[a]	100 ha	Not available
Energy product	Upgraded fuel (from biogas)		Heat and upgraded fuel (from biogas)	Heat and electricity or upgraded fuel (from biogas)	Fuel (from bioethanol)	Heat and electricity (from biogas)	Bioethanol blended with fuel
Co-products	Fertilizer		Fertilizer	Fertilizer	–	Fertilizer	Animal feed
EROI target	3[c]		1[d]	1[d]	1[c]	3[c]	1[e]
EROI result	0.76[c]	1.48[c]	3.1[d]	2.7–3.8[d,f]	0.4[c]	0.98[c]	1.7[e]
EURED GHG savings	−20%	37%	80%	–	–	–	–

[a] These studies do not consider cultivation. Therefore, scales are not comparable with this study.
[b] Other previous LCA studies (e.g. Langlois et al., 2012) have not been considered due to the lack of clarity in either the case study description or energy analysis standards employed.
[c] EROI method used following Murphy and Hall (2010).
[d] Evaluated with energy input-output ratio (IOR) defined in Pöschl et al. (2010), which is an inverse of EROI.
[e] EROI method used but no referenced standard provided.
[f] Scenario and product dependent (Risén et al., 2014).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.07.220.

References

Ahlgren, S., Baky, A., Bernesson, S., Nordberg, Å., Norén, O., Hansson, P.-A., 2012. Consequential life cycle assessment of nitrogen fertilisers based on biomass–a Swedish perspective. Insur. J. 2, 80–101.

Aitken, D., Bulboa, C., Godoy-Faundez, A., Turrion-Gomez, J.L., Antizar-Ladislao, B., 2014. Life cycle assessment of macroalgae cultivation and processing for biofuel production. J. Clean. Prod. 75, 45–56.

Alberici, S., Hamelinck, C., 2010. Annotated Example of a GHG Calculation Using the EU Renewable Energy Directive Methodology. European Comission, London, United Kingdom.

Atlason, R., Unnthorsson, R., 2014. Ideal EROI (energy return on investment) deepens the understanding of energy systems. Energy 67, 241–245.

Bardi, U., Lavacchi, A., Yaxley, L., 2011. Modelling EROEI and net energy in the exploitation of non renewable resources. Ecol. Model. 223, 54–58.

Berglund, M., Börjesson, P., 2006. Assessment of energy performance in the life-cycle of biogas production. Biomass Bioenergy 30, 254–266.

Biogasportalen, 2015. Svenska anläggningar [Biogas plant in Sweden]. Energigas Sverige, Stockholm,Swedenhttp://www.biogasportalen.se/BiogasISverigeOchVarlden/Anlaggningskarta.aspx#lan=VästraGötalandslän (Access Date March 14th 2016).

Blaas, H., Kroeze, C., 2014. Possible future effects of large-scale algae cultivation for biofuels on coastal eutrophication in Europe. Sci. Total Environ. 496, 45–53.

Blidberg, E., Gröndahl, F., Cahill, B., Koreiviene, J., Belous, O., Shabayeva, D., 2012. Macroalgae Harvesting and Cultivation. In: Schultz-Zehden, A., Matczak, M. (Eds.), SUBMARINER Compendium: An Assessment of Innovative and Sustainable Uses of Baltic Marine Resources. Maritime Institute of Gdansk, Gdansk, Poland, pp. 49–76.

Börjesson, P., Berglund, M., 2006. Environmental systems analysis of biogas systems—part I: fuel-cycle emissions. Biomass Bioenergy 30, 469–485.

Brown, M.T., 2004. A picture is worth a thousand words: energy systems language and simulation. Ecol. Model. 178, 83–100.

Brown, M.T., Ulgiati, S., 2004. Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems. Ecol. Model. 178, 201–213.

Budarin, V.L., Zhao, Y., Gronnow, M.J., Shuttleworth, P.S., Breeden, S.W., Macquarrie, D.J., Clark, J.H., 2011. Microwave-mediated pyrolysis of macro-algae. Green Chem. 13, 2330–2333.

Carlsson, M., Schnürer, A., 2011. Handbok Metanpotential (Handbook Methane Potential). Svenskt Gastekniskt Center AB, Malmö, Sweden.

Demirbas, A., Demirbas, M.F., 2010. Algae Energy: Algae as a New Source of Biodiesel. Springer-Verlag, London, United Kingdom.

EC, 2010. Communication from the commission on the practical implementation of the EU biofuels and bioliquids sustainability scheme and on counting rules for biofuels. European Commission 2010/C 160/02 (Ed.).

EC, 2012. Innovating for sustainable growth: a bioeconomy for Europe. Directorate-General for Research Innovation (Ed.). Publications Office of the European Union, Brussels.

EC, 2014. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions: Innovation in the Blue Economy: realising the potential of our seas and oceans for jobs and growth. European Commission (Ed.), Brussels.

FAO, 2011. World Aquaculture 2010. Food and Agriculture Organization of the United Nations, Rome, Italy, p. 4.

Flavin, K., Flavin, N., Flahive, B., 2013. Kelp Farming Manual a Guide to the Processes, Techniques, and Equipment for Farming Kelp in New England Waters. Ocean Approved, LLC, Portland, ME, United States of America.

Gao, K., McKinley, K.R., 1994. Use of macroalgae for marine biomass production and CO2 remediation: a review. J. Appl. Phycol. 6, 45–60.

Garpe, K., 2008. Ecosystem Services Provided by the Baltic Sea and Skagerrak. Naturvårdsverket (Swedish Environmental Protection Agency), Bromma, Sweden.

Giampietro, M., Mayumi, K., 2009. The Biofuel Delusion: The Fallacy of Large Scale Agro-biofuels Production. Routledge (Taylor Francis Group), United Kingdom.

Gode, J., Martinsson, F., Hagberg, L., Öman, A., Höglund, J., Palm, D., 2011. Miljöfaktaboken 2011-Uppskattade emissionsfaktorer för bränslen, el, värme och transporter (Estimated Emission Factors for Fuels, Electricity, Heat, and Transport in Sweden). Värmeforsk Service AB, Stockholm, Sweden.

Hall, C.A., Balogh, S., Murphy, D.J., 2009. What is the minimum EROI that a sustainable society must have? Energy 2, 25–47.

Hall, C.A., Lambert, J.G., Balogh, S.B., 2014. EROI of different fuels and the implications for society. Energ Policy 64, 141–152.

IFIAS, 1978. International federation of institutes for advanced studies workshop report, energy analysis and economics. Resour. Energy 1, 151–204.

John, R.P., Anisha, G.S., Nampoothiri, K.M., Pandey, A., 2011. Micro and macroalgal biomass: a renewable source for bioethanol. Bioresour. Technol. 102, 186–193.

Jordbruksverk, S., 2011. Skörd för ekologisk och konventionell odling 2011 Spannmål, trindsäd, oljeväxter, matpotatis och slåttervall Slutlig statistik [Production of organic and non-organic farming 2011 Cereals, dried pulses, oilseed crops, table potatoes and temporary grasses Final statistics]. Statens Jordbruksverk (Ed.). Statistika Centralbyrån [Statistics Sweden], Sweden.

Karlsson, J., 2007. Övervakning av vegetationsklädda hårdbottnar vid svenska västkusten 1993–2006 (Biodiversity of the West coast report 1993–2006). Naturvårdsverket (Swedish Environmental Protection Agency). Göteborg University, Sweden.

Klugman, S., 2008. Energy Systems Analysis of Swedish Pulp and Paper Industries from a Regional Cooperation Perspective: Case Study Modeling and Optimization. Department of Management and Engineering. Linköping University, Sweden.

Langlois, J., Sassi, J.-F., Jard, G., Steyer, J.-P., Delgenes, J.-P., Hélias, A., 2012. Life cycle assessment of biomethane from offshore-cultivated seaweed. Biofuels Bioprod. Biorefin. 6, 387–404.

Lindahl, O., Hart, R., Hernroth, B., Kollberg, S., Loo, L.-O., Olrog, L., Rehnstam-Holm, A.-S., Svensson, J., Svensson, S., Syversen, U., 2005. Improving marine water quality by mussel farming: a profitable solution for Swedish society. AMBIO 34, 131–138.

Mulder, K., Hagens, N.J., 2008. Energy return on investment: toward a consistent framework. AMBIO 37, 74–79.

Murphy, D.J., Hall, C.A., 2010. Year in review—EROI or energy return on (energy) invested. Ann. N. Y. Acad. Sci. 1185, 102–118.

Murphy, D.J., Hall, C.A., Dale, M., Cleveland, C., 2011. Order from chaos: a preliminary protocol for determining the EROI of fuels. Sustainability 3, 1888–1907.

Odum, H.T., 1972. An energy circuit language for ecological and social systems: its physical basis. In: Patten, B.C. (Ed.), Systems Analysis and Simulation in Ecology Vol. 2. Academic Press, New York, USA, pp. 139–211.

Odum, H.T., Peterson, N., 1996. Simulation and evaluation with energy systems blocks. Ecol. Model. 93, 155–173.

Philippsen, A., Wild, P., Rowe, A., 2014. Energy input, carbon intensity and cost for ethanol produced from farmed seaweed. Renew. Sust. Energ. Rev. 38, 609–623.

Pöschl, M., Ward, S., Owende, P., 2010. Evaluation of energy efficiency of various biogas production and utilization pathways. Appl. Energy 87, 3305–3321.

Rana, R., Ingrao, C., Lombardi, M., Tricase, C., 2016. Greenhouse gas emissions of an agro-biogas energy system: estimation under the renewable energy directive. Sci. Total Environ. 550, 1182–1195.

Rebours, C., Marinho-Soriano, E., Zertuche-González, J.A., Hayashi, L., Vásquez, J.A., Kradolfer, P., Soriano, G., Ugarte, R., Abreu, M.H., Bay-Larsen, I., 2014. Seaweeds: an opportunity for wealth and sustainable livelihood for coastal communities. J. Appl. Phycol. 26, 1939–1951.

Redmond, S., Green, L., Yarish, C., Kim, J., Neefus, C., 2014. New England Seaweed Culture Handbook-Nursery Systems. Connecticut Sea Grant Connecticut, USA.

Risén, E., Gregeby, E., Tatarchenko, O., Blidberg, E., Malmström, M.E., Welander, U., Gröndahl, F., 2013. Assessment of biomethane production from maritime common reed. J. Clean. Prod. 53, 186–194.

Risén, E., Tatarchenko, O., Gröndahl, F., Malmström, M.E., 2014. Harvesting of drifting filamentous macroalgae in the Baltic Sea: an energy assessment. J. Renewable Sustainable Energy 6, 013116.

Ross, A., Jones, J., Kubacki, M., Bridgeman, T., 2008. Classification of macroalgae as fuel and its thermochemical behaviour. Bioresour. Technol. 99, 6494–6504.

Rowbotham, J.S., Dyer, P.W., Greenwell, H.C., Theodorou, M.K., 2012. Thermochemical processing of macroalgae: a late bloomer in the development of third-generation biofuels? Biofuels 3, 441–461.

Seghetta, M., Østergård, H., Bastianoni, S., 2014. Energy analysis of using macroalgae from eutrophic waters as a bioethanol feedstock. Ecol. Model. 288, 25–37.

Singh, A., Nigam, P.S., Murphy, J.D., 2011. Renewable fuels from algae: an answer to debatable land based fuels. Bioresour. Technol. 102, 10–16.