Configuring the Future Norwegian Macroalgae Industry Using Life Cycle Analysis

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Abstract. The continuous increase in global population and living standards, is leading to an increase in demand for food and feed resources. The world's oceans have the largest unlocked potential for meeting such demands. Norway already has an extensive aquaculture industry, but still has great ambitions and possibilities to develop and expand this industry. One of the important topics for improving the value chain of Norwegian aquaculture is to secure the access to feed resources and to improve the environmental impacts. Today, most of the feed-protein sources used in aquaculture are imported in the form of soy protein. The research project Energy efficient PROcessing of MACroalgae in blue-green value chains (PROMAC) aimed, among other research questions, to investigate cultivated seaweeds as a potential raw material for fish feed. This paper assesses Life Cycle Analysis (LCA)-perspectives of scenarios for future seaweed production of feed-protein for fish and compares this with today's situation of imported soy protein for fish feed. The insights from the LCA are very important for the configuration of the entire production value chain, to ensure that the environmental aspects are taken into account in a holistic fashion.

Keywords: LCA · Macroalgae · Bio-economy · Seaweed and soy protein

1 Introduction

As the world population is projected to reach 9.8 billion in 2050, feeding this population implies an increase in food production by at least 70% [1]. Today, only approximately 2% of food originates from the oceans [2]. Therefore, attention has been drawn to the oceans as the largest unlocked potential to meet these demands for food production. Norway is the second largest exporter of seafood in the world, and still has ambitions to develop and expand this industry. However, these ambitions also have to comply with the increasing environmental awareness of the public and the consumers, and the increasing environmental regulations imposed by the policymakers. Previous studies utilizing Life Cycle Assessments (LCAs) show that the fish feed is the main

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driver for environmental impacts within the Norwegian aquaculture industry [3]. One of the main ingredients in the fish feed used in Norway, is Soy Protein Concentrate (SPC), which is by far the largest source of protein used by the Norwegian aquaculture industry [4]. Norway imported approximately 360 000 tons of SPC for fish feed in 2013, from which roughly 80% originated from Brazil [5]. This strong link to the Brazilian soy industry is quite problematic for the Norwegian aquaculture industry, since it is heavily associated with deforestation, ecosystem degradation, resource depletion and major Greenhouse Gases (GHG) emissions [6].

The challenge of accessing sustainable protein sources for a continuous rising demand, has partly led to the growing interest of developing new and innovative industries within the bio-economy in Norway. The research project PROMAC, funded by the Norwegian Research Council, is one of these projects – focusing on new marine value chains. More specifically, PROMAC aims to investigate seaweeds (or macroalgae) as novel raw materials for human food and feed applications. One of the objectives in this project was to visualize and analyze the economic and environmental impacts of the entire value chain of the cultivated and processed seaweed. The aim of this work was also to identify ways of improving the production system, so that seaweed protein can be economic and environmentally attractive for aquaculture feed production.

Against this backdrop, this paper aims to present the theoretical approaches made to analyze the future Norwegian macroalgae industry – using LCA methodology. The main contribution of this paper, is to integrate the entire value chain, from cradle to gate, with scenarios for full industrial implementation – not just case studies of certain aspects of the value chain. This gives valuable insight in terms of configuration of technologies, for a viable sustainable production system.

The paper proceeds as follows. We commence by presenting the goal and scope of performing LCA analysis where the system boundaries, the functional unit, and the assumptions made for the scenarios of the future industry are discussed. We then present some preliminary results. Finally, we discuss the findings and provide an outline for further research.

2 Goal and Scope

The overall goal for performing this analysis is to provide insight and documentation that can serve as decision support for the process of facilitating and developing the future Norwegian macroalgae industry.

2.1 System Boundaries and Functional Unit

The functional unit was chosen so that our analysis could serve as a valuable comparison. The function that we want to compare between the soy and the seaweed production system was the amount of proteins delivered for the feed production. Hence, our functional units were set to be 1 ton of SPC and 1 ton Seaweed Protein Concentrate (SWPC). Here, it is important to mention that the crude protein content of SPC is 62% [3], while the crude protein content of SWPC is roughly 31% [7]. Thus, by adjusting our results accordingly, we will need 2 tons of SWPC to deliver the same amount of protein as 1 ton SPC.

The LCA performed is a cradle to gate-LCA. This means that we include the production from the beginning of the value chain, and stop when the product has reached the stage of our functional unit – SWPC. Figure 1 shows which main steps of the value chain are included in the analysis. "Seaweed hatchery" describes the laboratory stage of our value chain, which includes the cultivation of gametophytes and sporophytes. Energy consumption for heat and lighting, and infrastructure are the main contributors to the impacts from this stage. "Deployment and growth at sea" describes the transportation of seeded ropes from the laboratory to the docks by truck, and transport/deployment of the cultivation system into the ocean using boat. Here, direct energy consumption related to transport and deployment, and the cultivation infrastructure (ropes and buoys) - are the most important drivers. "Harvesting, transportation" is basically the opposite stage of the previous one, except here you transport all the full-grown biomass instead of the seeded rope structures. When harvested, the biomass is cut from the ropes and transported in bulk. The direct energy consumption related to harvesting and transportation are the most important drivers of this process. "Preservation, storing" describes the most energy intensive process of the value chain [8] – including the drying of the seaweed. Natural gas is used as the energy source for the drying in our LCA model. "Processing" describes the process of transforming and extraction of proteins, yielding the finished product, the SWPC.

Three different species of macroalgae were investigated in the PROMAC project, but for the LCA – the main focus was directed towards *Saccharina latissima*, since this species is the most suited for industrial cultivation.

Fig. 1. The steps of the macroalgae industry-value chain included in the LCA

2.2 Scenarios for Industrial Implementation

The aim of this study is to look at life cycle perspectives of the future Norwegian macroalgae industry. Since this industry is still at a very novel stage, scenarios were made to represent the different levels and scale of implementation of this industry. The different scenarios are configurated using a combination of state-of-the-art knowledge from the literature [9, 10] and the most up-to-date available technologies within the industry. The major difference between the scenarios, is the deployment at sea - which areas are adopted, how large areas are adopted in total, and transportation solutions for these alternatives. The main characteristics of the different cultivation scenarios are shown in Table 1. This table shows for each scenario - number of locations, are per location in hectare, yield – in ton wet weight (ww) biomass per hectare, production per location – in ton wet weight biomass, and total annual production per scenario in ton wet weight biomass.

The first scenario, the "Solund example" is our reference scenario - describing today's situation. This scenario utilizes data collected from a facility at the west coast of Norway (Solund) that belongs to one of the partners in the PROMAC project – Hortimare AS. This facility – and company, is at the very front of the technology development within macroalgae cultivation. This facility utilizes a relatively small cultivation area – 1 hectare (ha) - and with a yield of 60 tons ww biomass per ha, this gives an annual production of 60 tons ww.

The second scenario entails integration of seaweed cultivation at every already existing fish farming site in Norway. Integrated multi-trophic aquaculture (IMTA) builds on the concept from nature, where byproducts and biological waste – in this case excess feed and excrements from the fish farming - serve as nutrients for the seaweed. There are currently 1132 active fish farming sites in Norway, and with 2, 5 ha for seaweed cultivation per location and a yield of 60 tons ww biomass per ha, this would result in a total annual production of 170 000 tons.

The third scenario involves cultivation of the same total annual production as the IMTA-scenario, but with fewer and larger sites. Seaweed Energy Solutions (SES) is another company that is a partner in the PROMAC project. They have concession for cultivation on a site with the size of 32 ha. With cultivation sites this size, 90 locations are needed to produce the same annual biomass as in the IMTA-scenario.

In the fourth scenario, we really scale up. We assume that most fish farm sites in Norway (1000) integrates seaweed cultivation on an area of 100 ha each. This scenario yields a total annual production of 6 000 000 tons ww biomass.

In the fifth scenario, six large-scale offshore cultivation sites are imagined. These sites will have an area of 13 300 ha each, and produce 75 tons ww per ha. The total annual production volume would be the same as in scenario 4: 6 000 000 tons ww biomass.

Table 1. Cultivation scenarios

Scenario	Number of locations	Area per location [ha]	Yield [t ww/ha]	Production per location [t ww]	Total annual production [t ww]
1. Solund example	1	1	60	60	60
2. IMTA at every fish farm	1132	2.5	60	150	170 000
3. SES-size	90	32	60	1 900	170 000
4. Most fish farms	1000	100	60	6 000	6 000 000
5. Large scale	6	13 300	75	1 000 000	6 000 000

2.3 Data Quality

The data used in the LCA is compiled from several sources. Empirical data has been collected in collaboration with industry partners and research divisions with industry experience. This has then been combined with data from literature and generic data from the LCA databases GaBi Professional and ecoinvent. The scenarios for industrial upscaling and implementation have been built up using today's available technologies where applicable, and combined with assumptions for technology development for the future seaweed industry.

3 Results

The LCA results show how the five main cultivation scenarios perform, compared to the modeled SPC production (See Fig. 2). Additionally, we show the results for the reference scenario (Solund example), where excess heat from a waste incineration plant has been adopted for the drying seaweed. In this scenario, no environmental impact was allocated from the incineration of waste, but the otherwise lost energy from the incineration is exploited for drying. We can see that the total impact is reduced, as the scope of the industrial scenario increases in production volume. This reduction is mainly due to more effective transportation solutions and reduced transportation distances for the harvested biomass.

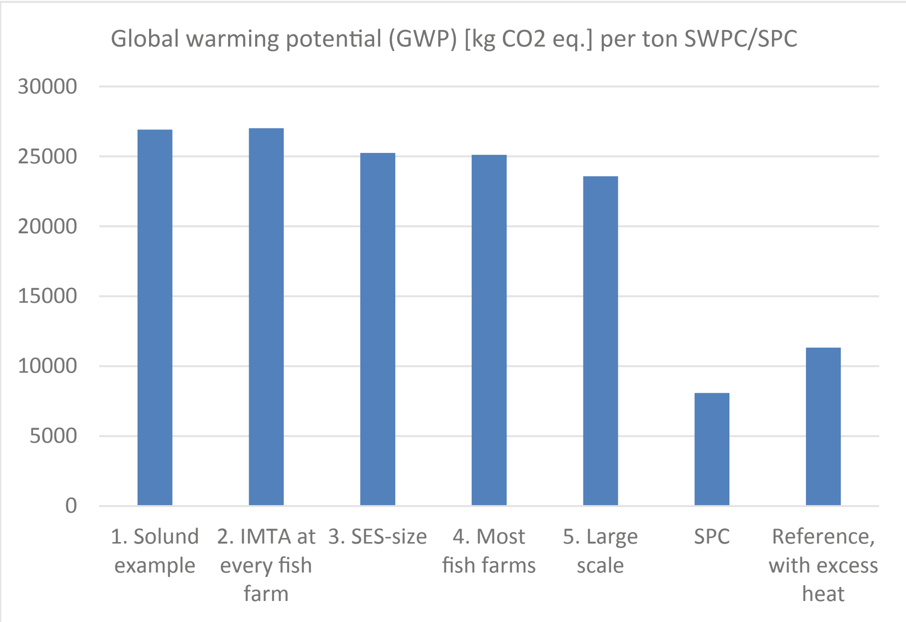

Fig. 2. Global warming potential (GWP) for the five different cultivation scenarios, SPC production and an alternative version of scenario 1.

Figure 3 shows how the environmental impacts in terms of GWP are distributed among the main steps of the value chain. The reference scenario – "Solund example" - is used for this example. We see that the drying of the biomass is by far the most intensive step of the value chain. Deployment represents the process with second most impacts, followed by harvesting. We see that the hatchery and processing steps of the value chain have minimal impacts compared to the rest.

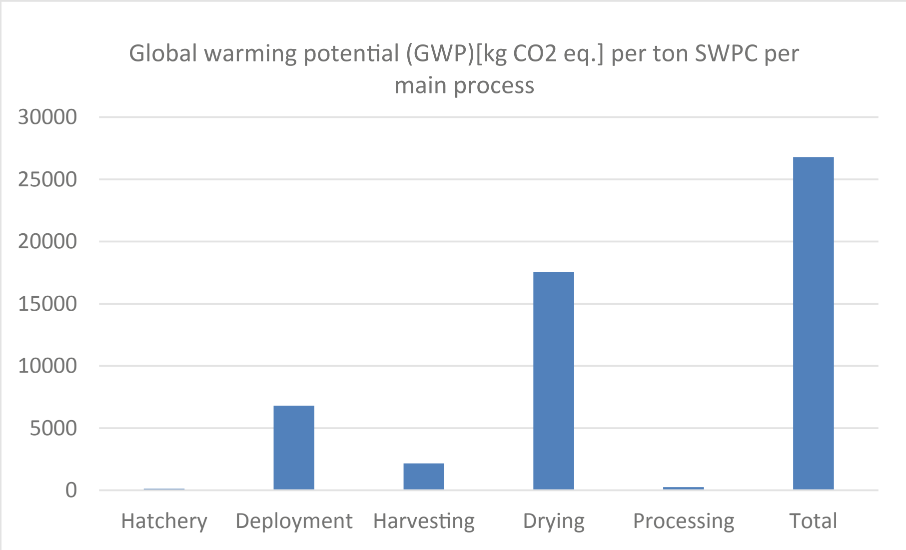

Fig. 3. Global warming potential (GWP) for the reference scenario (Solund example), shown per main step of the value chain.

4 Discussion

As we can see from the results presented in Fig. 2, SWPC still has some challenges in terms of environmental performance, compared to SPC. This is mainly due to the drying and extraction process, which is challenging and energy demanding for SWPC relative to SPC, as SWPC consists of 85%–90% water and only about 10% of the dry matter is protein. However, as the interest in macroalgae, and demand for alternative food and feed ingredients increases, continuous effort and research will be put into this topic, and technologies can develop fast.

One of the most important stages of the value chain is the preservation of the biomass after it is harvested. The biomass is quite delicate and needs to be handled carefully to avoid loss of valuable compounds. This challenge increases as the production volumes goes up, and the biomass needs to be handled in bulk. Different technological solutions to this challenge has been considered and tested, and there are several dedicated research projects focusing on this. Ensilage, freezing and refrigerated seawater storage are among the solutions that are investigated. Development of technological solutions in this stage are also important to expand the operating window of biorefineries that utilize the biomass, to not only operate seasonally when the biomass is fresh and newly harvested.

Another important element to consider is the fact that in parallel with the focus on the development of this industry for utilizing macroalgae for food and feed purposes, there are several other application areas for seaweeds. Within pharmaceutical and cosmetics industries, the potential is enormous, as macroalgae contain several high value compounds that already have a very high demand. As the processing technologies develop, it will be easier to extract more valuable compounds of the seaweeds, making it easy to allocate and justify the environmental effects of the industry.

This study and these preliminary results have their clear limitations. This industry is still only in the starting blocks, and major technology development should therefore be expected in the near future. In this study, many assumptions have been made, in terms of completing compilation of the data. This has been dealt with – combining methodology and inventory data uncertainty analysis [11]. So, although there is a significant amount of uncertainty in our results, they still serve as indications to where to put the efforts for improving the industry. It is also important with continuous improvement on the LCA-methodology – in terms of increased transparency on methodological choices and inventory data, to continue the development and standing of this tool. The LCA-methodology proves to aid the configuration of the future Norwegian macroalgae industry, with its holistic approach, to secure the most sustainable production system possible.

5 Concluding Remarks

Our study shows that the production of SWPC with today's technology has a significantly larger environmental impact than the production of SPC. But then again, we know that this industry has barely started its development. With the expected continuous growth of interest and focus on this area, the technology development is also expected to follow. Several processes within the value chain have major improvement potentials, and it is expected and needed to follow up with further research on these processes. This applies mainly to the cultivation-, harvesting-, stabilization and extraction-technologies. With mature and developed biorefineries, the utilization of all the valuable compounds of the seaweed will contribute to lower the environmental impacts, but also to increase the economic viability of the industry. It is also expected that LCA will be used as an additional tool in the future production management system, with improved methodology on impact allocation and improved access to inventory data, to ensure the best possible configuration to evolve it into a sustainable production system.

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