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

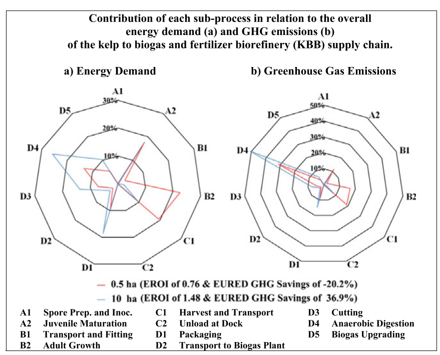
Joseph S. Pechsiri [a,*], Jean-Baptiste E. Thomas [a], Emma Risén [a,b], Mauricio S. Ribeiro [a], Maria E. Malmström [a], Göran M. Nylund [c], Anette Jansson [d], Ulrika Welander [d], Henrik Pavia [c], Fredrik Gröndahl [a]

[a] Industrial Ecology, Department of Sustainable Development, Environmental Science and Engineering (SEED), KTH Royal Institute of Technology, Teknikringen 34, 10044 Stockholm, Sweden
[b] Currently at Sweco Environment AB, Gjörwellsgatan 22, Stockholm, Sweden
[c] Department of Marine Sciences - Tjärnö, University of Gothenburg, SE-452 96 Strömstad, Sweden
[d] School of Built Environment and Energy Technology, Linnæus University, SE-351 95 Växjö, Sweden

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.

* Corresponding author.
E-mail address: pechsiri@kth.se (J.S. Pechsiri).

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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