Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Anna Eliassen Sand

Exploring Carbon Capture Opportunities Through Exposed Large Scale Kelp Cultivation

Master's thesis in Department of Marine Technology
Supervisor: Bjørn Egil Asbjørnslett
June 2022

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NTNU Trondheim
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Department of Marine Technology

MASTER THESIS IN MARINE TECHNOLOGY

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For stud.techn.

Anna Eliassen Sand

Exploring Carbon Capture Opportunities Through Exposed Large Scale Kelp Cultivation

Background

Carbon capture and sequestration is identified as one of the central ways to mitigate climate change and make the 2-degree goal achievable. One possibility for capturing carbon from the atmosphere is through organisms performing photosynthesis, such as plants and algae. As available areas for cultivation of terrestrial plants are limited, algae, and in particular seaweed, is an interesting option for this purpose. In general, products made from seaweed are recognised as highly sustainable and can possibly play an essential role in preventing climate change by replacing products currently produced from less sustainable resources. There is however no consensus about the actual potential of carbon capture through seaweed cultivation. It is believed that this potential will depend on both the farm design, how the farm is operated, and the seaweed growth rates.

Objective

The objective of this master thesis is primarily to evaluate the potential of global warming mitigation through cultivation of seaweed, in the form of sugar kelp. Further, it is aimed to provide decision support for cultivation rig design and operations management for large scale kelp cultivation with regards to reducing the global warming potential, and hence increasing the carbon mitigation potential. A life cycle assessment of the kelp cultivation, from cradle to gate, will be used to quantify the impact. Results will be used to assess the potential of mitigating global warming through kelp cultivation and to the design of the cultivation system related to this potential.

Tasks

The candidate is recommended to cover the following parts in the project thesis:

a. Study the process of carbon capture and potential capturing pathways made possible by kelp cultivation.
b. Review the state of the art methods for kelp cultivation.
c. Outline a suitable rig design for large scale kelp cultivation in exposed locations.
d. Outline the operations required for installing, operating and disassembling a kelp cultivation rig.
e. Perform an LCA for seaweed cultivation based on the facility design and operations outlined.
f. Evaluate potentials for global warming mitigation based on the LCA and studies of carbon capture.
g. Discuss how the cultivation rig design and operations management relate to the carbon reduction potential of the kelp
h. Evaluate strengths and weaknesses of the assessment and present suggestions for improvements

General
In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.
The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Supervision:
Main supervisor: Bjørn Egil Asbjørnslett

Deadline: 11.06.2022

Abstract

Large scale seaweed production is a concept which has caught interest here in Norway due to its potential as a sustainable substitution for several products such as foods, feeds and fuels. High production costs relative to the value of the biomass have been a barrier to scaling up the industry. Although, it is believed that an increasing urge for sustainable products and lower costs due to technology development can make an upscale feasible in the future.

Another opportunity making large scale cultivation interesting is the carbon capture and storage effect provided by the kelp as it, through photosynthesis, has the ability to absorb carbon from the atmosphere. The captured carbon can then be stored, either through that biomass is eroded and sinks to the seabed or is buried in the shelf, or through actively storing the carbonaceous mass.

Through this thesis, a facility for large scale kelp cultivation is designed and operations needed to cultivate the kelp are outlined. Further, a cradle to gate life cycle assessment is being used to evaluate the global warming potential of the kelp. In addition, studies of the carbon capture potential of kelp due to erosion during the grow out phase and possibilities for utilization of the energy stored in the harvested biomass are performed.

From the interpretation of the LCA results, it is evident that the raw material for the ropes has a significant impact on the GWP, and thereby that extending the functional life of the ropes shows can help decrease the impacts. Other tested parameters include the rig size and operational efficiency, both having a moderate positive impact on the results. Lastly, the negative consequence of increasing the distance from the location to shore is assessed, and this proves to be minor.

From the base case assessment results, a GWP of 38.9 kg CO_2-eq per tonne of fresh harvested kelp was calculated. Combining this with the estimated carbon capture potentials with and without reduction due to substitution of fossil fuels, a GWP per cultivated hectare of -14.7 and 0.6 t CO_2-eq, respectively, was estimated. However, large uncertainty and variations are related to these results, mainly due to variations in biomass yields from one location to another and variations in harvesting strategies.

It is concluded that carbon mitigation through large scale kelp cultivation is a possibility. However, the circumstances of the cultivation, especially related to the choice of location and seasonality, will have a great impact on the possibility of producing biomass and sequestering carbon. Even though the focus of this work is the global warming potential, results indicate that other environmental effects of the cultivation can be critical and should hence not be ignored when assessing the value of kelp cultivation.

Sammendrag

Storskala taredyrking er en idé som får stadig økende oppmerksomhet her i Norge grunnet potensialet biomassen har som en mer bærekraftig erstatning til en rekke formål som for eksempel mat, fôr, og drivstoff. Høye produksjonskostnader i forhold til verdien av biomassen har så langt vært en barriere for oppskalering av dagens produksjon. Imidlertid forventes det at økende krav til bærekraftig produksjon, samt kutt i kostnader ved bruk av ny teknologi, skal kunne gjøre dette mulig i fremtiden.

En annen mulighet ved storskala taredyrking er utnyttelse av tarens evne til å fange karbon fra atmosfæren gjennom fotosyntese. Karbonet kan da langtidslagres enten ved at erodert biomasse synker til dypet eller begraves i sokkelen, eller gjennom metoder for å aktivt lagre karbonholdig masse.

Gjennom denne oppgaven presenteres et mulig design for et storskala taredyrkningsanlegg, samt operasjoner som kreves for å dyrke taren. Videre vil det gjennomføres en livssyklusanalyse for å estimere GWP for taren. I tillegg gjennomføres en studie av tarens potensiale til å fange karbon gjennom erosjon i vekstfasen samt av potensialer for utnyttelse av energien som er lagret i den høstede biomassen.

Analysen viser at råmaterialene brukt for å produsere tau har stor innvirkning, og videre vises det også at betydningen av tauenes livstid er av stor betydning. Andre faktorer som studeres er størrelse på anlegget og operasjonseffektiviteten, som begge viser seg å bare ha moderat betydning. Også negative konsekvenser av å øke avstanden fra anlegget til land, og dette viser seg å gi minimale utslag på totalt GWP.

For grunntilfelle som ble testet i LCAen beregnes det en GWP på 38.9 kg CO_2-eq per tonn våt biomasse. Ved å kombinere dette med estimater for karbonfangstpotensialer blir total GWP, med og uten reduksjon på grunn av potensiale for å erstatte fossile drivstoff, på henholdsvis 14.7 og 0.6 tonn CO_2-eq per hektar dyrket. Det må likevel påpekes at det er store variasjoner i parameterne som er brukt for å beregne disse potensialene, de største grunnet variasjon i vekstrater og erosjonsrater.

Ut fra resultatene konkluderes det med at det eksisterer et karbonfangstpotensiale knyttet til storskala taredyrkning. Dette potensiale vil dog avhenge av omstendigheter rundt dyrkningen, spesielt med tanke på lokasjon og tidspunkt for utsetting og høsting ettersom disse i stor grad påvirker vekstrate og erosjonsrate. Selv om fokuset gjennom om denne studien er på global oppvarming, viser resultatene at det kan knyttes andre effekter av utslipp fra taredyrkingen som kan ha store miljømessige konsekvenser. En mer helhetlig vurdering av miljøeffekten bør derfor tas hensyn til for å evaluere en verdien av taren.

Preface

This thesis marks the end of my Masters of Science in Marine Technology with specialisation in Marine Systems Design at the Norwegian University of Science and Technology. The masters thesis was carried out the spring of 2022 and is a mandatory activity of the master giving 30 credits.

In addition to my specialization in Marine Systems Design, I have chosen courses that have given me basic knowledge about aquaculture and utilization of marine resources. This, along with an interest for sustainable resources drove me towards a thesis focusing on the potential of seaweed cultivation. The thesis is partly built upon my project thesis, written the autumn 2021, which was an evaluation of the seaweed cultivation industry with focus on state of the art cultivation methods and technical challenges related to these.

Neither seaweed aquaculture, CCS or the LCA approach have been thoroughly covered by any of the courses I have taken through my studies and my knowledge in these subjects where very limited as I started the work. Therefore, much time have been spent reading and exploring these three subjects and it have been challenging to gather the necessary information to complete the study. However, working with these topics have been truly interesting and I am very satisfied with choice of topic for the thesis.

To make the rest of the thesis comprehensible for readers with the same knowledge basis I had at the beginning of the semester, it felt appropriate to include an introduction of the three topics mentioned above. Hence, a significant part of the thesis consist of theory regarding the these. Not all theory presented in this parts will be utilized directly in the assessment, but as it reflects my own knowledge about the topics and thereby the basis of the discussion and conclusion of the thesis, it is considered valuable for the reader.

I would like to thank my supervisor, Bjørn Egil Asbjørnslett, for valuable discussions about progress, structure and content of the thesis. Moreover, I would like to thank Eivind Lona, Shraddha Mehta and Ole Jacob Broch from SINTEF Ocean for discussions and answers regarding seaweed cultivation and CCS.

Working this intensively on a single project, and to a large extent without having anyone to discuss the studied subjects with has been exhausting and. Therefore, I am very thankful for the support and encouragement I have gotten from my friends and family throughout the semester, keeping me motivated to keep up the work.

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Abbreviations

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APOS	Allocation at the point of substitution
BAL	BioArchitecture Lab
BECCS	Bioenergy with Carbon Capture and Storage
CCS	Carbon Capture and Sequestration
DOC	Dissolved Organic Carbon
DOC	Life Cycle Impact Assessment
EOR	Enhanced Oil Recovery
FAO	Food and Agriculture Organization of the United Nations
FW	Fresh weight
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
IEA	International Energy Agency
IMTA	Integrated Mulitrophic Aquaculture
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MPV	Multi Purpose Vessel
PE	Polyethylene
POC	Particulate Organic Carbon
ROV	Remotely Operated Vehicle

1 Introduction

1.1 Background

An ever increasing urgency to stall climate change calls for more carbon neutral production as well as possibilities to capture and store away carbon from the atmosphere. To reach the 2-degree goal set by The Intergovernmental Panel on Climate Change, the method of carbon capture and sequestrations (CCS) will be necessary. This motivates the development of new technology and strategies for lowering costs and increasing the availability of CCS.

Macroalgae, commonly known as seaweed, is a primary producer which can be cultivated without the use of fresh water, fertilisers or pesticides (Lona, Sunde, Berggren et al. 2021). Products made out of seaweed are therefore recognised as highly sustainable and can play an essential role in preventing climate change by replacing products currently produced of less sustainable resources, for instance food, feed and fuels.

In addition to the positive environmental effects related to the substitution of less sustainable products, seaweed, just like terrestrial plants, has the ability to capture and store carbon and thereby reduce the carbon dioxide levels in the atmosphere. This ecosystem service is provided by all photosynthesising organisms. Still, as the available land area for terrestrial plants is limited and should preferably be utilised for food production, aquatic plants are a better opportunity for the purpose of CCS. During the seaweed grow out phase, much of the carbon stored in the plants will reenter the ecosystem as the biomass is utilised or dissolved. However, a fracture of the biomass that erodes as the plants grow will sink to the deep sea or settle in the sediments, where it will be long term stored (Krause-Jensen and Duarte 2016). The natural population of seaweed along the coast is already contributing to reducing atmospheric carbon dioxide, and a cultivated population will be able to increase this effect.

Today, seaweed cultivation is a relatively small industry in the Western world, and the main application of the biomass is as additives in food and pharmaceuticals. To develop a market for seaweed bioenergy or other large volume products, the biomass production will have to be scaled up significantly. For Norway, it has been suggested that, in scaling up the seaweed industry, the main priority should be scaling up the biomass production and further, sugar kelp has been targeted as a central species. For this to be possible, large cultivation areas are required.

The idea of taking the production offshore has caught interest in the industry as this can reduce conflicts regarding nearshore area utilisation and ecosystem impact in the coastal zones. As well, offshore production has shown to give less fouling, which is a significant challenge in the inshore industry, and in some cases, also increased biomass yields. On the other hand, offshore production introduces a demand for more advanced equipment and more challenging operations. For instance, the rig holding the kelp will have to be designed to withstand larger wave and current forces. Moreover, stability requirements for the vessels operating the farm, as well as transit and transport time from farm to shore, will increase.

An increased demand from society for sustainable products and services has driven more and more companies to set goals of becoming net-zero companies within the following decades. Currently, 200 companies, among them the American giant Amazon, have committed to reaching the net-zero goal by 2040 (Este 2021). As cutting 100 % of the emissions related to a product or service in most cases will be impossible, the companies will have to contribute to services providing a negative input to the global carbon accounting to achieve their goal. Due to seaweed's ability to store carbon, seaweed cultivation can potentially provide a net negative contribution. However, both the infrastructure and the operations required to cultivate the kelp will have emissions related to them. To find the net carbon uptake potential of the cultivation, both the sequestration potential and the emissions of the cultivation will have to be evaluated. It is believed that the impact related to these two aspects will depend highly on the methods used for cultivation, both with regards to the rig design, operations and logistics.

1.2 Objective

The main objective of this thesis is to evaluate the potential of carbon capture through large scale kelp cultivation outside the coast of central Norway. This is going to be done in combination with the exploration of rig design for cultivation at exposed sites and marine operations necessary to install, operate and decommission the rig. Moreover, it is aimed to highlight how the rig design and operation planning can be improved with regards to the global warming potential (GWP) of the rig and evaluate how moving the rigs further from shore will affect this.

1.3 Scope and Limitations

There are two main topics addressed in this thesis: kelp cultivation and CCS. To be able to answer to the goal of the thesis, a thorough study of these two topics will be carried out. For seaweed cultivation, state of the art methods will be studied and used as a basis to outline a rig design and plan for the operations. By use of life cycle assessment (LCA), the GWP related to the cultivation process is going to be evaluated. Calculations of carbon sequestration will further be carried out. These calculations will be based on data obtained through the literature study. In the end, by combining results from the LCA and CCS-potential calculations, the net carbon capture potential of kelp cultivation will be estimated.

The LCA for the kelp is limited to the production, from the hatchery and to the biomass is harvested. Hence, life cycle impacts from preservation and processing of the kelp biomass is not included. Although the structure and hence the components of the rig will be a focus, the materials used to model the components will not be thoroughly explored. Impacts from different carbon capture methods and mechanisms, except the GWP of the captured carbon itself, will not be assessed either.

1.4 Contribution

This work will contribute to increased knowledge about the impacts of large scale kelp cultivation and to what extent it can contribute to mitigating climate change. In addition, it will raise awareness about the importance of design and logistics choices related to the GWP of kelp cultivation.

1.5 Structure of the thesis

The thesis starts with a presentation of kelp cultivation. First, a presentation of the seaweed market is given before moving on to the potential for increasing the cultivation yields, followed by a review of the state of the art cultivation methods, possibilities for large scale production and lastly, the cultivation cycle of the kelp.

This is followed by a section presenting the concept of carbon capture, which starts with an introduction to bioenergy with carbon capture and storage (BECCS), followed by a short review of potentials for bioenergy production from kelp. Lastly in this section, the specific carbon capture possibilities for algae and further, for sugar kelp, are discussed.

In section 4, the LCA methodology is explained. Here, the steps contained in the method, their purpose and procedure and underlying mathematical theory are presented. Thereafter a literature review of LCAs addressing seaweed cultivation is presented.

Then, in section 5, the base case for the LCA is built. This is done by first presenting all the different rig components and how it is operated, before outlining the base case rig and operations, which will be modelled in the LCA. Section 4 is the presentation of the LCA itself. Here, modelled case, along with all choices made through the assessment, will be explained. Further, the methods and choices made with regards to calculating the results and doing a sensitivity analysis are presented.

The results from the LCA follow in the first part of section 7. Thereafter, data obtained in the CCS study are used to estimate a sequestration potential and a bioenergy production potential of the kelp. The combined result, giving the net carbon reduction potential, will then be presented. Results are followed by a discussion in section 8, where findings in the results will be evaluated along with a discussion of the weakness of the assessment and possible ways of improving it. The thesis is ended with a conclusion answering to its objective and presenting final recommendations for further work.

2 Introduction to Seaweed Aquaculture

Seaweed is the commonly used name for macroalgae. It is a primary producer, meaning that it captures carbon dioxide alongside with energy from the sunlight to form oxygen and energy in the form of organic matter (Pereira 2021). The macroalgae can be divided into three main groups based on their pigment composition: red algae, green algae and brown algae.

Human has harvested and used wild seaweed for hundreds of years, mainly for human consumption but also for other applications such as fertilizer for agriculture (Pereira 2021). The method of farming seaweed came much later, but through the last decades, this has become the dominant way of harvesting seaweed. The global production trend of farmed and harvested wild seaweed is shown in figure 2.1. As indicated by the figure, there has been an almost exponential growth in seaweed aquaculture up until 2015.

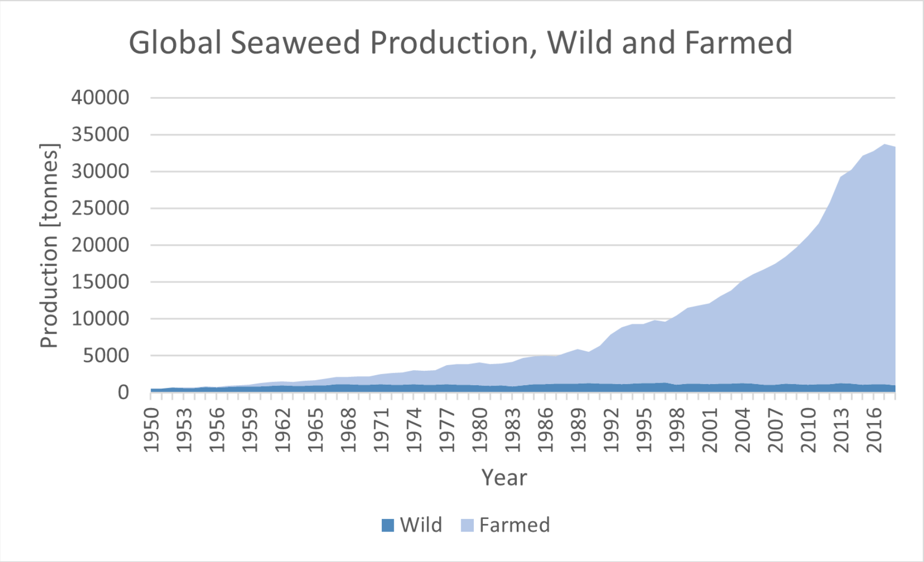


Figure 2.1: Trending of seaweed production by farming and harvesting from the wild the last 70 years. Numbers from FAO 2020.

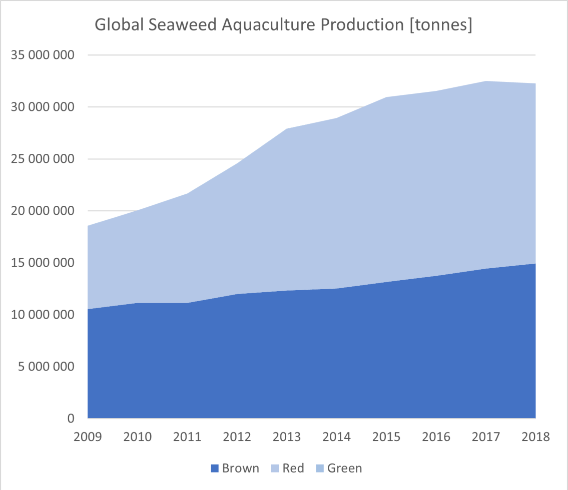
A typical cultivation cycle within the Northern European seaweed industry consists of hatchery and substrate seedling, cultivation, harvesting and preservation, steps which will be further explained in section 2.6. Globally, there are large variations in how the different steps are being carried out. In section 2.3, the various methods and the state of the art farming system will be presented.

Kelp is a subgroup of brown algae, accounting for about 35,4% of the global production. The best known species of the kelps is the sugar kelp (Saccharina latissima). This is the largest species within Norwegian seaweed aquaculture, and there are several reasons for this: In addition to being a robust species that can withstand wave heights corresponding to storm, it has the highest growth rate among European kelps (Skjermo, Aasen et al. 2014). With a high carbon concentration as well, it has become a favourable candidate for the production of biofuels (Saifullah et al. 2021).

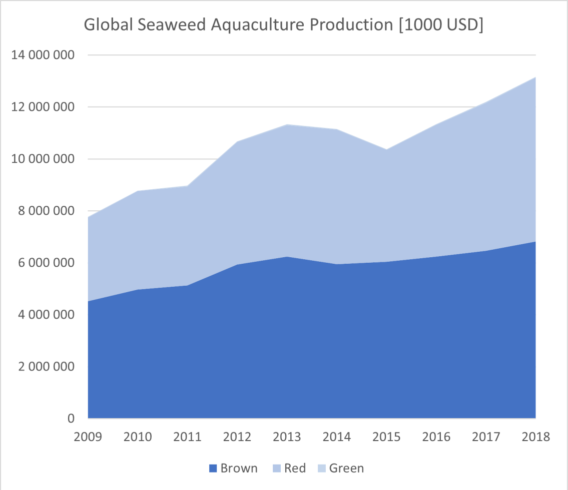
2.1 The Seaweed Industry

In 2018, Asian countries produced 32 million tonnes of farmed aquatic plants, accounting for 99.5% of the global production. In the same year, European countries produced 5396 tonnes, a doubling from 2017, but still a negligible amount when compared to the Eastern part of the world (FAO 2020). This is representative for the global trend in seaweed production throughout all time, where both the market and the industry in the western world have been more or less non-existing.

Figure 2.2a and 2.2b show how both the total global production and the total value of seaweed changed in the period from 2009 to 2018. As the graphs indicate, the volume and economic value of green algae are negligible compared to that of red and brown algae. There has generally been a stable increase in the total production, but the increase in the production of red algae has been much larger than that for brown algae. It can also be seen that, while the mean price for brown algae has kept more or less constant through the decade, the price of the red algae has had a slight decrement from about 400 USD/t in 2009 to 360 USD/t in 2018.



(a) Trend of global mass produced for red, brown and green algae (FAO 2020).



(b) Trend of global value for red, brown and green algae (FAO 2020).

The long coastline of Norway has proven to be well suited for different types of aquaculture. Even though seaweed farming has not been a significant branch of this aquaculture, there seems to have been an increasing interest in the industry since the first commercial permits came in 2014. In addition to the long coastline, the marine industry of Norway has much valuable knowledge from both fish farming and operating offshore oil and gas facilities that can be helpful for technology development within the seaweed industry.

Although there are many species suitable for cultivation, in practice, only sugar kelp and winged kelp are currently cultivated in Norway. There seem to be two reasons for this: Firstly, they grow fast in the environment provided by the Northern Atlantic Ocean, and secondly, cultivation routines are well known (Bremnes et al. 2017). As for sugar kelp, being the largest species in forms of produced mass, this has been identified as particularly well suited for harsh environments and is therefore a good candidate for cultivation in exposed locations. Figure 2.3 shows the trends of the Norwegian production of two species in Norwegian aquaculture through the last five years. As seen, there has been a significant increase in production from 2017 to 2019, especially for sugar kelp.

Today, the industry is characterized by low profit, making it hard to commercialize large scale production in the western part of the world. Although, the interest in developing large scale production and technology for cultivation at more exposed sites has been increasing through the last decade. Olafsen et al. 2012 suggests that the Norwegian aquaculture will be able to produce about 20 million tonnes of kelp, with a potential annual income of NOK 40 billions, by 2050. Although, this is based on the assumption that the production takes place in favourable environments and not necessarily along the Norwegian coast.

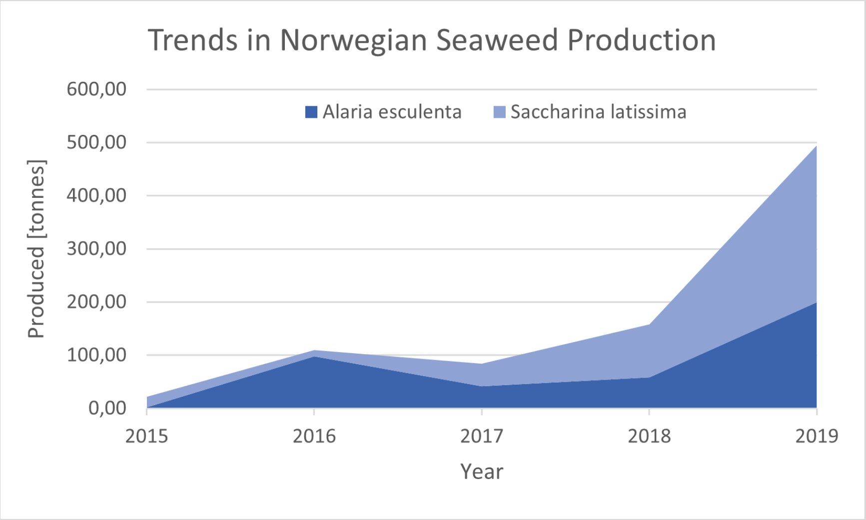


Figure 2.3: Trending of production of sugar kelp (Saccharina latissima) and winged kelp (Alaria Esculenta) the last years (FAO 2021).

2.1.1 Applications and Market Value

Today, 61% of the biomass produced by European countries is used for feed and human consumption, either in the form of food or for food-related uses (Araújo et al. 2021). In addition to proteins, seaweed offers high levels of fibres, minerals and omega-3 acids (Rajapakse and Kim 2011) and is hence a healthy supplement to the human diet. It also produces soluble fibres that can be extracted and used for consumption, some of which are known for their health benefits and others well suited to use as stabilisers or thickeners in food.

The value and nutrient composition of seaweed vary between the species and seasons. In Norway, the production is currently dominated by high value products. In 2015, the price of the two major species, sugar kelp and winged kelp, was 350 and 965 euros per tonne, respectively (Barbier et al. 2019). While sugar kelp is usually sold for the purpose of being used for either human consumption or as animal feed, the winged kelp, which is produced in much smaller quantities, is mainly used for high value food ingredients. In comparison, the estimated retail value of seaweed globally was 181 euros per tonne. In 2014 it was estimated that the market value of one tonne of biomass used for producing the hydrocolloid carrageenan was about three times the value of one tonne used to produce fertilisers and 14 times that for seaweed meal (Nayar and Bott 2014). As this indicates, the market value of different seaweed products varies highly.

Animal feed, fertilisers, textiles, bioplastics and biofuels are among the lower value products that potentially can be produced by seaweed. The usage of kelp in biofuels is said to be the initial motivation behind the increased Norwegian research effort on seaweed cultivation and processing technology (Stévant, Rebours and Chapman 2017). The challenge with producing these low value products is, as mentioned, that the production costs are too high, and hence, it is not profitable.

To optimise the profit, both location for the grow out phase and cultivation cycle should be adjusted for the purpose of the biomass. For sugar kelp, it has been shown a significant deviation in the protein content through different times of the year and in different localities (Mols-Mortensen et al. 2017; Sharma et al. 2018). Figure 2.4 shows how the protein content in sugar kelp vary during the growth season. The results are from a study of the growth and nutrient content in three locations with different exposure at the Faroe Islands. As seen, there is a significant decrease in protein from May to July, and the sheltered location seems to have the largest changes (Mols-Mortensen et al.

2017).

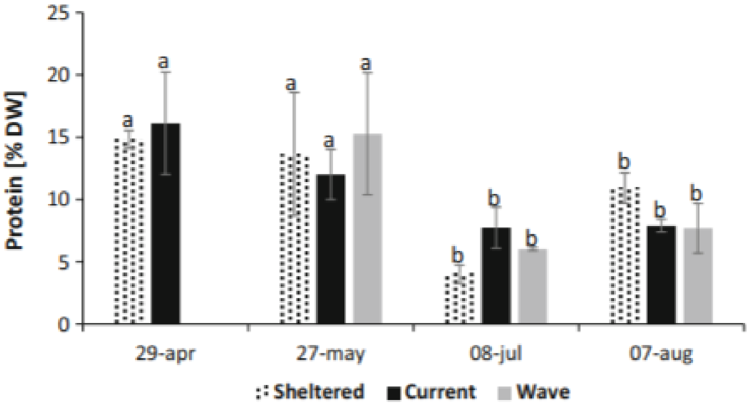


Figure 2.4: Seasonal variation in protein content in sugar kelp measured for three different locations (Mols-Mortensen et al. 2017).

Sugar kelp has a relatively high carbohydrate content and a relatively low protein content, making it suitable to use as feedstock for biofuels but less suited for purposes where protein and lipid content is more important, for instance fish feed. Even though sugar kelp and winged kelp are the species being explored by most studies today, other species should not be excluded as relevant for cultivation in the Norwegian coast. However, it is assumed that experiments looking at other species need more comprehensive biological research before technical solutions can be assessed.

The use of seaweed biomass for energy production, for instance in the form of biofuels, has not been done commercially yet. This is mainly due to a lack of economic incentives for such production. Such incentives may arise due to higher oil and gas prices or if laws and regulations to a larger extent favour renewable energy production, for instance by raising taxes for CO_2-emission. The International Energy Agency (IE), forecasts that biofuel demands will increase by 28 % by 2026 and calls for developing new technologies for and commercialization of non-food-crop production for biofuels IEA 2022. Assuming that the market for seaweed as food is limited, using cultivated seaweed biomass for biofuel production is a suitable option for increasing global bioenergy production.

2.2 Biomass Yields

The growth rate of the seaweed depends on abiotic factors such as temperature, salinity, light, current and nutrient, as well as biotic factors such as animals, fungi and bacteria. Different species have different ideal growth environments. Even though seaweed has no roots to transport nutrients from the ground such as terrestrial plants, most species are dependent on a substrate, usually rocks or reefs, to which they can attach, to grow. This, in combination with the need for sunlight, is the reason most wild seaweed is located near the coast and in shallow waters.

There are significant variations within measured and estimated biomass yields and thereby also the estimated cost and impact per tonne of harvested biomass. Table 2.1 includes values reported from both existing facilities and studies of sugar kelp yield. The weights are given in fresh weight (FW), i.e. before preservation or efforts for drying has been made. As seen, the values range from 25 tonnes per hectare up to an optimistic value of 383 tonnes per hectare. The yields in the table will be used as a basis when calculating the environmental impact of the cultivation in section 7.

Table 2.1: Biomass yield, measured in harvested fresh weight, for Saccharina latissima cultivated at locations along the Norwegian coast and comparable sites. More details about the numbers are provided in appendix C.

FW[t/ha]	Location	Remarks	Ref
220	Scotland	Upscaled from IMTA trial	Broch et al. 2019
35	Galicia		Broch et al. 2019
95	Eastern Canada		Broch et al. 2019
200	Northern Norway		Broch et al. 2019
25	Sweeden		Broch et al. 2019
383	Central Norway	Best case - scaled up from trial	Broch et al. 2019
75	Norway	Simulated - average Norway	Broch et al. 2019
230	Norway	Simulated - optimal location	Broch et al. 2019
30	Central Norway	Shallow depth, horizontal ropes	Bale 2017
63	Ireland	2D Sheets	Bale 2017
230	Western Norway	Horizontal ropes	Bale 2017
10	Limfjorden, Denmark	Average of 10 locations	Seghetta et al. 2016
116	Average		
157	Average Norway		
383	Best case		

2.2.1 Farming Density and Cultivation Depth

As mentioned, seaweed is dependent on sufficient access to light and nutrients to grow. It has been shown that, due to this, biomass yields are limited by the plant density (Xiao et al. 2019). Additionally, abiotic factors such as salinity and temperature of the water will affect the growth. Skjermo, Schmedes et al. 2020 identifies seasonality, location along the latitudinal gradient and depth as the most important factors with regards to growth and biochemical composition of the sugar kelp.

The optimal growing depth for seaweed is generally between 1 and 5 meters from the surface (Barbier et al. 2019). Forbord, Matsson et al. 2020 found that cultivation at shallow depth yielded more biomass, whereas protein, ash and nitrogen compound were higher in the kelp grown in deeper water. However, the optimal depth has also shown to be highly varying and depending on both species, season and environmental factors at the location of the facility (Forbord, Matsson et al. 2020). This means that there will probably be other optimal depths at the more exposed areas than what has been found in the case of inshore facilities. There will be a further evaluation of localities in section 2.2.3.

2.2.2 Deployment and Harvesting Season

The timing of deployment and harvesting is crucial to optimize the amount of yielded biomass (Bak, Gregersen et al. 2020). Both current, light saturation, temperature and nutrient composition of the water will vary throughout the year and hence affect the growth. For exposed locations, the wave exposure will be larger and hence, the harvesting cycle will possibly have to be adjusted such that there are large enough weather windows to operate during deployment and harvesting season.

Optimal deployment season for the Norwegian coast varies from late summer to early winter, while harvesting typically happens in the period from late spring to late summer. The growth season varies highly from southern to northern parts of the Norwegian coast. Forbord, Matsson et al. 2020 estimates that maximum biomass yield can be expected about two months later in the northern locations compared to the southern ones. It has also been shown that the biomass yield for the kelp peaks later in exposed localities than for coastal ones (Skjermo, Schmedes et al. 2020). The timing of deployment should be decided by the growth pattern of the kelp at the given location, while the timing of the harvest season is dependent on when biofouling starts degrading the plants. The effect and timing of biofouling will be discussed in section 2.2.3.

The standard practice in Norwegian seaweed aquaculture is to harvest from the farms once during the yearly cycle and then take the ropes on shore to prepare them for seeding again. Among reports from the Norwegian industry, there were not found any cases where regrowth was practised, i. e. that harvesting is done by harvesting blades only, such that holdfast is left on the cultivation rope and the plants can regrow from it. When using this method, harvest can happen several times during one year. However, regrowth was practised in a trial of exposed cultivation conducted at the Faroe Islands, which will be further discussed in section 2.3.

2.2.3 Locations and Exposure

The biomass yield in kelp cultivation depends on the growth rate and the degradation rate due to biofouling. These two factors are highly dependent on different biotic and abiotic factors which will vary between locations, and therefore, the growth potential will vary a lot from one location to another. It has been identified that both depth, temperature, salinity, light conditions, nitrogen and phosphate content and wave and current exposure are among the factors affecting the yield potential of a location (Handå et al. 2012; Bruhn et al. 2016; Visch et al. 2020).

One of the major challenges in the kelp farming industry has been biofouling, which can both degrade the quality of the kelp and reduce the total biomass. Several studies have pointed to how increased exposure in the location will decrease the rate of biofouling (Visch et al. 2020; Skjermo, Broch et al. 2020). And while Visch et al. 2020 showed that increased exposure can lead to decreased growth rates, Peteiro and Freire 2009 states that, for sugar kelp, cultivation in moderately exposed environments gives higher biomass per individual plant compared to those cultivated in sheltered areas. This was also the conclusion drawn from SINTEF Oceans's research project TAREAL 2 (Skjermo, Broch et al. 2020) and for trials on giant kelp cultivation outside Chile (Camus et al. 2018). Additionally, an increased carbon content has been observed in exposed areas (Visch 2019), which is beneficial if the biomass is going to be used as an energy source. Furthermore, this implies that more carbon has been captured, which implies an increased CCS potential.

In the period from 2012 to 2016, a Norwegian research team from SINTEF Ocean and Norwegian Institute for Water Research (NIVA) simulated the growth of sugar kelp using a 3D hydrodynamic-biogeochemical-kelp modelling system to gain insight in the growth pattern for different locations (Broch et al. 2019). By the use of simulation, it was possible to map the growth potential along all of the Norwegian coast. The knowledge collected by the project is valuable to assess which areas to target for large scale cultivation. Such information can for instance indicate where it is beneficial to establish new fabrics.

Some key take away point from the study are:

- Maximum cultivation potential of 150 - 200 tonnes per hectare per year.
- A generally higher production potential offshore than inshore.
- In the south, the timing of the cultivation is important, and the potential is significantly higher for kelp deployed in the early autumn (September) than in the winter (February). This difference in biomass yields is much lower for the two deployment times in the north.

2.2.4 Optimal Growth Conditions

Based on the reviewed studies of parameters affecting the biomass yield, it should be possible to drive the cultivation towards the high yield estimates. To best manage the growth, seasonality is particularly important and this should be adjusted to the location: Further north, harvesting should happen later than in the southern parts of Norway and for exposed locations, less fouling can allow postponed harvest. As a second take away point the density and depth of the plants should be adjusted such that the plants get sufficient access to light and nutrient. Lastly, a moderate exposure seems to be beneficial for the growth of the kelp as long as the cultivation facility is robust enough to withstand it.

2.3 State of the Arts Farms and Operation

Although wild seaweed harvesting has been done for decades, the first trials on seaweed aquaculture in Norway started in 2005. About nine years later, in 2014, the first commercial permits for seaweed cultivation were granted by the authorities (Stévant, Rebours and Chapman 2017). Cultivation of seaweed has, throughout all time, been characterized by manual work and has therefore been a labour intensive industry (Alver et al. 2018). This is also the case for the large scale farms in Asia (Lona, Endresen et al. 2020a) and most production facilities around the world today, which can explain why there has not been significant production in western countries with high labour costs, such as Norway.

Within the Norwegian fish farming industry, the cylindrical net cage has been recognized as a robust and cost efficient solution. This type of cage has therefore become the standard construction for fish farming along the Norwegian coast. Using standardized design makes it possible for the gear manufacturers to mass produce the gear, which will allow them to lower the prices. As of today, there seems to be no consensus about what is the optimal way of farming seaweed. Skjermo, Schmedes et al. 2020 highlights standard farming solutions as an important step to be able to scale up the industry. However, other design criteria apply for farms in exposed locations than that for inshore farms, and as there have been few successful farm trials in exposed locations so far, the experience in this area is limited. Thereby, it is difficult to establish an optimal design.

As a contribution to SINTEF's project "MACROSEA" (Alver et al. 2018), a short questionnaire was conducted among participants in the Norwegian seaweed farming industry. Results from this indicated that the most common technology used today is horizontal pre-seeded ropes attached to a floating structure that is moored to the seabed. The rig design itself varies, and it is evident that there is no consensus about what design is the most optimal. The interview also points to the use of manual work and equipment that is not specialized for the purpose. This is confirmed by Lona, Endresen et al. 2020a, which explains that the harvesting usually is done by use of small industry vessels or vessels used in other branches of the aquaculture industry, in some cases equipped with cranes and winches. Further, it is highlighted that the cultivation ropes are detached from the mooring system manually before being pulled or lifted on board for harvesting, which is an operation that can be quite time consuming.

Figure 2.5 shows examples of four European farming concepts: [B] Bulandet 10 and [C] Seaweed carrier, which are Norwegian concepts, along with [A] AtSeaNova, designed in Belgium, and [D] MACR(Macro Algae Cultivation Rig), designed for cultivation in the Faroe Islands. While MACR and Bulandet 10 operate with one-dimensional substrates, i.e. ropes, the other two use 2D-substrates. 2D-substrates will provide greater plant density but also cause larger forces on the structure. As well, it has been shown that, as the growth rates of the kelp depend on irradiance and access to nutrients, the growth will be limited by high densities (Xiao et al. 2019). The mooring configuration and the number of anchoring points vary as well. Four lines and anchoring points seem to be the most common configuration, but there are also other solutions, such as the one used for the Seaweed Carrier, having one single mooring line and anchoring point for each structure. The latter solution provides freedom for the system to rotate with the current. The depth in which the seaweed grows ranges from the surface down to about 10 meters depth for MACR. As the figure shows, there is no consensus on whether the cultivation rope should be horizontal or vertical.

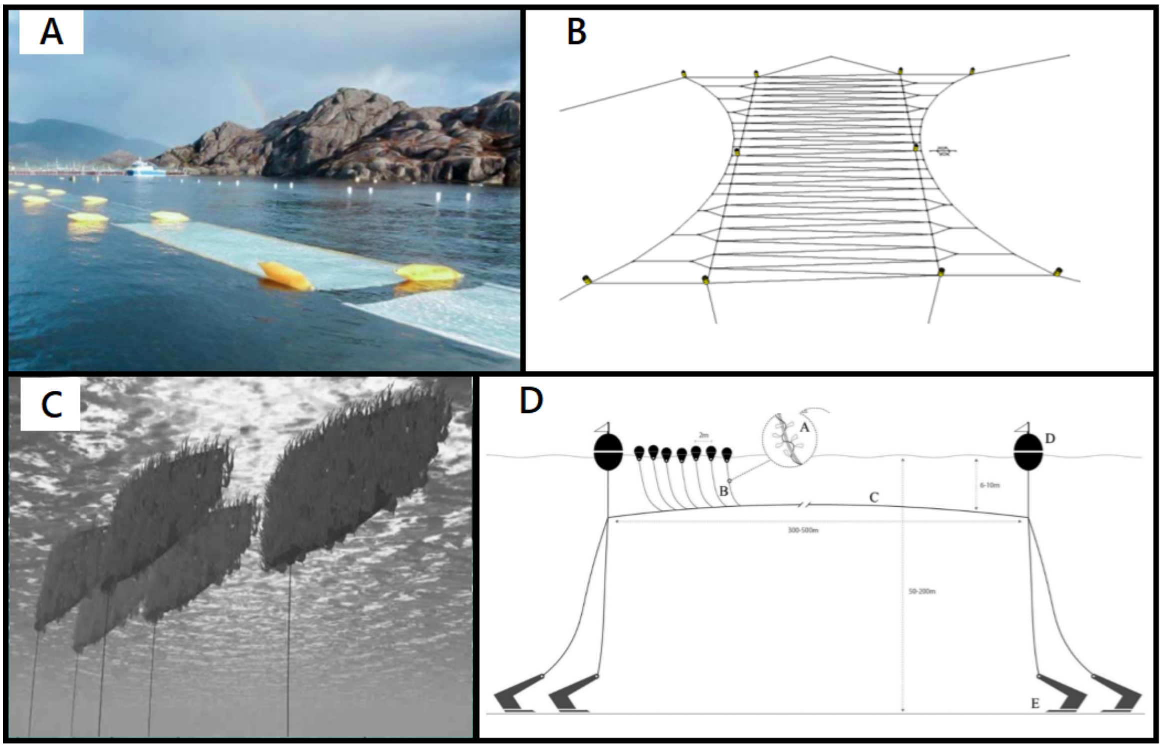


Figure 2.5: Macroalgae Cultivation Concepts: A: Mini-farm by AtSeaNova (AtSeaNova 2021) B: Bulandet 10 by Værlandet fiskeredskap (Lona, Endresen et al. 2020a) C: Seaweed Carrier by Seaweed Solutions (Seaweed Solution 2021) D: MACR by Ocean Rainforest (Bak, Ó. Gregersen et al. 2018).

Most vessels used in seaweed farming are currently either multi purpose vessels or vessels initially built for other aquaculture purposes. Scaling up the production may be an incentive to build more specialized vessels as this can increase the efficiency and safety of operations. For offshore purposes, another incentive for building specialized vessels is that harsh weather entails more stability and robustness. In this case, some of the smaller traditional aquaculture vessels may not be robust enough.

2.4 Large Scale Cultivation - Exposed Locations

For the production of low value products to be profitable, such as biofuels and animal feed, large biomass volumes must be produced and production costs should be reduced to a minimum. Large production volumes call for large production areas, and the lack of suitable nearshore areas is identified as a restricting factor for scaling up the production (Bak, Gregersen et al. 2020). This has strengthened the motivation to develop methods for cultivation further from the coast and hence in deeper waters with more wave- and current exposure. As mentioned, another important incentive to develop large scale seaweed cultivation is the potential CCS. Methods and potentials for sequestering carbon through seaweed will be further discussed in section 3.

The terms "offshore" and "exposed" aquaculture are often used to explain the same concept. However, it should be specified that, while "offshore" is addressing the distance from shore to the facility, "exposed" concerns the weather conditions. An exposed location does not necessarily have to be located far from the coast. Nevertheless, locating a facility further from the shore will, in most cases, imply locating it in more exposed conditions. Therefore, when addressing challenges related to the increased distance to the facility, "offshore location" will be used, while when discussing the challenges related to increased exposure, "exposed location" is more appropriate. On the other hand, when talking about "inshore locations", it is implied that the location is also a sheltered location.

Compared to inshore cultivation rigs, constructions located in more exposed areas have to withstand larger forces from waves and currents. Additionally, taking the farms further offshore will often imply increased depth and hence a more extensive mooring system. Lastly, more exposure yields more complicated and hazardous operations. As mentioned, the seaweed industry is currently characterized by a lot of manual work and some of the operations that traditionally have been carried out manually, like detaching the cultivation rope from the frame, may have to be automatized. It is therefore essential that the rig is designed in such a way that it can be operated by use of for instance cranes or ROVs.

The first offshore farm was tested in the early 70s (Bak, Gregersen et al. 2020). Since then, several trials on offshore seaweed cultivation have been conducted, but few of the trials have been successful. This has mainly been due to high costs and insufficient robustness of the farms Bak, Gregersen et al. 2020. Although, newer trials have also proven feasibility for cultivation in exposed locations (Forbord, Steinhovden et al. 2018; Peteiro, Sanchez et al. 2013; Azevedo et al. 2019). Table 2.2 gives an overview of trials and the conditions they were exposed to.

Table 2.2: Highest significant wave height and currents measured at sites used for exposed seaweed cultivation projects.

Concept/trial	**Location**	V_c**[cm/s]**	H_s**[m]**	**Cite**
BAL	Quentac, Chile	20	3	Bak, Gregersen et al. 2020
MACR	Faroe Islands	300	4	Bak, Gregersen et al. 2020
TAREAL 2,	Klovningen	54.9	3.7	Lona, Endresen et al. 2020b

Based on the literature review of studies on exposed seaweed cultivation, it seems that two of the most successful trials on exposed seaweed cultivation have been the MACR in the Faroe Islands and The BioArchitecture Lab (BAL) in Chile. These farm concepts will therefore be further looked into and used as a basis for the farm design presented in section 5. In addition, TAERAL 2, which is a trial conducted by SINTEF just outside Kristiansund, Norway, will be used as the main reference system for the base case design used for the LCA. The TAREAL 2 facility will be presented in section 5.5 while a shorter presentation of BAL and MACR will be given here.

The Chilean BAL was constructed to cultivate giant kelp (Macrocystis Pyrifera) and tested at Quenac, an exposed location with a depth of 60 meters and an average current velocity of 20 cm per second (Camus et al. 2018). Figure 6 shows the concept of the farm, consisting of horizontal ropes attached in a grid system, kept in place by several mooring lines and buoys (Camus et al. 2019), almost like the grids used for fish cages in traditional Norwegian fish aquaculture. For this concept, it was evident that the most significant cost drivers were anchors and ropes. The average yield at the farm was 12.4 kg/m rope (Bak, Gregersen et al. 2020).

For MARC, as was described in section 2.3, the aim was to develop a production in the Atlantic Ocean that could be applicable and economically profitable. The species that were cultivated in the project were sugar kelp and winged kelp, and the cultivation system used was constructed by Ocean Rainforest and can be seen in figure 5 (Araújo et al. 2021). The rig was based on existing equipment and components produced for other aquaculture purposes, and the operations were conducted without the use of automation. Harvesting was done manually by using a knife. Unlike in most Norwegian farms, the method of multiple partial harvest was used. The project concluded that the site was suitable and that the method of multiple partial harvest gave increased yield for these species in the given environment. On the other hand, it was concluded that exposed seaweed cultivation would require more innovation to lower operational costs. The average yield was only about half that of BAL, but at the same time, the installation costs were relatively low due to spatially efficient design and re-use of existing components from the aquaculture industry (Araújo et al. 2021).

2.5 Regulations

As there are currently no standards or requirements directed specifically to seaweed farms, the Norwegian Standard for fish farms, NS9415, is applied in the industry today (Endresen et al. 2020). However, as the purpose of this standard is to prevent fish escapes, and the consequences of technical failure for a seaweed farm are very different to that of a fish farm. Endresen et al. 2020 suggests that there can be considered lower safety factors for seaweed farms than what is used today, making it possible to utilize lighter structures and possibly to increase the functional life of different components.

2.6 Seaweed Cultivation Cycle

The following sections describe the state of the art seaweed cultivation cycle and methods used in the different stages of the cultivation process. There will also be given comments on which parameters are the most important ones to consider when planning the process and what considerations must be taken when operating a farm located in an exposed area.

Step 1: Hatchery
The seaweed cultivation cycle starts with spore preparation, which is done by collecting spores from mature plants and manipulating them in the laboratory by adjusting temperature and irradiance to induce reproduction (Siji 2015). Sporophytes will then be developed. The sporophytes will be applied to a seedling line which is further kept in a hatchery in optimal environmental conditions until the plants are ready for deployment at sea. Different methods can be used to get the sporophytes to attach to the line, but it seems there are mainly two options used in kelp cultivation today:

- *Direct seedling* where the cultivation rope is treated with a glue-like coat before being directly placed in the sporophyte solution such that the sporophytes attach to the cultivation rope. The cultivation rope can then be directly transferred to the sea.
- *Twine seedling* where the sporophytes are added to a thin seedling line where they spend their first growth phase before the line is twined around the cultivation rope that will be deployed.

Optimal juvenile production is crucial to optimize the biomass and several studies pay special attention to developing the hatchery technology (Barbier et al. 2019). However, studying this part of the production cycle requires extensive knowledge about seaweed biology, and therefore it will not be an area of focus through this thesis.

For cultivation in exposed areas, it is essential the plants are robust and well attached to the substrate when deployed. The choice of seedling method may therefore be more critical for the biomass yield in this case than for cultivation in sheltered areas. Skjermo, Schmedes et al. 2020 showed that twine seedling and a hatchery period of 6 weeks resulted in much better growth rates than cases with direct seeding or shorter hatchery periods. The latter is assumed to be because the sporophytes need some time to develop hold fasts before they are ready to withstand waves and currents.

Step 2: Deployment
After the hatchery period, the carrier ropes, holding seedlings or seedling lines, are outplanted in the sea. This usually happens either in the autumn (September/October) or in the winter (January/February). The period from late November and until mid January is more critical due to harsh weather, and operations in this period are therefore usually avoided.

A pre-installed, stationary offshore cultivation rig is used to hold the ropes. After transporting the ropes to the cultivation site, the deployment is done by connecting the cultivation ropes to the frame rope of the rig. In many cases, this operation is done manually and is a time consuming and hence expensive operation. As discussed, operating in more exposed areas is often more hazardous than that in more sheltered locations. To lower the risk for human health and to increase the efficiency of the deployment, it is assumed beneficial if this operation can be automatized by using cranes or ROVs with manipulators. The latter is particularly relevant if the carrier ropes are being attached at significant depths and it is not possible to elevate the frame rope above the surface during the attachment operation.

Step 3: Grow out phase
As the plants grow, the forces from currents and waves on the rig will increase due to limited current flow-through caused by increased blade length and density. To make sure the cultivation rig and plants are intact, it is necessary to monitor the rig throughout the grow out period. This can be done either with manual inspections, by use of cameras and sensors or a combination of the two.

A factor limiting the yield when producing seaweed for food purposes is the biofouling that starts during summer. In order to keep the quality of the biomass high, it is often necessary to harvest the kelp before reaching maximum yields (SRSL 2019). However, this is not the case for non-food-related applications and hence, maximum yield should be the main criteria when deciding the time of harvest. In cases with less strict requirements for the biomass, it is assumed that the inspection frequency can be kept lower.

Step 4: Harvesting
Harvesting of the kelp usually happens sometime during summer, as this is when the biomass peaks and biofouling starts. For the case where harvest only happens once a season, it is common to retrieve the cultivation ropes holding the kelp from the rig before cutting the kelp off the ropes. The kelp is then cut, either on board the vessel, before transport, or on land after transport. Cutting can either be done manually by use of a knife or other sharp tools, or mechanically by use of machines.

Step 5: Preservation and processing
Degradation of the biomass starts the second it is harvested. Due to biodegradation and high water content, quick handling and efficient conversion of the biomass is identified as one of the keys to reducing costs of the production in the industry (Fernand et al. 2017; Stévant and Rebours 2021).

Harvested seaweed has a high water content, and it is assumed that the wet to dry ratio of kelp is 5:1 (Roesijadi et al. 2008). Drying of the seaweed has traditionally been the first step of the preservation, as this will decrease the degradation of the biomass and hence secure its quality (Badmus et al. 2019). This can be done either thermally, usually by the use of heat, or mechanically, by pressing or centrifuging the biomass. As the drying process is very energy intensive, lactic acid fermentation has become an alternative for large volume products. The quality and shelf life of the biomass preserved by fermentation is not necessarily as good as that for drying. Still, the energy consumption for this process is relatively low, and for several applications, the biomass quality is sufficient (Stévant and Rebours 2021). After the biomass is preserved, it can be packed and transported to the customers for further processing before it is taken into use.

3 Carbon Capture and Sequestration

While carbon capture itself is the process of extracting carbon or carbonaceous gasses, carbon capture and sequestration also include removing the carbon in such a way that it can no longer affect the earth's atmosphere. In carbon capture and utilization, on the other hand, the carbon is extracted for the purpose of being utilized.

Since the 1970s, technology for carbon capture has been used to extract CO_2 for the purpose of Enhanced Oil Recovery (EOR), a method where CO_2 is injected into the well of an oil field to enhance oil recovery (IEA 2013). As concerns about climate change and global warming have arisen, the interest in using carbon capture technology to store away CO_2 from the atmosphere has grown. As of 2016, 15 large scale CCS projects were in operation with 6 more planned within 2018 (IEA 2016). In fact, it has been concluded that CCS is unavoidable if the 2 degrees limit is going to be met (Bui et al. 2018; Tatarewicz et al. 2021).

Figure 3.1 show the three processes conventionally used for carbon capture; post-combustion capture, pre-combustion capture and oxy-combustion capture, post-combustion capture using amine-based solvents being the most mature method (IEA 2016). After the carbon dioxide has been captured, it is transported, either through pipelines or by sea, to the location where it is either used or stored.

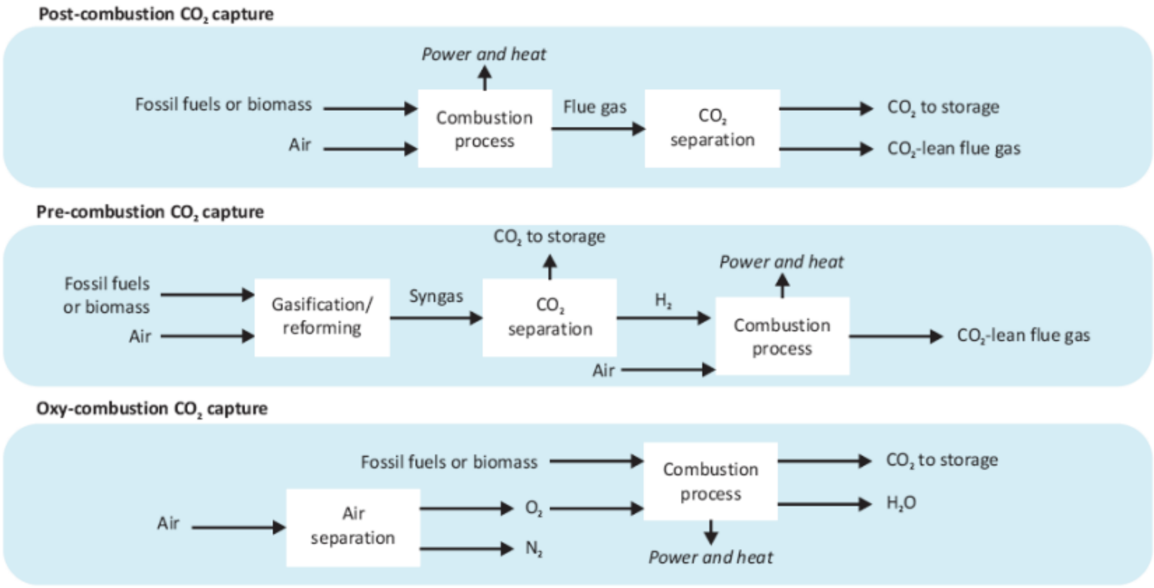


Figure 3.1: The three main methods for extracting carbon dioxide (IEA 2012).

For CCS through seaweed cultivation, it should be distinguished between carbon sequestration that happens during the grow out phase and the possibility of sequestering the carbon after harvest. Sequestration during the grow out phase, hereby referred to as natural sequestration, happens due to that biomass is being eroded from the plant and enters the ocean as particles. The particles can then be sequestered in two ways; either by being buried in the shelf or by sinking to the deep where oxygen levels are low. Natural sequestration will be further discussed in section 3.3. After harvesting, sequestration happens either by using the energy stored in the biomass combined with CCS technologies to capture the CO_2 during the combustion or by storing the carbonaceous harvested biomass directly.

When the biomass is utilized for consumer goods or bioenergy without carbon capture, the carbon will reenter the atmosphere and hence, there will be no long term storage effect. In this case, the GWP-equation would in reality only include the emissions used to produce and transport the biomass, and there will be no carbon reduction effect.

To account for the positive contribution of using carbon neutral products, which is of interest if the product is going to be compared to alternative products, a compensation due to the effect of substitution can be added to the GWP-equation. This is done by letting the carbon neutral product, for instance energy from biofuels, replace another product, for instance energy from fossil fuels, and account for this by subtracting the GWP of the fossil fuel-energy product from the GWP-equation of the biofuel-energy. The result will then be a net negative GWP as long as the GWP of processing the biofuel does not exceed that of producing and burning the fossil fuel.

3.1 Bioenergy with Carbon Capture and Storage

BECCS is the concept where biomass is used to produce bioenergy and further, in the use phase of the energy, CCS is used to remove the CO_2. As the carbon absorbed by photosynthesis during biomass production is recaptured by CCS during energy utilization, the result is a net negative carbon emission in addition to energy supply which can substitute fossil energy.

Among existing methods to generate negative emissions, BECCS technology is seen as the most mature (IEA 2016). One of the challenges in developing BECCS today is that the technology used for CCS is relatively expensive, making the capital costs for BECCS initiatives high (Tatarewicz et al. 2021). It seems that most ongoing or former BECCS projects are focusing on terrestrial plants Kemper 2017 despite the well known challenge of limited land areas and water usage in terrestrial agriculture. Figure 3.2 show IEA's outlook on the contribution of different CCS technologies until 2050. As seen, BECCS-technology is still in its infancy, and challenges related to costs, sustainable biomass production and infrastructure for CO_2 transport are still restricting the expansion of the BECCS concept.

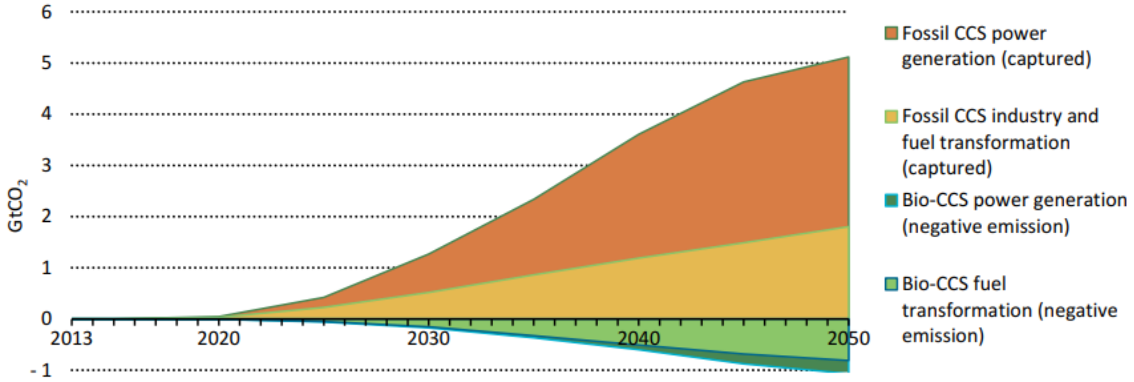


Figure 3.2: IEA's outlook on CCS showing the negative emissions from BECCS.

BECCS with biomass from seaweeds can for instance be done through post combustion capturing after utilizing the energy in the biomass. By doing this, it is possible to both utilize the energy stored in the biomass and at the same time capture and sequester CO_2. Figure 3.3 illustrates the CO_2-flow of a BECCS-scenario where the energy from the biomass is utilized for industrial purposes in a facility where carbon capture is possible. After the carbon has been captured and preserved, transport to a suitable sequestration site where it is pumped into reservoirs follows, for instance depleted oil and gas reservoirs.

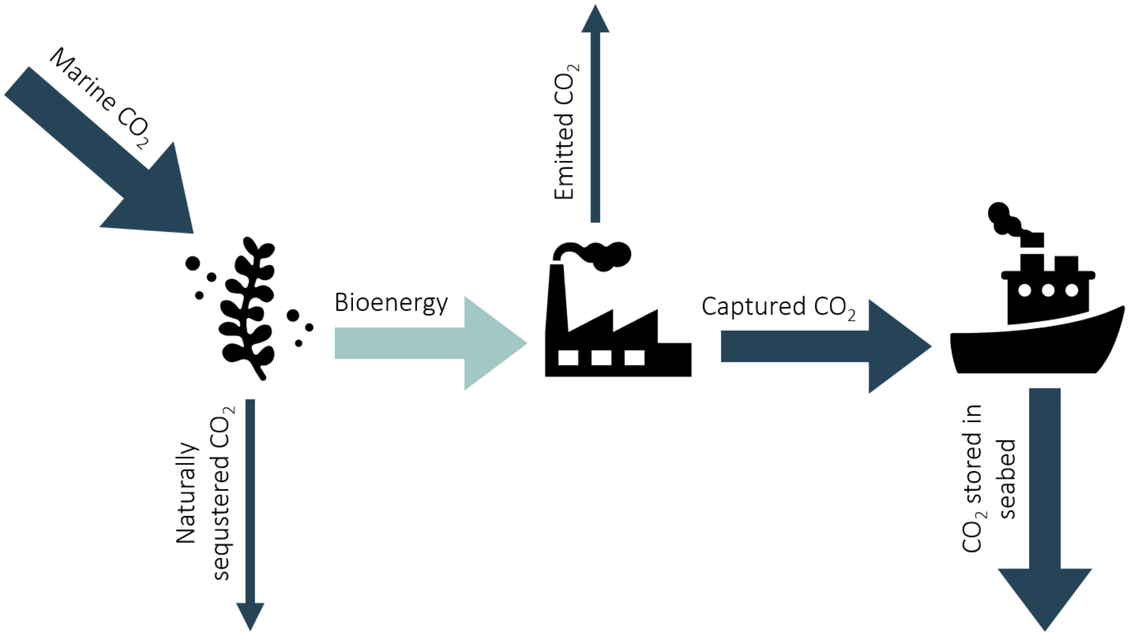


Figure 3.3: Possible CO_2 flow of a BECCS process using seaweed as an energy source in an industrial facility with possibilities of carbon capture

The technology for capturing and sequestering carbon exists, but as of today, due to high costs, low technology availability and several poorly understood environmental risks related to deep sea ecosystems, no large scale seaweed BECCS projects exist (Caldeira et al. 2019). Moreover, commercial large scale BECCS- are assumed unfeasible in the short term. Although, it is interesting to look at the possible impact of such a system in the case that such solutions become available in the future.

Efficiency and cost of carbon capture depend highly on what methods are used. Due to time limitations, capture processes and costs related to such methods will not be assessed in this thesis. As for the capture efficiency, measured in CO_2-equivalent reduction, results from reviewed studies ranges from 65 - 84 % (Odeh and Cockerill 2008;Viebahn et al. 2007;Zhang et al. 2014). ..Hvordan inkludere dette i karbonaccounting?

3.2 Bioenergy Production

There are several methods of utilizing the energy stored in the seaweed biomass, all requiring a varying grade of pre-processing. While direct combustion, conventional biodiesel production, pyrolysis and gasification require biomass drying, wet biomass can be used directly in methods such as anaerobic digestion, fermentation and hydrothermal treatments (Milledge et al. 2014). A high water content in the fresh biomass, along with high ash rates, seems to be the main challenges in the production of bioenergy from seaweeds. As will be discussed in section 4.3, seaweed drying is usually an energy intensive process increasing both the cost and impact of the energy. As mentioned, this is usually carried out by either heating or mechanical drying methods, such as centrifuging or pressing.

Due to the high energy demands for drying, processing pathways utilizing the wet biomass directly have become an interesting topic. Among these methods, methane gas production through anaerobic digestion seems to be the most mature and economically feasible one (Milledge et al. 2014;Fashati et al. 2022). Allen et al. 2015 found a potential biomethane yield from Saccharina latissima of 34.5 m^3 per tonne of wet weight biomass, which gave a much higher yield per hectare than terrestrial options like palm oil diesel and sugar cane ethanol. A more conservative estimate was made by the

Irish study Bruton et al. 2009, where a yield of 22 m^3 of methane per tonne of fresh sugar kelp was assumed. These two methane yields correspond to an energy yield of about 1380 MJ and 880 MJ, respectively.

3.3 Carbon Sequestration in Marine Sediments

As biomass from aquatic plants is eroded and enters the ocean as either particulate organic carbon (POC) or dissolved organic carbon (DOC), a share of it will sink to the deep oceans or settle in the sediments. This will lead to that some of the carbon gets long term stored away from the ocean ecosystem and hence also the atmosphere. This sequestration effect is an essential ecosystem service that helps balance the carbon levels in the atmosphere. It has been estimated that this natural sequestration of aquatic plants and other organisms is removing carbon in a range of 61-268 Tg per year, which accounts for about 10 % of the net global primary production (Krause-Jensen and Duarte 2016). Some studies have also suggested that an increased concentration of atmospheric CO_2 can lead to increased CO_2-sequestration by organisms in the ocean (Arrigo 2007) as if the system is seeking equilibrium.

Figure 3.4 shows the different pathways carbon can be sequestered through seaweed. The sequestration starts by erosion of the plants, such that detritus material on forms of either DOC or POC is released into the ocean. Further, while most of the carbon is either remineralized or retained in the shelf, some is buried directly in the shelf or sinks to deep oceans. As indicated, it is believed that the largest contribution to the sequestration effect comes from DOC being exported to the deep ocean.

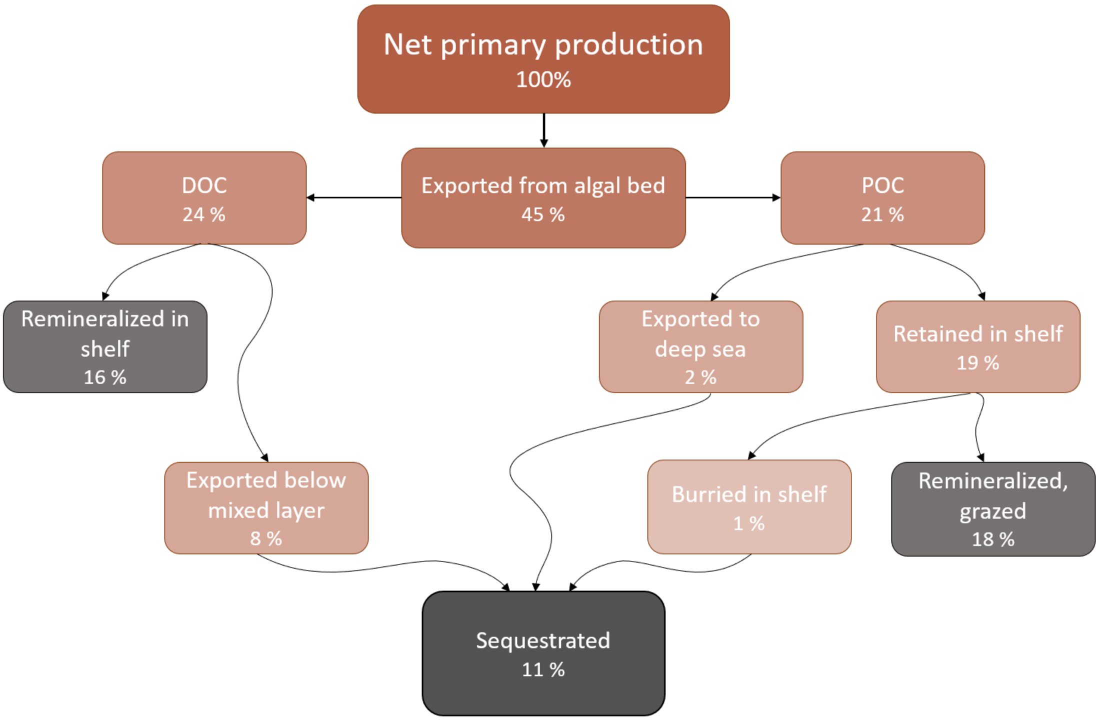


Figure 3.4: Overview of how natural organic carbon from seaweeds i sequestrated in the seabed. Inspired by figure with corresponding numbers in Krause-Jensen and Duarte 2016.

3.4 Carbon Content and Sequestration of Saccharina latissima

Varying chemical composition from one seaweed species to another leads to varying rates of erosion and hence also carbon transport. To estimate the carbon sequestration due to kelp erosion, the carbon content in the plants, along with the erosion rate and estimates of the particle sequestration potentials, are essential parameters.

Equation 3.1 can be used to calculate the amount of sequestrated CO_2 from m_{sw} tonnes of kelp. Here, α is the mass percentage of carbon in the seaweed, β is the erosion rate, M_{m,CO_2} and $M_{m,C}$ is the molar mass of carbon dioxide and carbon, respectively and γ is the rate of the eroded mass.

$$m_{CO_2} = \alpha \cdot \beta \cdot \frac{M_{m,CO_2}}{M_{m,C}} \cdot \gamma \cdot m_{sw} \tag{3.1}$$

The molar mass of carbon and oxygen is 12 g/mol and 16 g/mol respectively, meaning that carbon comprises 27.27% of the mass of CO_2. Assuming that 100 % of the carbon in the harvested kelp is absorbed CO_2 from the ocean, 1 kg of carbon in the kelp then corresponds to 3.67 kg of absorbed CO_2.

As mentioned earlier, Saccharina latissima is a species with a relatively high carbon content compared to other species. Table 3.1 shows the reported carbon contents found in the kelp from different studies. As can be seen, the concentration varies with both cultivation depth and season. Although the carbon concentration seems to be higher earlier in the season, a much higher biomass yield can be expected later in the season, making the total carbon content larger later in the season.

Table 3.1: Carbon content in Saccharina latissima reported by different European studies.

α	**Location**	**Remarks**	Source
33 %	Central Norway	3 m depth, August	Sharma et al. 2018
29 %	Central Norway	8 m depth, August	Sharma et al. 2018
28 %	English Channel	Of dry weight, avergae over a season	Gevvaert et al. 2001
27 %	Central Norway		Fieler et al. 2021
24 %	Northern Norway		Fieler et al. 2021
23 %	Northern Portugal	In the blade, July, exposed location	Azevedo et al. 2019
27 %	Scotland	Wild seaweed	Schiener et al. 2015
28 %	Average Norway		
27 %	Average all		

Erosion rates of the plants will depend highly on how late in the season it is harvested. Forbord, Matsson et al. 2020 shows how the biomass and length of sugar kelp vary through the season in different latitudes along the Norwegian coast. The biomass peak varies from June at 58 °N to august at 69 °N, indicating increased erosion rates when waiting past this point with harvesting the biomass. This is confirmed by Fieler et al. 2021, in which a study of the erosion rates of Saccharina latissima at two locations along the Norwegian coast was carried out. Here, it was reported erosion rates of 49 % and 13 % of kelp harvested in central Norway and northern Norway, respectively. In both cases, the kelp was deployed in February and harvested in August.

As indicated by figure 3.4, the sequestration depends on several processes, each with relatively large uncertainties regarding the amount of biomass and particles that are affected. Therefore, there is a great uncertainty related to the final estimation of sequestered carbon. From reviewed research, a rate of between 10 and 15 % can be assumed (Hughes et al. 2012; Krause-Jensen and Duarte 2016).

4 Introduction to Life Cycle Assessment

LCA is a method developed for assessment of the environmental impact of a product or a process. Environmental impacts in this regard are impacts related to natural resources, human health and ecosystems. All relevant energy and material flows that follow the product through its production, user phase and end of life are accounted for in the assessment.

Raw material extraction, processing, utilization and waste handling of each material generates a series of emissions as well as impacts related to land and water usage. In the LCA, these are added up for all materials included in a product, along with emissions and land use related to the assembly, utilization and waste handling of the product itself. The result is further used to quantify the environmental impact of the product.

The international standard framework for LCA is explained by ISO 14040 and ISO 14044 (ISO 2006a; ISO 2006b), which will also be the basis of the LCA performed in this thesis. This framework divides the assessment into four main stages; a goal and scope definition, a life cycle inventory (LCI), a life cycle impact assessment(LCIA) and an interpretation. The work methodology follows the flowchart in figure 4.1. As seen, the interpretation is done continuously throughout the process. This is important because it, in many cases, will be necessary to adjust boundaries, input data and assumptions as new information about the system is obtained or due to lack of data.

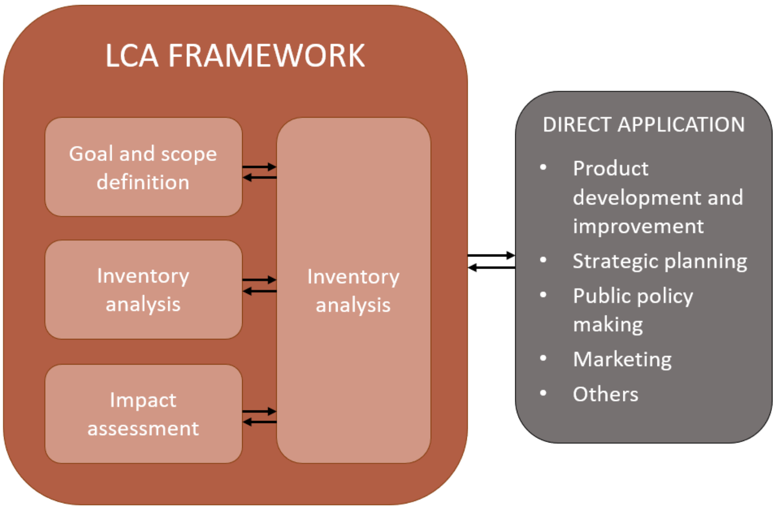


Figure 4.1: The LCA framework as described by ISO 14040.

The frame to the right in figure 4.1 presents stakeholders that typically share an interest in the results given by an LCA. One application of the LCA is as a basis for an unbiased comparison of different products that can fulfil the same function. Other than for comparison purposes, the assessment will give an overview of contributions from the different input flows related to a product and hence the impact hotspots. This makes up a good basis for considering which materials or processes have the most significant mitigation potential. Both comparison assessments and hotspot assessments can serve as design support tools, as they indicate either the best of two or more solutions or if there are environmental weaknesses of a product that should be reconsidered. Besides being a design support tool, the LCA can be used solely as a reporting tool from the producer to customers or policymakers.

Not all LCA take the complete life cycle into account. As indicated by figure 4.2, an assessment of the entire life cycle is referred to as a cradle to grave assessment. In contrast, a cradle to gate assessments accounts for the production phase only, a gate to gate assessments accounts for the user phase and lastly, a gate to grave assessment studies the end of life phase. In many cases, it will be sufficient to look into only parts of the life cycle, but this depends on the goal of the assessment. Considering that the LCA is usually a very comprehensive study, focusing on only parts of the life cycle can open possibilities for going more into detail in the study.

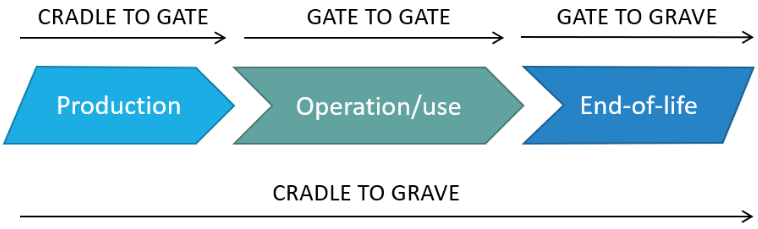


Figure 4.2: A LCA can include either the whole life cycle or focus only on the production or use phase.

4.1 Methodology

The following sections describe the different steps of the LCA. It should be noted that LCAs can be conducted in many different ways depending on the goal and application of the results(Finkenbeiner 2014).

4.1.1 Goal and Scope Definition

The goal lays the foundation for all choices made throughout the assessment. A well-defined goal is therefore essential. Based on the goal, a scope with well-defined boundaries, main focus areas and functional unit for the assessment is decided. It is important that all these aspects are adjusted such that the assessment gives results suitable for answering to the goal. If this is found to be difficult due to for instance lack of data, one should consider adjusting the goal of the assessment.

An important aspect of the LCA is that it evaluates the function that the product provides and not the product itself. This way, it is easier to compare different products providing the same function. For instance, instead of assessing the environmental performance of a specific car or ship, you assess the ability the car or ship has to transport some specific type of goods. The impact will then be measured per tonne of transported goods and hence, it is possible to compare a series of different methods for transporting the goods. The unit used to assess a product is called the functional unit. For the example above, the functional unit can for instance be impact per tonne of material transported from one specified city to another.

The functional unit must answer to the goal of the LCA, and for the purpose of comparing results with other assessments, one should seek to make it as general as possible. For kelp cultivation, the functional unit should match the application of the biomass. For instance, if the application of the kelp is fish feed, it is usually aimed to produce as much protein as possible, and hence, the functional unit should be based on the amount of protein attained in the production. However, if the biomass is to be used as a biofuel, the functional unit should be based on the amount of energy that is possible to obtain.

In the goal and scope definition, it is also necessary to set boundaries for the assessment and specify foreground and background processes. The foreground processes of an LCA are the activities or subproducts that are in focus in the assessment. For these, data should be as specific for the assessed case as possible. The remaining, and often up to 99 %, are background processes where data is collected from generic cases in LCI databases ('The ecoinvent database version 3 (part I): overview and methodology' 2016).

Describing the boundaries of the assessment thoroughly strengthens its credibility and makes it easier to reuse the results for comparison in other analyses. The boundary description should inform the reader about the following:

- Neglected processes and approximations
- Geographic limits
- How multifunctionality is dealt with
- How waste materials are handled

Approximations and neglects are often necessary due to limited data and resources. As well, it will often not be essential to include all material and energy flows of a life cycle in order to obtain sufficient results. Making reasonable assumptions can make the assessment less time consuming without reducing the value of the results.

For most processes and materials in the databases, the geographic origin is specified. This can have a significant influence on the impacts, often due to differences in the energy mix used in different countries. Additionally, waste handling regimes will also differ from country to country. Due to this, relevant geographic boundaries must be specified in the scope of the LCA.

The two latter points are in many cases easier to describe through the inventory phase and are further described in section 4.1.2.

4.1.2 Inventory Analysis

To calculate the impact of a product, extensive amounts of data about the materials and processes in a life cycle need to be collected. The data is collected through the inventory analysis. Depending on the level of detail required, the process of gathering data can be very time consuming. It is therefore common to use data from standardized LCI-databases, which provide LCI-data on a range of different processes. A more thorough discussion on such databases follows in section 4.2.

The analysis is divided into three stages: The assembly, which is the production phase of the product, the life cycle, where processes related to the usage of the products are accounted for and lastly, the end of life phase. In the latter stage, it is necessary to specify what happens with the product after its functional life through a disposal scenario. Here it can then either be disassembled, reused or sent directly to waste treatment.

If the product is disassembled, one will end up with a set of subassemblies, which again needs to be allocated to a disposal scenario. If the product can be reused as it is, the reuse can be credited in a closed loop where flows needed to make reuse possible are added, and the impacts of product itself is subtracted from the system. Lastly, in the waste scenario, the assembly will be sent directly to waste treatment, where it is split up into separate materials such that each material can be treated separately. For each assembly or subassembly, the proportion being sent to each of the three scenarios is specified.

When gathering data, it is necessary to choose how multifunctionality and interconnected processes and materials, meaning that they in some way serve in processes outside the boundaries of the assessment itself, are dealt with. There are mainly two different ways of modelling this; by consequential modelling or by allocation.

In consequential modelling, the consequence of introducing a material or product that can possibly replace another is taken into account. Hence, the product can be rewarded for the emissions avoided by not producing a competing product. Further, this type of modelling takes the product's impact on the global market into account, often making the assessment more comprehensive. Consequential modelling is typically used in cases where it is aimed to investigate the result of a baseline change in the form of replacing one product with another (PRé-Sustainability 2020).

Attributional modelling is less complicated as it mainly accounts for the system itself and uses average product and energy flows from the markets. Here, multifunctionality can either be dealt with by allocation or subdivision. In allocation, one allocates a part of the total impact from a process to the studied output based on a physical relation between the studied product and co-products, usually energy, mass or economic value. Using subdivision, processes are divided into sub-processes at a level where the studied product can be treated separately from the others (Environment and Sustainability 2010; ISO 2006b). In line with ISO 2006b, subdivision is the preferred of the two methods. However, subdivision requires data with a high level of detail and is therefore often not possible.

4.1.3 Impact Analysis

The third step of the LCA is the impact analysis. Here, the stressors from all processes and materials specified in the inventory analysis are used to calculate the environmental impact. The calculations are carried out by allocating the impact of the stressors to so called midpoint categories. These are physical environmental effects, for instance GWP, eutrophication or human toxicity. The midpoint categories can further be used to calculate more general endpoint categories, typically impacts on human health and ecosystems.

ISO 2006a divides the impact analysis into six different steps:

1. Selection of impact categories, indicators and characterization models
2. Classification, where LCI results are assigned to the impact categories
3. Characterization, where category indicators are calculated
4. Grouping of the impacts
5. Weighing of the impacts
6. Data quality analysis

The first three are stated to be mandatory, while the remaining three are optional steps which are recommended if the goal of the assessment requires it or they can substantiate the results.

Usually, standardized methods for weighing and calculating the mid- and endpoint impacts are used. This makes it easier to compare the results to similar studies. The methods differ in the number of categories taken into account, which substances they cover and whether they have a midpoint approach, an endpoint approach, or a combined approach. ReCiPe is an example of the most commonly used models, where 18 different midpoint categories are taken into account. These categories are used to calculate the three endpoint categories damage to resource availability, damage to human health and damage to the ecosystem (Huijbregts et al. 2017). Hence, this is a method combining midpoint and endpoint categories, in contrast to other methods focusing on only one of the two. An overview of the stressors, mid- and endpoint indicators, and how they are infected by each other is given by figure 4.3.

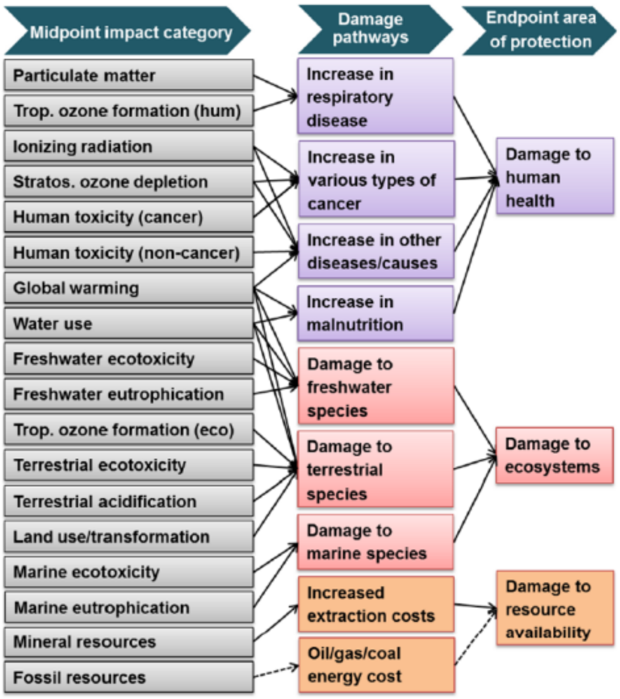


Figure 4.3: Overview over the pathways from midpoint indicators to the three endpoint indicators in ReCiPe2016, PRé-Sustainability 2020.

The choice of impact categories should be based on the goal of the assessment. Many assessments focus solely on specific environmental impacts, for instance global warming potential or human toxicity. For such studies, a single issue method focusing on the given category isolatedly can be more valuable than the typical mid- and endpoint methods. Single issue methods are not included in the ISO standards but are generally robust and easy to understand (PRé-Sustainability 2020). For the particular assessment carried out in this thesis, where the main goal is to find the net carbon uptake potential, a single issue method estimating GWP is more interesting than a more general LCIA method. Though single-point issues can help answer questions regarding the impact in the studied category, one should be aware of the limitation of the results, which will never give a complete impression of the environmental impact of the product.

4.1.4 Interpretation

The interpretation is an iterative process carried out continuously through the assessment, where the three other parts are evaluated and adjusted. Here, weaknesses and limitations of the assessment, along with a review of the possible effects these will have on the result, should be discussed. This part often includes a sensitivity analysis, where the significance of the different parameters is assessed. Lastly, this is also the discussion- and conclusion part of the assessment, and where the goal of the study should be answered to.

It is common to perform a sensitivity analysis to be able to interpret the relative impact of different parameters in the analysis. The sensitivity analysis is carried out by redoing the LCIA with adjusted parameters. Each parameter will have to be tested separately, and it is common to adjust the parameters from 50% to 150% of the base case value. This way, it is possible to discover if the results are very sensitive to changes in certain parameters. If so, inaccuracies or uncertainty in such parameters can lead to significant inaccuracy or uncertainty in the final results.

In addition to revealing weaknesses in the results, sensitivity analysis can be used as a tool to compare different scenarios by letting the scenarios be a variation of the base case. As the LCA performed in this thesis will be applied as design support, and it is aimed to explore how changes in the design parameters will affect the GWP, a scenario-based sensitivity analysis will be carried out. This analysis will further be the basis for the discussion of impact reduction potentials of the base case.

4.2 Databases and Software

4.2.1 LCI databases

When performing the inventory analysis, LCI-databases are used to make the process of data gathering manageable. There are different options when choosing a database, each with varying levels of details and data accuracy. Some databases focus on specific countries or industries, while others are more general. Ecoinvent is known to be a reliable database and one of the most consistent sources of emission data, covering a wide range of industries (SimaPro 2022; 'The ecoinvent database version 3 (part I): overview and methodology' 2016). It also seems to be the most used database in the LCA literature review.

There will not be a thorough evaluation of alternative database options. However, it is important to be aware of the discrepancy that can occur as a result of using different databases. Several studies have shown a large variations in results (Pauer et al. 2020). Comparing ecoinvent to another well known and often used database, GaBi, research has shown that the discrepancy in results related to climate change is relatively small while ecoinvent generally has given higher impacts in the other categories (Pauer et al. 2020; Emami et al. 2019).

In principle, combining data from different databases is not problematic, but as discussed above, different databases can provide results with significant differences. Therefore, and due to limited knowledge about the quality and framework of other databases, ecoinvent is chosen for the assessment carried out in this thesis.

4.2.2 SimaPro

Several tools simplifying life cycle assessments are available. In this thesis, SimaPro will be used to do the calculations. SimaPro gives access to the ecoinvent database, among others, and several standardized impact assessment methods such as ReCiPe. SimaPro is a well established LCA software and seems to be the most frequently used in the industry. Another advantage is the easy access to guidance, tutorials and documentation.

When modelling an assessment in SimaPro, the inventory analysis is divided into five stages: Assembly, life cycle, disposal scenario, disassembly and reuse. In the assembly, all material flows, along with processes needed to assemble the products required through the life cycle, are introduced. Under the life cycle, all stages of the life cycle, from the assembly, operation and end of life, are linked together. Further, in the disposal scenario, flows from the assembly are linked to flows in the disassembly and reuse such that all material entering the system also leaves the system. In the disassembly and reuse, processes that make it possible to dispose or recycle the materials introduced in the assembly are added. This structure has two purposes; to help the user organize the data and the program read the data correctly, in particular, linking the materials introduced in the assembly to the materials treated in the disposal and reuse phase.

While the ISO framework divides the LCIA into six steps, in SimaPro, the calculations are performed in five steps: Characterization, damage assessment, normalization, weighing and addition (PRé-Sustainability 2020). The choice of categories, i.e. the first step in the ISO framework, is done manually when an LCIA method, for instance, ReCiPe midpoint, is chosen. Further, the classification step is predefined in the chosen LCIA-method.

As the stressors from the modelled process are assigned to impact categories, the relative contribution from each stressor in each category is calculated by multiplying with characterization factors. The damage assessment, being an optional step, is added to assign impacts to endpoint categories, if this is of interest for the analysis. Further, in the normalization step, which is optional as well, the impact in each category is divided by a chosen reference value, making it possible to compare the impact to a reference impact, for instance the average yearly impact of a Norwegian household. The weighting can then be carried out to convert relative impacts to a total score, or independent total scores for each category.

4.2.3 Mathematical Framework for LCA

All calculations, except those done to calculate quantities in the inventory analysis, are carried out by SimaPro. In this section, a short explanation of the mathematical framework that the LCA, the inventory analysis and the LCIA in particular, is built on, will be presented. Understanding this is considered important to understand and interpret the results given by the analysis.

The mathematics behind an input-output analysis is often used to explain the LCA methodology. This will also be the basis for this explanation, which is based on W.Leontief 1986.

First, letting the x be a vector representing all outputs from a process, y be a vector with all inputs and A be a matrix with values a_{ij}, which gives the amount of process i needed for each unit process j, equation 4.1 represents the relation between the input and output of a process.

$$x = Ax + y \tag{4.1}$$

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \end{bmatrix} = \begin{bmatrix} a_{11} & \cdots & a_{1j} \\ \vdots & \ddots & \vdots \\ a_{i1} & \cdots & a_{ij} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ \vdots \end{bmatrix} + \begin{bmatrix} y_1 \\ y_2 \\ \vdots \end{bmatrix}$$

It was Wassily Leontief who first described this model. As shown by equation 4.2, the equation is made linear by inverting the process matrix, A, and the inverted matrix obtained is known as the Leontief inverse, L.

$$(I - A)x = y \implies x = (I - A)^{-1} \cdot y \implies x = L \cdot y \tag{4.2}$$

Further, a stressor matrix, S is introduced. The values in this matrix, s_{ij}, relates the input to stressor i from process j. Multiplying the stressor matrix with the output vector, as shown in equation 4.3, we get a vector, e, expressing the total impact in each stressor category.

$$e = Sx \tag{4.3}$$

$$\begin{bmatrix} e_1 \\ e_2 \\ \vdots \end{bmatrix} = \begin{bmatrix} s_{11} & \cdots & s_{1j} \\ \vdots & \ddots & \vdots \\ s_{i1} & \cdots & s_{ij} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ \vdots \end{bmatrix}$$

By transforming the output vector to a diagonal matrix, as shown below, and replacing this with $\hat{x}$ in equation 4.3, as shown in equation 4.4 it is possible to get a complete overview of each process' contribution to each stressor

$$\hat{x} = \begin{bmatrix} x_{11} & 0 & \cdots & 0 \\ 0 & x_{22} & \iddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & \cdots & x_{ij} \end{bmatrix}$$

$$\hat{e} = Sx \tag{4.4}$$

The mathematical relations presented so far will further be used to explain the methodology used in the LCIA when the stressors are going to be used as input to calculate the midpoint category impacts.

We now introduce the characterisation matrix, C, which contains the relation between a stressor j and an impact i. This is used to calculate the impacts in each chosen category, given by the vector d, as shown in equation 4.5. Here as well, x can be replaced $\hat{x}$ to get a better insight into how each stressor contributes to the categories.

$$C = \begin{bmatrix} c_{11} & \cdots & c_{1j} \\ \vdots & \ddots & \vdots \\ c_{i1} & \cdots & c_{ij} \end{bmatrix}$$

$$d = C \cdot e \tag{4.5a}$$

$$d = C \cdot \hat{x} \tag{4.5b}$$

4.3 Literature Review: LCA in Seaweed Aquaculture

To get a better understanding of the impacts flows of kelp cultivation and for comparison purposes, a literature review of comparative assessments is carried out. The focus of the different assessments varies, but energy from biogas and proteins for animal feed seems to be the most researched topics. Table 4.1 gives an overview of the reviewed studies before details and results from the studies are further discussed.

Table 4.1: Overview of the seaweed assessments reviewed.

Focus	**Functional unit**	**Main conclusion**	**Ref**
Comparative study of protein from seaweed and soy	1 t of protein	Seaweed has a higher impact than soy, mainly due to the drying process	(1)
Comparative study of protein from seaweed and soy in addition to evaluation of hotspots in the sugar kelp production value chain	1 t of protein	In most cases, seaweed has higher impact than soy	(2)
Comparative study of two different cultivation facilities	1 t of protein	Most significant impact from drying, similar results from the two systems	(3)
Comparative study of two seedling methods and four preservation methods	1 t of fresh kelp	Choice of preservation methods is important. In the supply chain, more CO_2 and PO_4 is absorbed than emitted	(4)
Finding impact hotspots for offshore cultivation	Different food products, looking at 1 kg of edible product	Transport to cultivation site is a hotspot. Including kelp in a diet will reduce land use and GWP	(5)
Energy return and impact of processing seaweed for bioethanol and biogas	1 MJ of energy (based on lower heating value of energy carrier)	Seaweed can compete with other feedstocks in terms of sustainability	(6)
Study environmental loads of producing biogas from seaweed	A year of energy production in a biogas plant	With regards to environmental loads, algal biogas performs 92 % better than natural gas from fossil resources	(7)
Comparing the impacts of biogas from seaweed and natural gas	1 km trip with a gas powered car	Algal biomehtane may potentially have a lower impact than natural gas, but not with available technology used at the time of the study	(8)
Comparison of GWP of bioethanol production from seaweed and terrestrial plants	1 kL of bioethanol	Long term, GWP for bioethanol from seaweed performs slightly better than that from terrestrial plants	(8)
Comparing two different long line systems for seaweed cultivation in Ireland and France	Biomass corresponding to 1 MJ	The greatest potentials for impacts reduction lays within energy demanding processes such as seedling and production	(9)
Comparing different production scenarios for production of bioethanol, liquid fertilizer and protein-additives for fish feed	Harvested biomass from 208 km^2	Seaweed cultivation has a carbon reduction potential of 10 and 280 kg CO_2-eq/ha in the base case and best case, respectively	(10)
Comparing two different pathways to utilize seaweed in biogas production and identify hotspots in the production cycle	Cultivation and processing of 1 t biomass (Dry weight)	GWP reduction potential of 446 and 184 kg CO_2-eq/ha for the two different scenarios. The seaweed cultivation was a hotspot in the production line	(11)

References
(1) Halfdanarson et al. 2019
(2) Koesling et al. 2021
(3) Oirschot et al. 2017
(4) Thomas et al. 2020
(5) Slegers et al. 2021
(6) Aitken et al. 2014
(7) Pilicka et al. 2012
(8) Langlois et al. 2012
(9) Jung et al. 2016
(10)Taelman et al. 2015
(11)Seghetta et al. 2016
(12)Alvarado-Morales et al. 2013

Halfdanarson et al. 2019 compares the impact of one ton of seaweed protein concentrate to the impact of one ton of soy protein to figure out whether seaweed is a good replacement for soy in fish feed. Due to high emissions in the drying phase, the study concludes that the protein from seaweed has a significantly larger footprint than protein from soy. In this LCA, the product is assessed from cradle to gate, i.e. from the beginning of the production to the functional unit is reached and hence, it does not account for utilization of the protein. The same conclusion is drawn by Koesling et al. 2021, where 23 different scenarios of sugar kelp cultivation were modelled. Here, deployment and harvesting season, protein content, sea farm location, the service life of the farm and energy source for drying are assessed parameters. Out of the 23 scenarios, only two give lower GWP than the modelled GWP for soy protein. In addition to energy for drying, the protein content and dry mass of the kelp have a significant influence on the results.

One ton seaweed protein is also the functional unit in the LCA presented in Oirschot et al. 2017. This study is comparative in the sense that two different farming systems are compared; one with a single strip at 2 m depth, consisting of several ropes in the horizontal plane, and one with two strips, on 2 m and 4 m depth. From this study, it is concluded that the impacts of the two different systems are very similar, with the dual strip configuration performing slightly better. Here, as in Halfdanarson et al. 2019, the drying process is highlighted as giving the most significant contribution, followed by the impacts of the materials used in the infrastructure.

Comparison of impacts of different seedling and preservation methods has also been of interest. Thomas et al. 2020 performs an LCA where two different seedling methods and four different preservation methods are compared. For one of the seedling methods, the spores settle directly onto a string by putting it into a concentrated spore solution. For the second one, the fertile gametophytes are sprayed onto the collector. The four compared drying methods are outdoor drying, where the kelp is kept on the substrate until after drying, cabinet drying, ensiling and freezing. As functional unit, one tonne of fresh kelp is chosen. This is mainly because the products resulting from the different preservation methods will be different. In this study, the LCA is performed from cradle to gate and hence, the utilization of the kelp is not included. The results are therefore from a stage where all the carbon is stored in the biomass. For this to have a long term carbon mitigation effect, the biomass will have to be handled so that the carbon is sequestrated.

Slegers et al. 2021 studies the impact of seaweed for different food purposes, from cradle to grave. Here, transport to the cultivation site related to installation, harvesting and observation is a hotspot in the production chain, accounting for between 73-80% of the total impact of the cultivation. In addition, system design and seaweed yield are highlighted as parameters having a significant influence on the total impact. The study concludes that including Saccharina latissima in a diet will contribute to reducing land use and GWP.

Several assessments focus on potential biofuel production, using the electrical or thermal energy of the biomass as functional unit. Aitken et al. 2014 assesses the energy return of three different macroalgae cultivated and processed for biofuels in Chile. In this study, energy return on investment, here represented by the lower heating value of the produced carrier divided by the total non-renewable fossil energy demand, is used as the main impact category. Additionally, climate change, acidification potential, eutrophication potential, stratospheric ozone depletion, photochemical oxidation and human toxicity are evaluated. It is concluded that the seaweed bioenergy can become highly competitive to other energy feedstocks in terms of sustainability. Another similar study found that algal biogas could perform as much as 92% better than natural gas in the comparison of real environmental loads of energy production(Pilicka et al. 2012).

Langlois et al. 2012 presents a cradle to grave study where it is looked into the impact of a 1-km trip with a gas-powered car. This assessment, which compares natural gas from both unpreserved whole seaweeds and alginate extraction residues, found that macroalgal biomethane had the potential of having a lower impact than that of natural gas. However, with the state of the art technology for cultivation at the time of the study, the impact of using macroalgae was found to be larger than that of natural gas from fossil resources.

Comparing seaweed biofuel to other types of biofuels has also been of interest. This was done in Jung et al. 2016, where the impact of bioethanol from the brown algae Laminaria japonica was compared to terrestrial bioethanols. Results indicated that the GWP of seaweed bioethanol, in the long term, was slightly smaller than that of terrestrial bioethanol. Here, cultivation equipment, conversion yield and productivity were found to be the largest contributors to the total footprint of the seaweed. For the biomass production alone, a GWP of 396 kg CO_2-eq/kL. Having a wet weight density of sugar kelp of 1092 kg/m^3, this GWP corresponds to 363 kg CO_2-eq. per tonne of fresh kelp.

In Taelman et al. 2015, two different cultivation systems are compared, as well as the energy production potential of seaweed compared to terrestrial plants. The first of the two systems is a long line system located on the West Coast of Ireland, while the other is a smaller raft system on the Northern coast of France. Fuel usage in transport accounts for a major part of the total impact, and increased distance from the hatchery/fabrication site to the farm will hence lead to a significant impact increase. Seaweed produced in the North-West Europe, as of 2015, was showed to be relatively resource efficient compared to energy production through microalgae and several terrestrial plants. The greatest potential in decreasing the footprint would be by reducing energy demanding processes such as transport and seedling production

A thorough assessment of the production cycle done by Seghetta et al. 2016 used the conservative biomass yields from Limfjorden in Denmark, as presented in table 2.1 as a basis. Here, the five parameters were tested; productivity (high/low), species (Saccharina latissima/Laminaria digitata), conversion technology (simultaneous saccharification and fermentation/separate hydrolysis and fermentation), harvesting season (spring/summer) and lastly, farm design (seeded line/hollow rope). This study accounts for the positive climate effect by substituting fossil products. In the base case, a negative 10 kg CO_2-equivalents per hectare were calculated, while in the best case scenario, which was the scenario with the highest productivity, the result showed a negative 280 kg CO_2-equivalents per hectare.

The assessment in Alvarado-Morales et al. 2013 evaluates biomass production and further processing into biofuels in Denmark. Here, two different scenarios are evaluated: Scenario one, where the biomass is directly processed into biogas through anaerobic digestion and scenario two, where the biomass is fermented to produce bioethanol while the ethanol stillage from the fermentation is further processed into biogas. Figure 4.4 shows the production pathways of the two different scenarios. Here as well, positive climate effects due to the substitution of fossil fuels are accounted for. Results showed a net negative GWP of 446 and 184 kg CO_2-equivalents per tonne of biomass cultivated, i.e. not included processing, for scenario one and scenario two, respectively. The study also concluded that the seaweed production itself was the most energy intensive through the production.

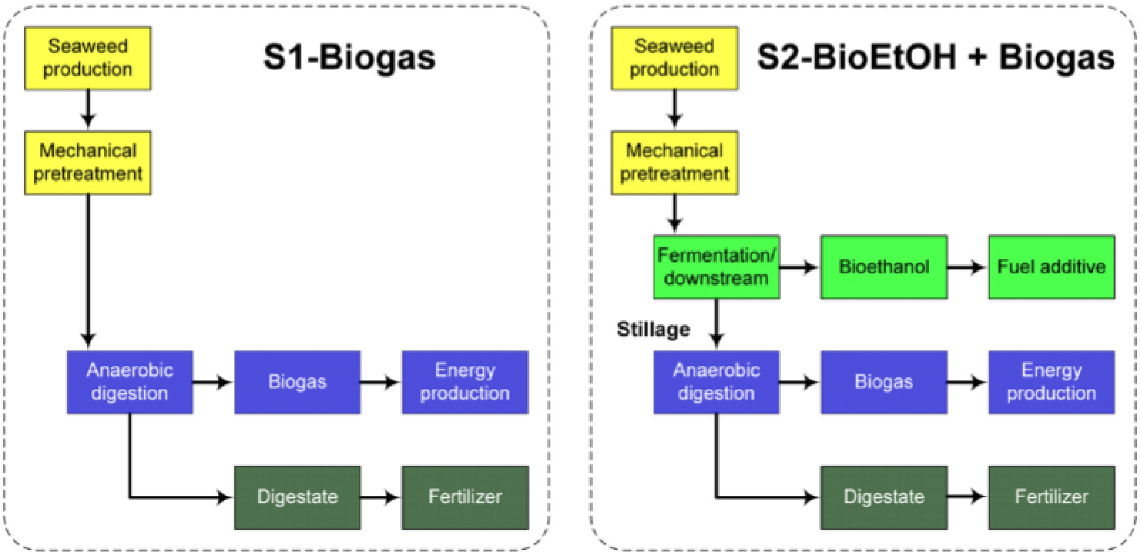


Figure 4.4: The two different biofuel production pathways studied in Alvarado-Morales et al. 2013, (Alvarado-Morales et al. 2013).

To summarize, there seems to be a consensus in that that seaweed has the potential of being a sustainable substitute for soy and fossil fuels. However, there are challenges related to the drying process that can lead to higher emissions for the seaweed product than the options, particularly when comparing seaweed and soy. Besides the drying process, the reported hotspots from the production vary: Both transport, seedling production, as well as the cultivation process itself are mentioned.

5 Cultivation Systems

The primary function of a kelp cultivation rig is to serve as a stationary substrate for seaweed. Further, it should be able to withstand the weather condition at the location for which it is designed and be easy to operate. In this section, the components and design of a kelp cultivation system will be evaluated, and this will be used to outline a base case design along with a logistics plan describing the operation of the rig.

Looking into which rig concepts which have proven successful in exposed areas, i.e. MACR and BAL, and the trial at Klovningen, it appears that the more traditional rig concepts are more robust than other, more inventive solutions. The design used as a base case will therefore be based on these, by the use of a grid based system with ropes, buoys and a mooring configuration similar to that used in fish aquaculture. Before describing the rig design as a whole, the different components are presented along with relevant design options and further, a description of the operations and options for these.

5.1 Components

Components included in the rig are divided into the mooring system, including the frame, the cultivation rope holding the plants, buoys or other floating elements and lastly, markers making the rig visible. While the cultivation ropes will be detached from the rest of the system each year during harvesting, the rest of the system is assumed to be fixed for all of its lifetime.

5.1.1 Mooring System

The mooring system of an offshore rig will be more massive than that of a rig located in sheltered locations. This is both due to increased exposure and but also due to increased depth. SRSL 2019 identifies grid-based systems as suitable for larger rigs or in the cases where space is a restriction. In a based grid system, several cultivation lines share the same mooring system. This is common in fish farm design, where such a solution makes the construction more flexible as the individual fish cages can be removed or replaced without having to affect the mooring system.

Some offshore trials have explored using smaller individual structures using one single mooring line. Examples are the Seaweed Carrier, which was illustrated in figure 2.5, by Seaweed Energy Solutions and the Proaqua rig, as shown in figure 5.1, a single line cultivation concept developed by Proaqua AS. This solution will provide freedom for each of the structures to rotate with the currents but lacks redundancy as each unit is dependent on a single mooring line to function.

Catenary mooring systems have become the standard within both aquaculture and offshore industry. The restoring forces from this system are provided by the weight of the mooring line, which usually consists of a combination of chain and synthetic fibre ropes. An alternative to this is a taut system, where the lines are pre-tensioned and leave the seabed at an angle. The forces here will mainly be taken by the anchor. Taut lines are restrictive in that the moored structure will not be able to adjust to tides and waves.

A taut and a catenary mooring system are illustrated in figure 5.2. As the figure indicates, the seabed impact from the catenary lines is much more significant than that for the taut lines as much of the chain in the catenary system will lay on the seabed. This is a motivation to explore possibilities for using taut lines instead of catenary lines. Studies have shown that taut systems could be feasible for instance for finfish aquaculture (Turner et al. 2018) and offshore renewable energy (Bach-Gansmo et al. 2020), which indicates that such a system could be feasible for offshore kelp cultivation as well.

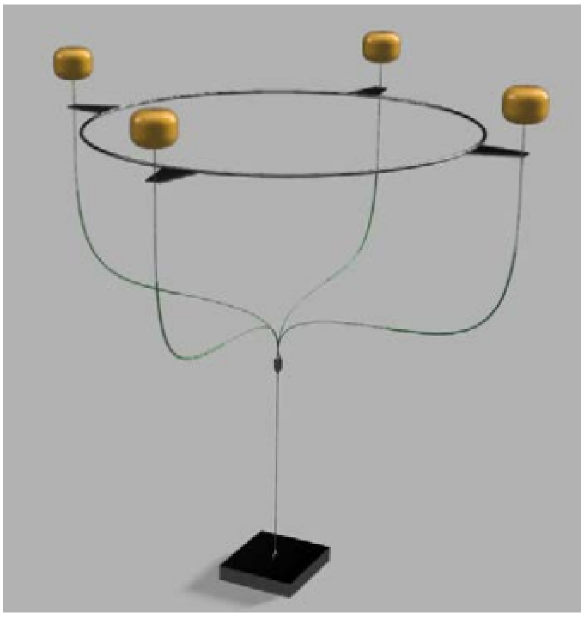


Figure 5.1: Illustration of Proaquas cultivation consept with one single mooring line (Lona, Endresen et al. 2020a).

However, due to limited knowledge about the consequences of choosing a taut mooring system, the catenary system is chosen for the design studied in this thesis.

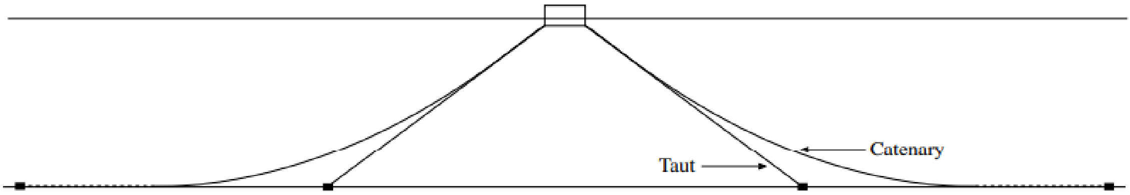


Figure 5.2: Illustration of how catenary and taut mooring lines behaves (Turner et al. 2018).

The choice of anchors should be based mainly on the load factors and the seabed conditions at the site. Figure 5.3 shows the marine sediments outside the coast of central Norway. As seen, sediment type varies, but many areas have either sandy, gravelly, sludgy sediments or a combination of these three. Fluke anchors, which seem to be the most commonly used anchor in fish aquaculture, are suitable for this type of sandy or mixed seabeds (Scale AQ 2022). Fluke anchors have been reported to have a holding capacity of 20-50 times their hown weight, depending on depth, seabed conditions and angle (Randolph and Gourvenec 2011). The traditional fluke anchors do not handle vertical loads well and are therefore mainly suitable for catenary mooring systems.

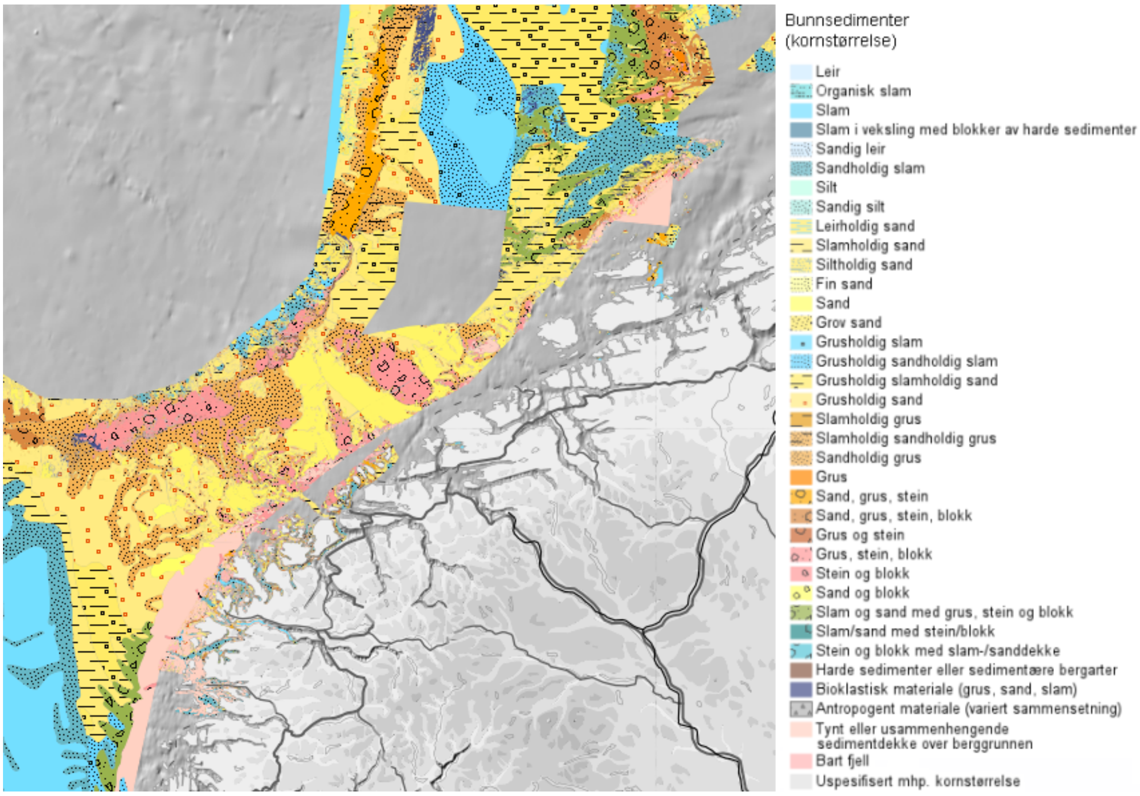


Figure 5.3: Marine sediments outside the coast of central Norway (Undersøkelser 2022).

Base on the options discussed above, a grid based catenary mooring system with fluke chain and fluke anchors to hold the system in place is considered the most suitable for cultivation in an exposed location outside the coast of central. Components of the system will then include mooring lines, mooring chain, anchors, bridle ropes connecting the mooring line and the frame, and lastly, the frame itself, to where the cultivation ropes are attached. In addition, there will be needed shackles to connect the chain to the anchor and the rope to the chain as well as a connector mechanism between the mooring rope, the frame rope and the rope that carries the buoy. Dimensions and capacity of the mooring system should be based on estimated forces that will act on the rig, and the choice of anchoring should be based on the seabed conditions at the site.

5.1.2 Substrate - Cultivation Rope

The substrate is the object on which the seaweed has its holdfast. One dimensional substrate consisting of ropes is the most common in the industry. However, concepts using 2D-substrates consisting of either nets, canvas or ribbons are used commercially as well (Lona, Endresen et al. 2020b). This solution will provide a more dense growth substrate and hence more dense growth, but as explained earlier, the density increases, each plant's access to nutrients and sunlight is reduced, which can lead to reduced growth. Increased plant density will also mean that the system gets a larger surface area, which will decrease the water flow further and thereby increase the forces. This may be unfortunate in exposed areas as the wave and current forces already are relatively large.

One example of the use of 2D-substrate is the former presented Seaweed Carrier by Norwegian-based seaweed farmer Seaweed Energy Solution's. The carrier is a 6.5x5 m sheet designed to withstand offshore conditions (Bak, Gregersen et al. 2020). Another example is Belgian AtSeaNova, who have designed 2D-substrates that are claimed to produce 3 to 5 times more biomass than traditional long lines (Barbier et al. 2019).

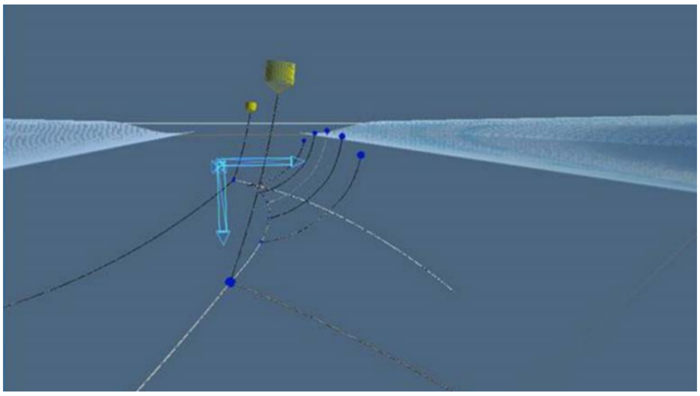


Figure 5.4: Illustration from SINTEF's simulation of a rig with vertical ropes in strong currents (Endresen et al. 2020).

The optimal density can vary from location to location, depending on currents, nutrient concentration and light availability In addition to density, the depth in which the kelp grows will affect light and nutrient exposure as well as waves and current forces. Trials and best practice studies report a range of different depths, ranging from 1-2 m beneath the surface and down to 12-15 m Bak, Gregersen et al. 2020; SRSL 2019).

The depth of the lines will also depend on whether the lines are vertically or horizontally orientated. Of course, the depth of the vertical lines will be in the same range as the length of the cultivation rope, reaching from the depth of the frame to which it is attahed. Generally, the deeper the lines, the less wave force will be experienced, but as well, the less light will reach the plants.

Endresen et al. 2020 studied two similar concepts, one with vertical cultivation ropes and another one with horizontal ones. Results from simulations showed that the rig holding vertical ropes experienced less hydrodynamic forces than the one holding horizontal ropes. The reason for this was the vertical ropes' ability to move with the currents as the ropes were fixed in one end only, and the other was floating freely, attached to a buoy, as shown in figure 5.4.

5.1.3 Buoys and Markers

For the rig to keep in position and at the desired depth, buoys adding positive buoyancy to the rig are used. The buoys can either be attached to the mooring system or directly to the cultivation rope. Another alternative is to use plastic pipes. This solution has been used in more sheltered locations (Mooney-McAuley et al. 2016) but is believed to be less suitable for exposed locations as the large pipes are much less flexible than single buoys and will therefore experience larges forces from waves and currents. Additionally, a failure of a pipe will affect much larger parts of the rig than a failure of a single buoy. Hence, the consequence of failure is higher for this solution.

The rig will also need some kind of markers, making it visible both to those operating it and to traffic. It can be beneficial that some markers at the rig, preferably in the corners of the frame, are lights.

5.1.4 Functional Life of the Components

The cultivation rig is assumed to have a total functional life of 20 years. In reality, this can probably be extended by doing necessary maintenance and replacing components throughout the rig life. As for the individual components, assumptions of their functional life is based on information collected through oral communication with different aquaculture gear suppliers.

All steel components, buoys and markers are assumes to have a functional life corresponding to the functional life of the rig, i.e. 20 years. As for frame and mooring ropes, these are assumed to be replaced every fifth year. Lastly, for the cultivation ropes, these are retrieved from the facility every year during harvest, and it is further assumed that new ropes will be used for each deployment, meaning that the functional life of these ropes is one year.

5.2 Operating Vessel

in the Norwegian seaweed industry, operations are often carried out by small fishing vessels. To perform operations in exposed environments, more robust vessels than those used in inshore, sheltered locations are needed. Forbord, Steinhovden et al. 2018 suggests using vessels with a minimum length of 15-25 m, but this will of course depend on the size of the cultivation system. The larger the system, the more cultivation ropes must be kept on board during deployment, and the more biomass will be transported to land during harvest. Based on the operations carried out during cultivation, further described in section 5.7, it is assumed that installation, operation and decommissioning can be carried out by a fleet consisting of a multipurpose vessel (MVP) and a remotely operated underwater vehicle (ROV). For scenarios where the distance to the processing facilities is large, a dedicated transport vessel could be beneficial. However, for the case studied here, it is assumed that the MPV is sufficient for the transport of the biomass all the way to the processing facility.

It is assumed that the same type of vessel, i.e. the MPV, can be utilized for all operations, including installation and maintenance and decommission of the rig, seaweed deployment and harvesting. For several of the operations, it is assumed beneficial if the MPV can be assisted by an ROV. For this to be possible, the vessel needs to be equipped with facilities for deploying and operating ROVs. Moreover, for harvesting operations, sufficient open deck area, storage rooms and cranes to handle the cultivation ropes will be required.

Most existing vessels use marine diesel oil or heavy fuel oil, but due to stricter emission reduction requirements, more and more vessels are equipped with diesel-electric systems with battery packs increasing the efficiency and lowering the fuel consumption and hence environmental impact. Lindstad et al. 2017 reports a possible 20% reduction in GWP by installing batteries in an offshore support vessel when operating in the North Sea area.

5.3 ROV

A traditional ROV consists of a floating block to provide buoyancy, thrusters for propulsion, cameras and lights, an umbilical to communicate with the vessel, a frame to contain the components and manipulators if needed. The vehicles can either be powered by batteries or receive power from the vessel through the umbilical system. From the reviewed literature, it seems the ROVs are not currently used for assistance in the operations carried out in kelp cultivation. Nevertheless, it is believed that the ROV can be helpful during operations in the production cycle that involves detaching, attaching and retrieving ropes, as well as for inspection. ¨

In the case that an ROV is utilized, it is believed that its main tasks in the production cycle will be assistance in cultivation rope handling during harvest and deployment. As well, it is assumed that it will assist when ropes and steel components are being connected and disconnected during installation, disassembly and maintenance. Lastly, the ROV will be used for inspection of the rig two times during the season. To be able to carry out these operations, it is required that it has good manoeuvrability and is equipped with cameras, lights and manipulator arms.

5.4 Operations

The operations carried out in the industry today are characterized by a lot of manual work and low-tech solutions (Endresen et al. 2020). A commonly used method used for harvesting is to lift the cultivation ropes from the ocean manually or by use of a crane before the seaweed is cut from the rope using a knife or similar equipment. Different concepts for specialized vessels or devices automatizing the harvesting process have been suggested, for instance SINTEFs kelp cultivation vessel or the SPOke-rig, presented in section 2.1. Such solutions would decrease the need for manpower in operations, which would be particularly beneficial for large scale production in more exposed locations.

Methods for operating the rig are based on Lona, Sunde, Mo et al. 2020, Bak, Gregersen et al. 2020 and Mooney-McAuley et al. 2016 but are generally leaned towards new technology granting more effective operations and less use of manpower, for instance use of ROV. Using an ROV will add cost and environmental impact related to construction and energy consumption. On the other hand, the efficiency of the operations is assumed to be decreased, and hence also the costs and impacts related to vessels and manpower.

In the sensitivity analysis in section 7.2, a scenario with increase operational efficiency will be evaluated. This is done partly due to uncertainty in the estimated operation durations but also because there is assumed to be a potential for improvement in the operational efficiency. For instance, it is believed that developing specialized on-board-equipment for retrieving and deploying the cultivation ropes can increase the efficiency in these processes significantly.

In the following, a short description of the activities necessary to install the rig and cultivate the seaweed is given. This will be the basis for the base case operations, presented in section 5.7, which will be used for the inventory analysis of the LCA.

Anchor installation
In fish aquaculture, the anchor handling is often carried out by aquaculture support vessels, which are multi-purpose working vessels able to perform most of the operations necessary for operating a fish farm. These usually have an LOA in a range of 15-40 m and a gross tonnage of 100-400 t. For some of the new large offshore farm concepts, anchor handling requires specialized anchor handling tug supply vessels (Andersen 2021), but for regular net cages it is most often sufficient to use multi-purpose vessels alongside with either ROVs or divers. This is assumed sufficient for the large scale kelp cultivation rigs as well.

During anchor installation, which is the first activity of the rig installation, each anchor is deployed and tensioned by the MPV. The buoys are assembled to the mooring lines to keep the lines floating and visible such that they can easily be retrieved in the frame-mooring line connection.

Frame-mooring line connection
As the mooring system will be pre-installed, the frame, which will hold the cultivation ropes, can be attached directly to the mooring system. It is further assumed that the frame can be deployed as one assembled piece and that the ROV alone, or assisted by a daughter craft, is able to retrieve the mooring lines and connect them to the frame as the frame is deployed from the MPV. This procedure is illustrated in figure 5.5.

Cultivation rope deployment
Deployment of the ropes is done by use of a crane onboard the MVP and the ROV. Cultivation

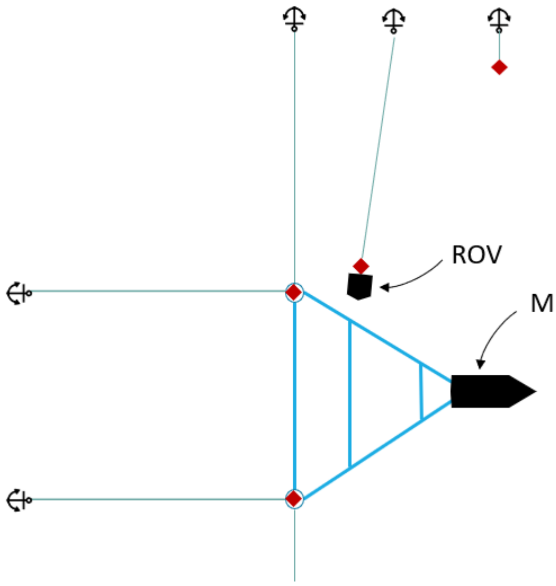


Figure 5.5: Illustration of deployment of the frame and how the pre-installed anchors are attached to the frame by use of an ROV.

ropes and buoys are assumed to be assembled prior to the operation. Having the MPV positioned alongside a frame rope, the hold-fast end of the cultivation rope is submerged to the depth of the frame rope by using the crane. Further, the ROV is used to position and fasten the hold-fast to the frame rope.

Rope disconnecting and harvesting
During harvesting, the cultivation ropes are detached from the frame by the ROV before the crane is used to lift the ropes onboard. Due to the large quantity of ropes, manual cutting is not considered sufficient and hence, this operation will be carried out by mechanical cutting equipment. Further processing of the biomass is assumed to be done after the biomass is transported to shore.

Inspection
After deploying the cultivation ropes, the growth phase starts. During the growth phase, the plants should be monitored to keep track of the growth, biofouling or other diseases and most importantly, the condition of the rig, to be able to predict or detect possible failures. Monitoring can either be done manually or by the use of an ROV or AUV.

Maintenance activities
It is difficult to foresee how much maintenance will be needed on the rig as there is no available failure data for this kind of structures. An estimate of six hours of maintenance each year is therefore assumed. This will include the time it takes to replace the ropes each fifth year, as this is the estimates functional life time for all ropes used on the rig except the cultivation ropes.

5.5 Base Case Rig Concept

The base case scenario outlines a case where seaweed is cultivated on a 10 ha rig located 5 km from the coastline in central Norway.

Initially, it was intended to use simulation software for flexible marine structures to simulate the forces on the rig due to wave and current exposure and further use this to adjust the dimensions of the mooring system. This way, it would have been possible to tailor the rig design to the given conditions and thereby avoid overestimating the dimensions of certain components. However, due to a limited time frame for the study and difficulties obtaining data or estimations on hydrodynamic forces on the kelp, no proper results from such simulations were obtained. Therefore, the design is based on SINTEF's test facility at Klovningen, but scaled up to rig covering a ten hectare surface area. Before the base case rig is outlined, a presentation of the Klovningen Rig will be given.

5.5.1 Test Rig at Klovningen

SINTEF's test rig located at Klovningen is a cultivation system located in an exposed area 6 km outside Kristiansund in central Norway. The location has a seabed with a sandy top layer, making it suitable for drag anchors, and does, according to simulations as described in Broch et al. 2019, provide good growth conditions for Saccharina latissima (Skjermo, Broch et al. 2020).

Detailed information about the rig is obtained from Lona, Endresen et al. 2020b. The rig, which was similar to MACR at the Faroe Islands, consisted of a single 60 m longline moored at 10 m depth on which 5 cultivation ropes, each with a length of 10 m, were attached. The free end of the cultivation ropes was attached to a buoy providing buoyancy, i.e. the cultivation ropes were oriented vertically in the water column. Figure 5.6 outlines the rig design with dimensions as used at Klovningen.

Deployment of the ropes was carried out at the end of January. During the winter, one of the mooring lines failed, causing four out of the five cultivation ropes to be submerged down to 6 meters deeper than originally located. Although the rig was restored not long after the failure, there were large variations in biomass yields for the five ropes, which is believed to be a result of the incident.

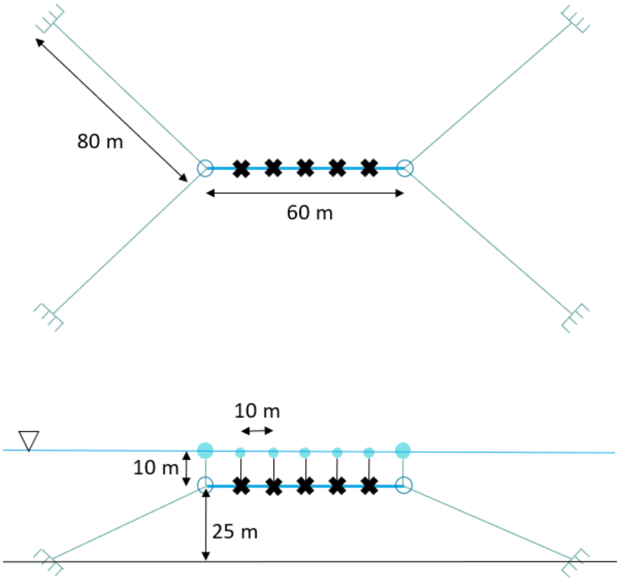


Figure 5.6: Outline of SINTEF's rig at Klovningen, based on sketches in Lona, Endresen et al. 2020b.

5.5.2 Base Case Rig

Figure 5.7 shows the model which was originally made for simulations, modelled in the AquaSim. Even though the model is not used for simulation purposes it is used here to illustrate the base case rig concept. As seen, this is a system of longlines arranged in a frame rather than just one single longline as used at Klovningen.

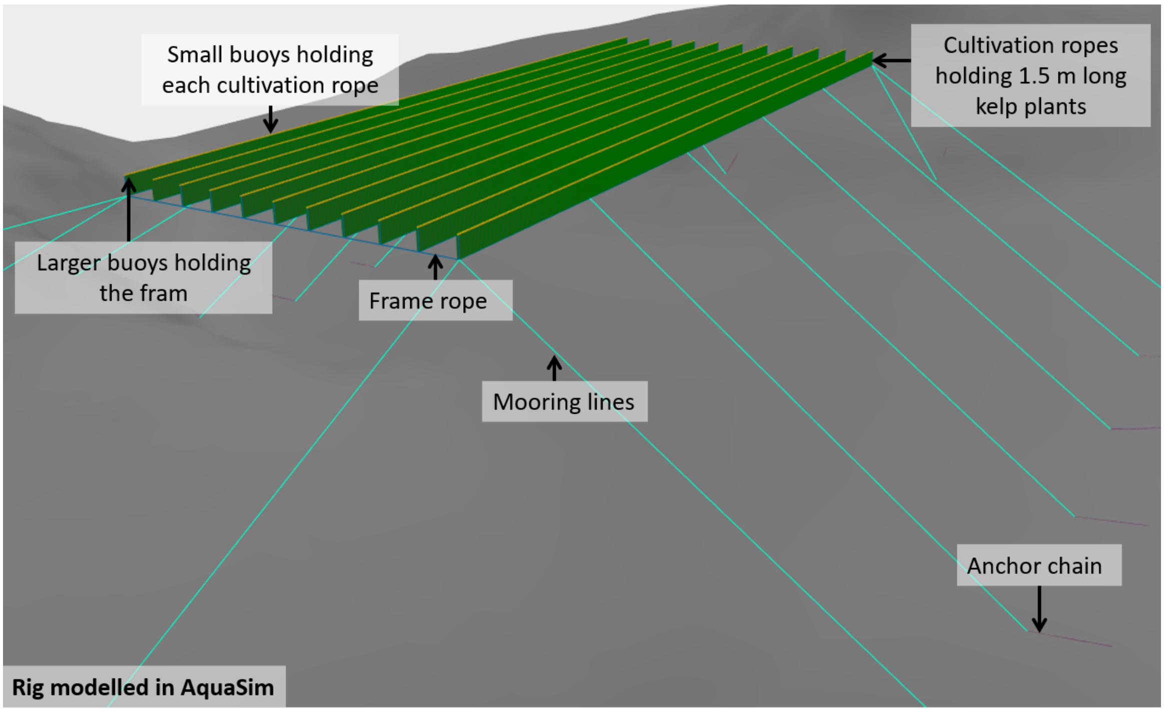


Figure 5.7: The cultivation rig modelled in AquaSim.

Figure 5.8 show the dimensions of the base case rig design. Compared to the Klovningen rig, forces from a larger amount of cultivation ropes will be allocated to each mooring line. This is assumed acceptable due to two reasons: First, test results from Klovningen showed that the frame rope-buoys took a significant part of the forces from waves and currents. Secondly, as all waves propagate in the same direction, along one single horizontal axis, wave forces acting on the three-dimensional rig structure will only affect a fracture of the rig at a given time (Lona 2022).

An overview of the concepts used in the base case design is given by table 5.1.

Table 5.1: Offshore seaweed rig components and characteristics.

Component	**Material**	**Specs**	**Amount**	
Frame rope	Polyethylene	3-strand twisted, 48 mm	6700	m
Mooring rope	Polyethylene	3-strand twisted, 48 mm	3200	m
Cultivation rope	Polyethylene	3-strand twisted, 16 mm	39400	m
Buoy rope	Polyethylene	3-strand twisted, 40 mm	120	m
Frame buoys	Polyethylene	CB 1800	12	units
Cultivation rope buoys	Polyethylene	Light fishing buoy	5477	units
Anchor chain	Chromium steel	30mm, studless	1600	m
Shackles	Chromium steel	Bow shackle	102	units
Thimbles	Chromium steel	Mooring rope thimble	70	units
Connection plate	Chromium steel	40mm, 8 holes	12	units
Anchor	Chromium steel	Fluke anchor, 700kg	12	units

Figure 5.9 shows the details of the mooring line connected to an anchor at the seabed and a buoy in the surface. This design is the basis used to count the number of smaller steel components included in the system. As seen from the figure, in all connections between steel and rope components, shackles and thimbles are added. Further, it is assumed that connection plates or rings are used in all connection points between the frame, mooring and buoy ropes.

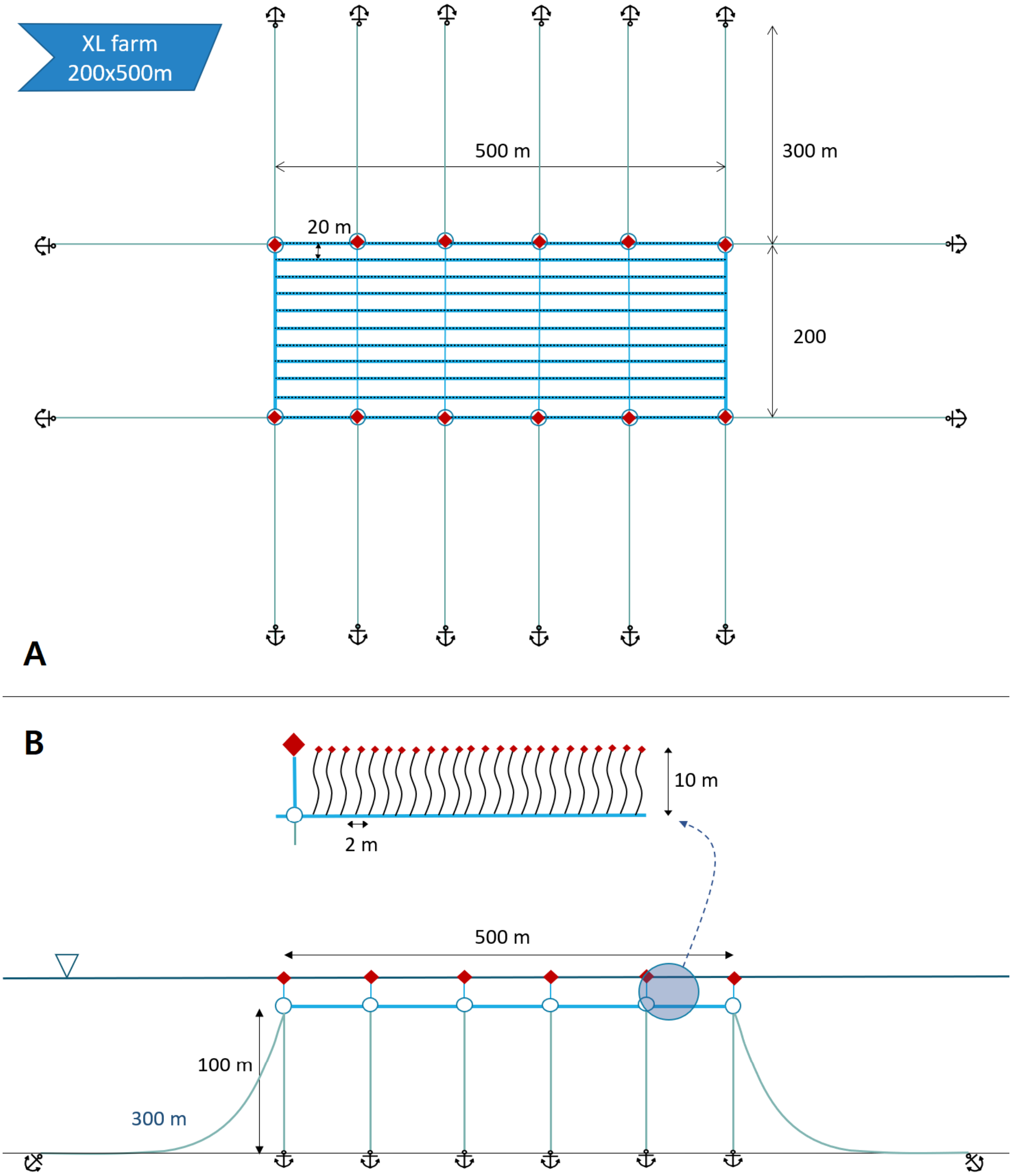


Figure 5.8: Outline of the base case design of the rig. A: Top view // B: Side view.

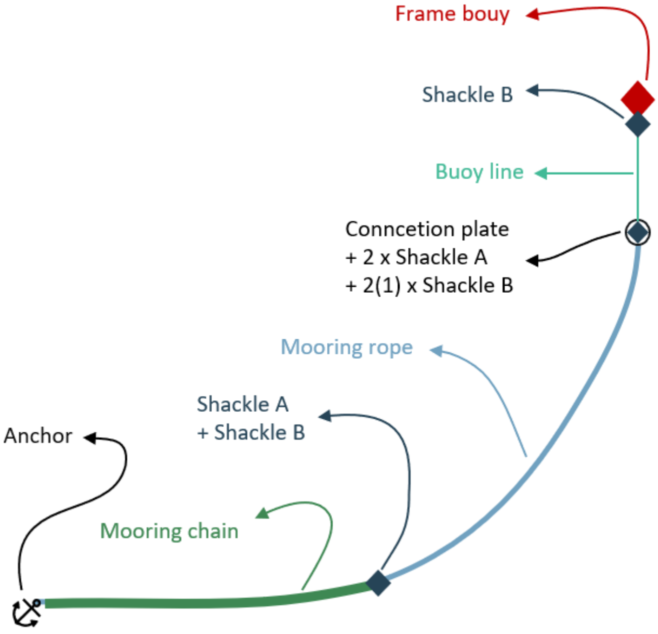


Figure 5.9: The composition of the mooring system - illustration of one single mooring line.

5.6 MPV and ROV

The international convention on Standards of Training Certification and Watchkeeping for Seafarers has a requirement saying that all ships having an installed main engine power of 750 kW should is obliged to have an authorized chief engineer onboard (Sjøfartsfirektoratet 2022). Many work vessels are designed to avoid this requirement by having a main engine power close to 750 kW (Lona 2022). This will therefore be set as a limit for the installed power for the MPV operating the cultivation system.

Further, the rig will be designed such that the MPV can manoeuvre between the frame ropes. To do this without damaging surrounding cultivation ropes, good manoeuvrability is required. This will also restrict the size of the vessel. To assure that the vessel is able to manoeuvre through the rig, it is set as a limit that the vessel breadth should not be greater than 50% of the distance between the frame ropes. Moreover, the draught should be below 50 % of the frame rope depth. At the same time, the vessel should be large enough to store the harvested kelp. To make sure this requirement is met, the deadweight of the vessel has to be at least 10 % of the yearly harvested biomass (FW) plus an extra 50 tones to have the capacity to carry the ROV and additional necessary equipment..

Based on the dimensions of the rig, the following requirements for the vessel dimensions are set:

- Max breadth: 10 m
- Max draught: 5 m
- Min deadweight: 207 t

A series of relevant reference vessels meeting the given requirements are used to set the vessel displacement and machinery size. Linear relations between the displacement and installed main engine power, in addition to the linear relation between displacement and deadweight for the reference vessels, are used to set the dimension for the MPV. Figure 5.10 shows the graphs giving the linear relations, and the chosen dimensions are given in table 5.2, where the lightweight of the ship is the difference between the displacement and the deadweight of the vessel. Details of the reference vessels can be found in appendix D.

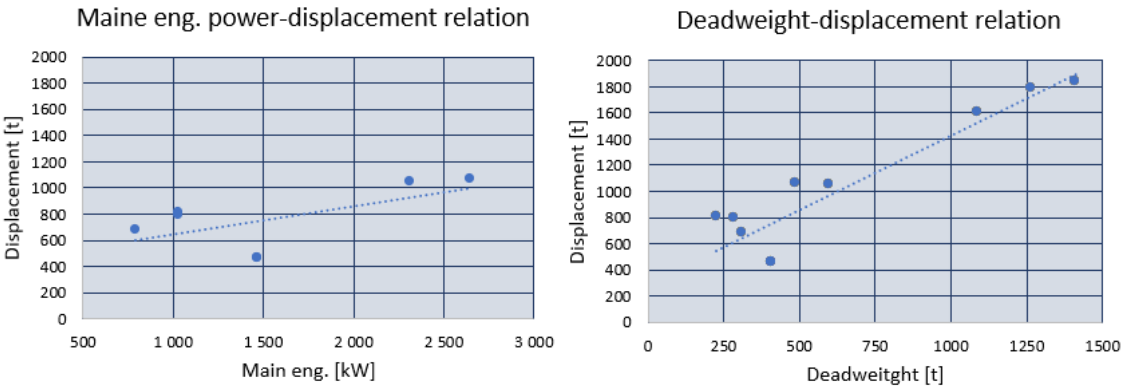


Figure 5.10: Linear relation between displacement and main engine power and displacement and deadweight given by reference vessels.

Table 5.2: Specifications for the MPV

Multi purpose vessel	
Installed main engine power	750 kW
Displacement	600 t
Deadweight	300 t
Lightweight	300 t

For the sake of the calculations, the vessel operation will be divided into two modes; transit and operation. Based on the outcome from Lindstad et al. 2017, it is assumed that the vessels operate at optimal machinery, 80% of the capacity, when they are in transit, and at 30% when they are operating. In the case with an installed power of 750 kW, this will correspond to 600 and 225 kW, respectively. Further, based on numbers for a medium speed diesel engine, a specific fuel consumption of 180 g/kWh at 80% load and 210 g/kWh at 30% load is assumed (Cuculić et al. 2018). The transit speed of the vessel is set to 10 m/s.

To assist the MPV, a working-class ROV is used. For inspection, it would have been sufficient to use an observation class ROV, which will require less power, but for simplicity, it is assumed that the same ROV can be used for all operations. Work class ROVs used in the offshore industry usually have a power consumption of about 100 kW or higher, depending on their size, propulsion system and operational requirements. However, these ROVs are often used for lifting of heavy objects and in deeper oceans. Based on this is considered sufficient to use a light works class ROV, and hence, an installed power of 60 kW is assumed to be sufficient.

The energy consumption of the ROV depends on the power requirements and duration of the different operations. It is assumed that, on average, the ROV will use about 25 % of its installed capacity, corresponding to 15 kW. In reality, this number will vary from operation to operation, but due to difficulties finding operational data for ROVs, this estimate will be used for all ROV operations.

5.7 Base Case Operations

Table 5.3 gives an overview of the operations carried out offshore, an estimated vessel- and ROV load and a tentative duration for each operation. Here, P_{MPV} and P_{ROV} is the estimated mean load used by the vessel and ROV, t is the time estimated per component, for instance, installation time per anchor. For inspection and maintenance activities, the duration is measured in time per hectare. N_{lc} is the number of times the operations will be carried out during the life cycle, based on an expected functional life for the rig of 20 years. As the inspection and maintenance are given per hectare, the number of activities for these activities is the product of the rig size, the operational frequency and the functional life of the rig. Lastly, T_{ROV} is the rate of the operation time that the ROV is participating. Here, a rate of 1 will indicate that the ROV is active during the whole operation, 0.5 indicating that it is active half of the time and so on. Due to difficulties obtaining comparable operational data to estimate the duration of the operations, significant uncertainty is related to these.

Table 5.3: Overview of the vessel operations carried out trough the kelp production cycle.

Operation	P_{MPV}	P_{ROV}	t [h]	N_{LC} [h]	T_{ROV}[%]
Transit	600	-	0.4	-	0
ROV deployment/retrieval	225	15	0.5	-	0
Anchor installation	225	15	2.0	16	0.1
Frame/mooring connection	225	15	0.5	16	1
Cultivation rope deployment	225	15	0.1	109540	1
Disconnecting and harvesting	225	15	0.1	109540	1
Inspection (per hectare)	0	15	2.0	800	1
Maintenance (per hectare)	225	15	1.0	200	0.2

* Time spent inspecting a cultivation area of 1 ha

6 Life Cycle Assessment of a Cultivation Facility

Referring to the goal and scope of the thesis, a LCA will be used as a basis for evaluating the potential net negative GWP effects of large scale exposed seaweed cultivation. This section specifies the methodology and data used in the analysis including the goal, scope and boundaries, the inventory analysis of the LCA and lastly, the basis of the LCIA and interpretation. The actual results and the interpretation of these will be presented in section 7.

6.1 Goal and Scope of the Assessment

As explained in the introduction, the goal of this LCA is to evaluate the GWP of large scale kelp cultivation. To do this, impacts directly related to the life cycle of the cultivation rig, as well as impacts from the kelp production cycle, will be assessed. The study will be focused on Northern Europe and in particular, the Norwegian Coast.

The modelled cultivation facility will be as described in section 5.5, and the cultivated species will be Saccharina latissima. Rig installation, operations related to the production cycle of the kelp and rig disassembly are based on the descriptions in section 5.7. It is aimed to use data from European markets and trials if possible. In cases where this is not available a global market is used.

6.1.1 Functional Unit

To answer the question of net carbon uptake and GWP of the kelp, the functional unit should ideally be focused on the amount of captured CO_2 relative to the CO_2-equivalents emitted through its production cycle. However, the carbon capture potential of the kelp depends highly on how the biomass is processed and used after harvest, and these two processes are not thoroughly assessed in this study. To avoid uncertainties related to processing and use, it was chosen to leave out these phases of the kelp life cycle in the LCA. Hence, the seaweed will be modelled from cradle to gate, i.e. from hatchery to harvest. The function studied in this LCA will therefore be the GWP of producing one tonne of sugar kelp, measured by fresh weight.

6.1.2 System Boundaries and Foreground Processes

The system studied, with system boundaries, is outlined in figure 6.1. The arrows indicate the life cycle of the seaweed biomass while the rectangular boxes are the material and process flows required to carry out the different stages of the production. Foreground processes are indicated with blue boxes and background processes in white boxes. The crossed-out boxes represent neglected processes.

The chosen foreground processes reflect the parts of the life cycle which are studied in more detail. These processes are chosen such that the results of the study can serve as a decision support tool for rig design and planning of the operations. For the background processes, data is obtained directly from the ecoinvent library, and therefore, these are not further branched such as the foreground processes.

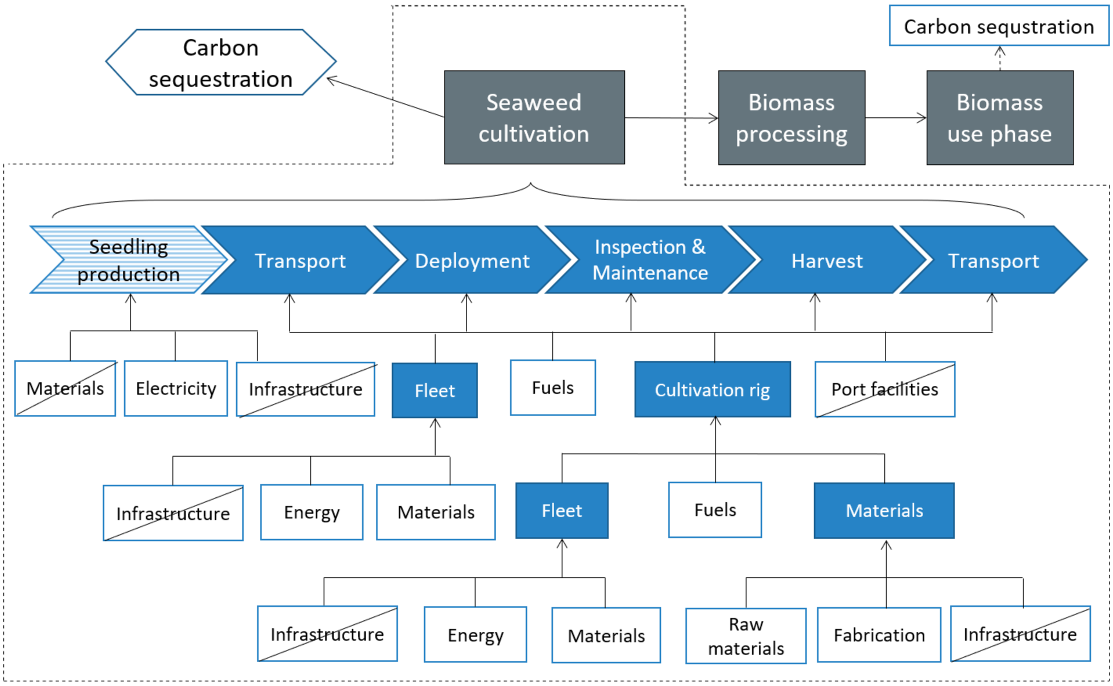


Figure 6.1: Flowchart showing the system boundaries and fore- and background processes of the LCA.

As can be seen from the flowchart, much of the infrastructure needed to produce different components are neglected. This is because it is assumed that the production of rig components for this specific rig is negligible relative to the total utility from the infrastructure provided throughout its lifetime. For instance, it is believed that the steel for chains and anchors constitutes a negligible part of the total amount of steel welded in a steel fabric. The same goes for rope fabrics and the port from which operations are commenced. Additionally, seedling production infrastructure is not accounted for as this is not an operation of significant interest in this LCA. However, based on the literature review of other LCAs of seaweed cultivation, it is believed that the impacts of electricity used for seedling production is much larger than the infrastructure and hence, the electricity is included in the study.

Meanwhile other infrastructures are neglected, the life cycle of the cultivation rig, which can also be categorized as infrastructure, is studied in detail. The rig is closely related to the functional unit as the production is measured over the functional life of the rig, meaning that 100 % of the rig capacity is allocated to cultivate the assessed kelp. Figure 6.2 outlines the rig life cycle and how the biomass production is related to it. All processes in the figure will be accounted for in the LCA.

It is considered that the rig design and operation management will influence the results, not only due to the influence on the material and energy usage but because they can affect the biomass yield. Additionally, a better farm design can possibly extend the functional life of the components, which may contribute to reduced material flows. Biomass yield is, as discussed in section 2.2, dependent on several design factors, for instance, the density and depth of the kelp. There is no consensus about what system that will optimal growth conditions. However, the indicators presented in section 2.2 can be used for qualitative assessments, and the influence of these will be further evaluated in the discussion part of the thesis.

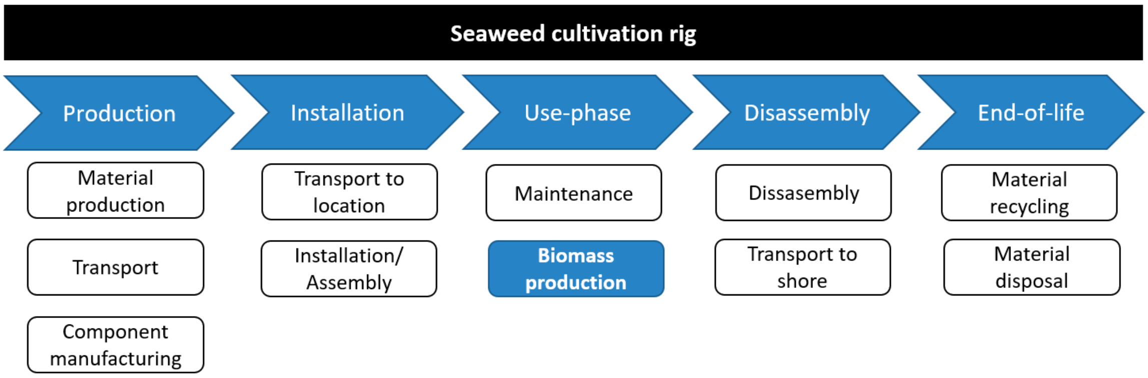


Figure 6.2: Flowchart outlining the cultivation rigs life cycle.

6.2 Life Cycle Inventory

As the boundaries of the assessments are outlined, the process of gathering inventory data starts. The basis for the data collection will be the life cycle flowchart in figure 6.1. Now, figure 6.3 shows how the different processes are related when the modelling of is done.

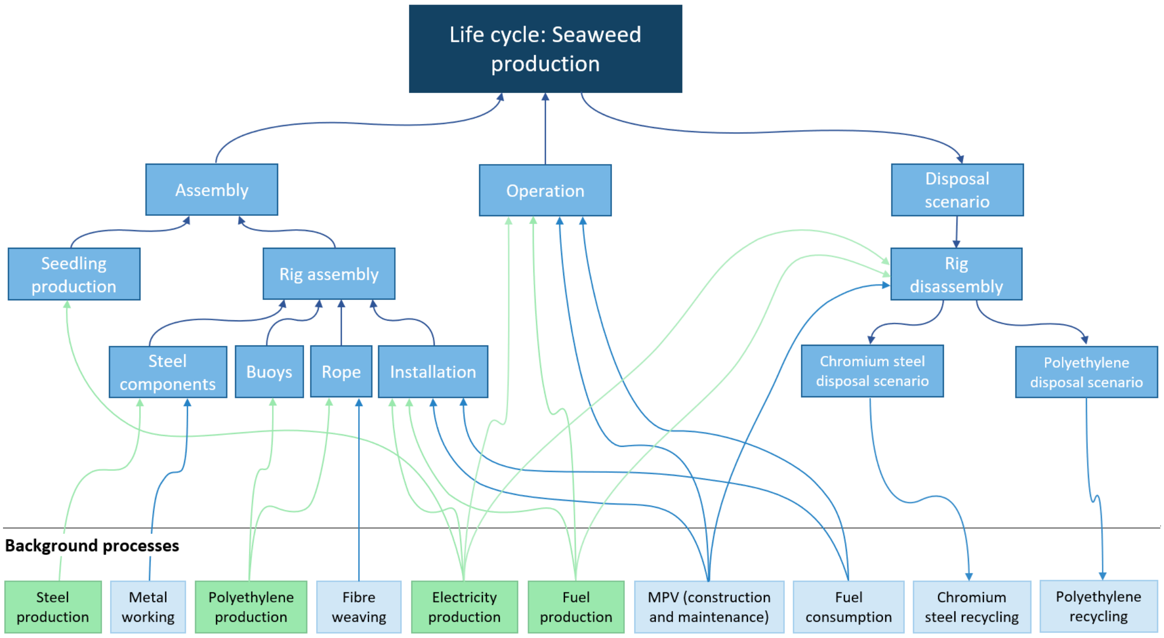


Figure 6.3: Flowchart showing how material and energy flows are connected in the inventory analysis.

For all background processes, it is chosen to use datasets where allocation at the point of substitution (APOS) is used. The APOS model is attributional and uses system expansion within treatment systems such that the credits and burdens due to waste treatment is shared between relevant users.

The materials used are based on reviews of product specifications and recommendations from various manufacturers of aquaculture equipment and systems. Details from the inventory is given in table 6.1, which is followed by information about the process and material flows used to model the system in SimaPro. Calculations and more additional information about components and processes from the LCI can be found in appendix A and specific input data for SimaPro in appendix B.

Table 6.1: Inventory data, calculated per tonne of seaweed (FW).

Item	**Material**	**Amount**		**Ref**	**FL [y]**
Anchor chain	Chromium steel	9.35E-01	kg	(1)	20
Anchor	Chromium steel	3.56E-01	kg	(1)	20
Minor steel components*	Chromium steel	3.42E-02	kg	(1)	20
Mooring rope	PE rope, 48 mm	4.23E-01	kg	(2)	5
Frame rope	PE rope, 48 mm	8.87E-01	kg	(2)	5
Cultivation rope	PE rope, 16 mm	5.33E+00	kg	(2)	5
Buoy rope	PE rope, 40 mm	1.10E-02	kg	(2)	5
Buoys	HDPE	2.47E-01	kg	(3)	20
Item	**Process**	**Amount**		**Ref**	**FL [y]**
Anchor chain	Metal working	9.35E-01	kg	(4)	20
Anchor	Metal working	3.56E-01	kg	(4)	20
Minor steel components*	Metal working	3.42E-02	kg	(4)	20
Mooring rope	Weaving	4.23E-01	kg	(5)	5
Frame rope	Weaving	8.87E-01	kg	(5)	5
Cultivation rope	Weaving	5.33E+00	kg	(5)	5
Buoy rope	Weaving	1.10E-02	kg	(5)	5
Buoys	Blow moulding	2.47E-01	kg	(6)	20
Seedling production	Electricity	4.51E+01	MJ	(7)	1
Installation	Vessel operation	1.30E-03	hours	(8)	20
Installation	Fuel	6.29E-02	kg	(9)	20
Installation - ROV	Fuel	8.37E-01	hours	(10)	20
Disassembly	Vessel operation	1.30E-03	hours	(9)	20
Disassembly	Fuel	6.29E-02	kg	(8)	20
Disassembly - ROV	Fuel	8.37E-01	MJ	(10)	20
Operations**	Vessel operation	7.53E-01	hours	(8)	1
Operations**	Fuel	1.93E+01	kg	(9)	1
Operation** - ROV	Fuel	3.91E+01	hours	(10)	1
Item	**Waste scenario**	**Amount**		**Ref**	**FL [y]**
Polyethylene disposal	Polyethylene recycling	2.67E-02	kg	(11,12)	5
C. steel disposal	C. steel recycling	1.33E-03	kg	(13,14)	20

Reference flow from EcoInvent

(1) Steel, chromium steel 18/8 [GLO], market for, APOS, S
(2) Fleece, polyethylene [GLO], market for, APOS, S
(3) Polyethylene, high density, granulate [RER]— production — APOS, S
(4) Metal working, average for metal product manufacturing [GLO], market for, APOS, S
(5) Weaving, synthetic fibre [GLO], weaving of synthetic fibre, for industrial use, APOS, S
(6) Blow moulding [RER]— blow moulding — APOS, S
(7) Electricity, low voltage [NO], market for, APOS, S
(8) Long liner, steel [RoW], long liner construction, steel, APOS, S
(9) Diesel, burned in fishing vessel [GLO], market for diesel, burned in fishing vessel, APOS, S
(10) Diesel, burned in diesel-electric generating set [GLO], market for, APOS, S
(11) PE (waste treatment) [GLO], recycling of PE, APOS, S (kg)
(12) Municipal solid waste (waste scenario) [NO], treatment of municipal solid waste, incineration, APOS, S (kg)
(13) Steel and iron (waste treatment) [GLO], recycling of steel and iron, APOS, S (kg)
(14) Scrap steel [Europe w/o Switzerland], treatment of scrap steel, inert material landfill, APOS, S (kg)

* Thimbles, shackles, rings and connection plates
** Deployment, harvesting,inspection and maintenance

6.2.1 Assembly and Life Cycle

Anchor and mooring chains

The anchors and mooring chains, as well as shackles, connection plates and thimbles, are assumed to be made out of chromium steel. To account for shaping and welding of the steel, a marked average for steel working is added to the model.

Ropes

Modern mooring ropes used in the aquaculture industry are usually made out of Dyneema-fibers, which are produced from ultra-high molecular weight polyethylene (UHMwPE). Due to difficulties finding detailed data on the production of such ropes, all ropes used at the rig are modeled by two inputs; the material polyethylene fleece and the process of synthetic fibre weaving to account for the fabrication.

Buoys

Two types of buoys are used for the rig; small buoys fastened to the upper end of the cultivation ropes and larger buoys holding up the frame. Both are assumed to be made out of polyethylene, and the fabrication is accounted for by blow moulding. As seen from table 6.1, the amount of polyethylene for buoys is negligible compared to the that used for the ropes.

Multi purpose vessels

Ideally, the life cycle of the MPV used to operate the cultivation system should have been modelled separately as a foreground process, but due to the complexity of working vessels and limited time and resources for the analysis, it was necessary to look for alternative ways of modelling the vessel operations. Ecoinvent provides life cycle data for a range of different vessels applied for transportation but very few for working vessels. However, the database provides a dataset for steel longliners based on data from smaller vessels. This model is applicable for longliners in the range of 25 to 40 m, and is scalable per kg of lightweight ship. Similar to the vessel required to operate a kelp cultivation rig, fishing vessels need sufficient deck space and storage room to store the catch as well as auxiliary equipment for handling the fishing gear and fish. As well, these vessels are often designed to work in harsh weather conditions and require good manoeuvrability. Based on this, the life cycle model of the long liner is therefore considered a suitable basis for the MPV.

When modelling vessel-use for each operation, the time and fuel used for transit are added to the operation-impact. For time consuming operations, a limit of 12 hours is set before it is assumed that the vessel will have to return to shore and carry on with operations the next day. Hereby, for every 12th hour, fuel and time for an extra roundtrip are added to the operation-impact.

For all ROV operations, the ROV will have to be deployed and retrieved from the vessel. It is estimated that these two operations will have a total duration of half an hour, meaning that, for each time the MPV is carrying out a operation assisted by ROV, 0.5 hours are added to the operation time. For operations lasting longer than the operating limit at 12 hours, another 0.5 hours is added to the total operation time for every 12th hour.

Details about the lifetime of the longliner are not provided in the Ecoinvent database. Though, vessels can generally be assumed to have a life span of 25 to 30 years (Papanikolaou 2019). However, this estimate of a vessel's life span includes a significant share of non-operating hours. By estimating the operating capacity of the vessel in the form of expected operating hours throughout its life, it is possible to allocate the vessel-impact by the amount of hours spent on the cultivation. The amount of expected lifetime-operating-hours is calculated by assuming that the vessel will operate 8 hours a day throughout all of its lifetime. The allocated impact can then be calculated using equation 6.1, where M is the amount of ship allocated to the process per operating hour, m is the mass of the vessel, t is average daily working hours and T is the expected lifetime of the vessel. For a 300 t vessel working 8 hours a day and having a lifespan of 25 years, 0.0041 tonnes of lightweight ship should be allocated to the process per hour the vessel is used.

$$M_{MPV} = \frac{m_{MPV}}{t \cdot 365 \cdot T} \tag{6.1}$$

ROV
Due to limited knowledge about ROV composition and limited time for the study, it was chosen to neglect materials and processes for construction and disposal of the ROV. However, the energy used by the ROV will be included by using the estimate of average power consumption of 15 kW.

Fuel production and consumption
Fuel consumption for vessel operations is not accounted for in the longliner model and hence, this needs to be modelled separately. For this purpose, ecoinvent provides a dataset giving impacts from diesel burned in a fishing vessel. The impact is given MJ used by the vessel and includes the impact of production and transport of the fuel as well. To account for the difference in specific fuel consumption for transit and operation, and hence have a model that reflects the operation pattern of the MPV in a better way, the dataset is modified such that it gives the impact per kg of fuel instead of MJ. Power for the ROV is modelled by energy from diesel burned in diesel-electric generating set and modified such that it is given per hour when the ROV is running on 15 kW.

Seedling production
The seedling production requires both infrastructure and electricity. However, based on the details in the result obtained in Taelman et al. 2015, it is assumed that the impact of the infrastructure is insignificant and hence, only the electricity will be accounted for. The electricity consumption used in the LCA is based on Taelman et al. 2015 and Thomas et al. 2020, both assessing two cases of this stage of the seaweed life cycle in detail. Both studies adresses one case of spray seedling and one of direct seedling. There were large variations in the reported results, varying from 7,2 kWh and up to 168,6 kWh per tonne of wet harvested biomass. The highest value, based on a case of direct seedling, deviated significantly from the other three. This is partly because of a low biomass yield but primarily due to the use of a highly energy-consuming electrical blower device, which is assumed by the authors to be very oversized. Therefore, this value is not taken into account when estimating the electricity consumption for seedling, which is calculated by taking the mean value of the three other cases. Details and results can be seen in table 6.2.

To be able to compare and use the results from Taelman et al. 2015, it is necessary to convert the results, which initially are expressed per MJ of energy provided by the biomass, such that they are expressed per tonne of biomass. Letting $E_{seedling}$ be the electricity required for seedling production, E_{sw} be the seaweed energy density per kilo wet weight and Y_{sw} be the seaweed yield, the energy density per tonne of seaweed can be calculated by equation 6.2, 6.3 and 6.4. Here, the yield per meter was calculated from the growth rate and amount of rope used in the base case of this LCA.

$$E_{sw}\left[\frac{MJ}{m}\right] = E_{seedling}\left[\frac{MJ}{kg}\right] \cdot Y_{sw}\left[\frac{kg}{m}\right] \tag{6.2}$$

$$E_{seedling}\left[\frac{kWh}{m}\right] = E_{seedling}\left[\frac{kWh}{MJ}\right] \cdot E_{sw}\left[\frac{MJ}{m}\right] \tag{6.3}$$

$$E_{seedling}\left[\frac{kWh}{t}\right] = \frac{E_{seedling}\left[\frac{kWh}{m}\right]}{Y_{sw}\left[\frac{t}{m}\right]} \tag{6.4}$$

Table 6.2: Reported electricity consumption during seedling production from two different studies.

Study	E [kWh/t]	Location	Remarks
Taelman et al. 2015	7,2	Ireland	Spray seedling, yield = 25 kg/m
	~~168,6~~	~~France~~	~~Direct seedling, yield = 5 kg/m~~
Thomas et al. 2020	11,7	Sweeden	Spray seedling, yield = 10 kg/m
	7,20	Sweeden	Direct seedling, yield = 10 kg/m
Average	12,5		

6.2.2 End of Life

As the seaweed itself is only modelled from cradle to gate, its end-of-life impacts will not be modelled. However, the whole life cycle of the cultivation rig is taken into account and hence, a decommission and disposal scenario for this will have to be modelled.

First, the rig will have to be retrieved from the ocean. This process will include disassembly of the frame and mooring system as well as anchor and mooring line retrieval and transport to land. As this to a large extent is a reversed version of the installation process, it is assumed that the fuel consumption and vessel requirement will be similar as well. Therefore, the decommission is modelled identically to the installation.

Disassembly of the rig will leave chromium steel, PE ropes and PE buoys, which are further modelled in separate disposal scenarios. Disposal of ropes and buoys are modelled by the same disposal scenario for polyethylene.

About 90 % of European stainless steel is collected and recycled (EuRIC 2022). This will be the basis for the disposal scenario for the chromium steel, in which 90 % is being sent to waste treatment for steel and iron, while the remaining is allocated as scarp steel for landfill.

Throughout the lifetime of the rig, extensive amounts of rope are used. The recycling potential of the ropes depends on their composition and whether they are impregnated. Nofir, a Norwegian recycling company, reported a recycling rate for fishnets of 76%, while 2% was reused, leaving 22% waste (Hennøen 2016). It should be noted that this, to a large extent, was nylon ropes, which are more common for typical gillnets and similar fishing gear. However, in the absence of better estimates, these numbers will be used as a basis for the base case disposal of PE ropes and buoys.

It is assumed there will be a high rate of wearing during the lifetime of the ropes. Additionally, the requirements for ropes used for mooring systems are relatively strict. Based on these two reasons, reuse of the ropes is assumed not to be feasible. Therefore, the last 2 % are shared between recycling and waste.

Recycled ropes usually end up as pellets or granules. The rope that is neither recycled or reused is allocated as municipal solid waste, modelled for Norway. As for the buoys, they are modelled with the same recycle, reuse and waste distribution as the rope. This is considered satisfactory due to the small amount of material required for the buoys relative to other components.

6.3 Life Cycle Impact Analysis

The main focus of the assessment is to estimate the GWP of the kelp cultivation. To calculate this, the life cycle of one tonne of kelp (FW) will be assessed, including the life cycle of the system used for the cultivation. This will be the basis for evaluating the kelps potential of carbon sequestration. As well, the analysis will point out hotspots through the production cycle, which will reveal the greatest potentials for system improvements related to the GWP. For the purpose of evaluating GWP, the single issue method for GWP with a 100 year timeframe, developed by IPCC, will be used.

Besides GWP, it is considered valuable to look into other environmental effects of the cultivation. Therefore, an analysis using the ReCiPe 2016 midpoint method, will be performed as well. This will make it possible to discuss the more general environmental effect of seaweed cultivation and the relative importance of the GWP relative to other environmental indicators.

6.4 Sensitivity Analysis

For the sensitivity analysis, which in this case will be used to assess the relative impacts of cultivation system parameters, 5 different variables and 7 different scenarios, including the base case, will be tested. The tested parameters are biomass yield, rig size, distance to shore, efficiency of harvest and deployment operations, and lastly, functional life of cultivation ropes. A description of the chosen parameters, followed by overview of the different scenarios (table 6.3), given by table is presented below.

1. *Biomass yield*
   The impact of cultivation will vary proportionally with the biomass yield. Here, three different scenarios, based on the yields from table 2.1, will be evaluated. The chosen scenarios are the average yield from all studies conducted in the Norwegian coast of 157 tonnes, the best case scenario estimated for cultivation outside central Norway of 383 tonnes and the average potential for all of the Norwegian coast of 75 tonnes. Due to the large variations in observed growth rates, the range of expected impact varies greatly as well, and it is considered important to bear this in mind when discussing the carbon uptake potential of the cultivation.
2. *Rig size*
   One of the concerns motivating this thesis was assessing the consequences of large scale cultivation. The impact of increasing the rig size further is therefore of interest. A second rig design, which is more or less an up scaled version of the base case design, is therefore tested. Figure 6.4 shows the rig design, which has twice the cultivation area as the base case rig. In this design, less material and space will be used for the mooring system relative to the cultivation area. An additional increase in force on each mooring line from the cultivation ropes will here be added. It is not known how much this can be increased before the dimensions of the mooring system must be revised.
3. *Distance to shore*
   Another important concern in this thesis is how the distance from shore will affect the total impact of the cultivation as the transit distance for vessels operating at the farm will increase. Here, one scenario with doubled distance and another, where the distance is ten times the base case distance, will be assessed.
4. *Operation efficiency*
   To find the impact reduction potential related to improving operational efficiency, a scenario where the duration of deployment and harvesting operations is decreased by 50 %, is evaluated. The purpose of this is to find the value of having a vessel that is better equipped for the operations or a rig that is easier to operate, or both.
5. *Functional life of cultivation ropes*
   Lastly, the reduction potential of using the cultivation ropes for more than one season is evaluated. This is done by increasing the functional life (f.l.) of the ropes by one year.

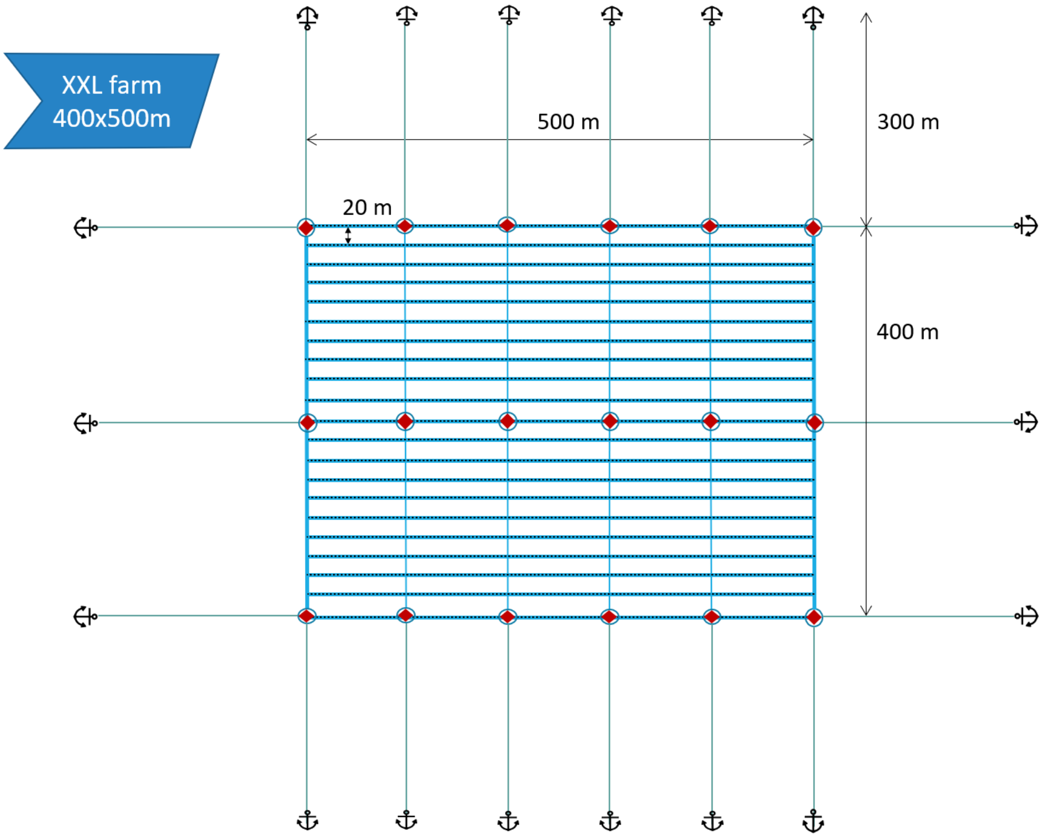


Figure 6.4: XXL version of the base case rig with a total cultivation area of 20 ha.

Table 6.3: Overview of the scenarios testes through the sensitivity analysis. The tested variable is marked in blue.

Case	**Growth[t/ha]**	**Rig size[ha]**	**Dist. to shore[m]**	**Op. efficiency[-]**	**Rope f.l.[y]**
BC	157	10	5000	1	1
1A	383	10	5000	1	1
1B	75	10	5000	1	1
2	157	20	5000	1	1
3	157	10	10 000	1	1
4	157	10	5000	1.5	1
5	157	10	5000	1	2

In addition to the scenarios which will be used to assess the GWP reduction potentials of the cultivation system, a sensitivity analysis of inventory data which have significant uncertainty related to them will also be evaluated. There are mainly two inventory flows that were difficult to obtain reliable inventory data for; the ROV energy consumption and the recycling grade for the PE components. Input values for the sensitivity analysis of these are presented in table 6.4.

Firstly, for the ROV, the power consumption is based on downscaling of installed power in large offshore ROVs. There is uncertainty related to both the rate in which the installed power is scaled down to and the percentage of this power which is used under the operations. Therefore, cases where the power consumption is increased and reduced by 50 % are tested.

As for the rope recycling rate, it is believed that 76 % is a somewhat optimistic estimate. Due to the uncertainty related to the recycling rate, two more pessimistic cases where 50 % and 25 % of the rope is recycled, are assessed.

Table 6.4: Sensitivity scenarios tested to examine uncertainty.

ROV power consumption	
BC	15 kW
+50 %	22.5 kW
-50 %	7.5 kW
PE recycling rate	
BC	75 %
-33 %	50 %
-67 %	25 %

7 Results

This section includes the LCIA-results followed by calculations of sequestration potentials and lastly, the combination of these two, which gives the kelps potential to store CO_2. In all cases, a cut off of 0.5 % is applied such that insignificant impacts are neglected. To assess GWP, IPCC 2013 GWP 100a is used, meaning that long term impacts are included.

In the impact assessment, the global warming potential of the cultivation and rig will be in focus. In addition, the ReCiPe midpoint method will be used to calculate other impacts. This is done to be able to evaluate the total environmental performance of the cultivation. After assessing the base case, the results from the different sensitivity scenarios will be presented. Lastly, the sensitivity analyses of the ROV power consumption and PE recycling rate are evaluated.

Table 7.1 summarizes the most important results from the assessment. As seen, large variation in the biomass yield leads to large variations in the estimated global warming potential of the kelp. As for the sequestration potential, which here is only presented by the average potential, the results indicate that the natural sequestration potential itself will not be enough to make up for the CO_2 output from the cultivation. However, when including a reduction due to the substitution of HFO, the negative GWP is significantly increased, and the result is a net negative GWP.

Table 7.1: A summary of the most important results from the assessment.

GWP of base case seaweed cultivation:	38.9 kg CO_2-eq./t
GWP of seaweed cultivation, high yield:	16.0 kg CO_2-eq./t
GWP of seaweed cultivation, low yield:	82.0 kg CO_2-eq./t
Natural sequestration potential, average:	6.1 t CO_2/ha
Natural sequestration potential, average:	5.5 t CO_2/ha
GWP reduction due to substitution of HFO:	15.3 t CO_2-eq./ha
Total reduction potential, average:	-14.7 t CO_2-eq./ha

7.1 Global Warming Potential of Seaweed Cultivation

Figure 7.1 shows how the impact flows are shared between the two main sub-compartments of the system: The rig, which includes materials and activities related to the assembly of the rig, and the operation, which includes activities related to the production cycle of the kelp. As seen, the rig represents the largest impact contribution, constituting almost 70 % of the total GWP. However, the impact from the operations is not insignificant, indicating an improvement potential for this as well. Further, figures 7.3 and 7.2 show the detailed networks for the two sub-compartments. Here as well, a cut-off of flows with a contribution of less than 0.5 % is used.

For the cultivation rig, the largest impact contributor is related to the PE used to produce rope. This is not very surprising as the functional life of the rope is shorter than other components, causing the total amount of rope used through the rig's life to be large relative to that for steel and PE for the buoys. The green flow lines in the network represent positive impacts or processes that reduce the total impact of the rig. In this case, GWP reduction is due to recycling of the PE and the steel, which can substitute production from raw materials. Summed up, the recycling processes reduces the total impact by about 14 %.

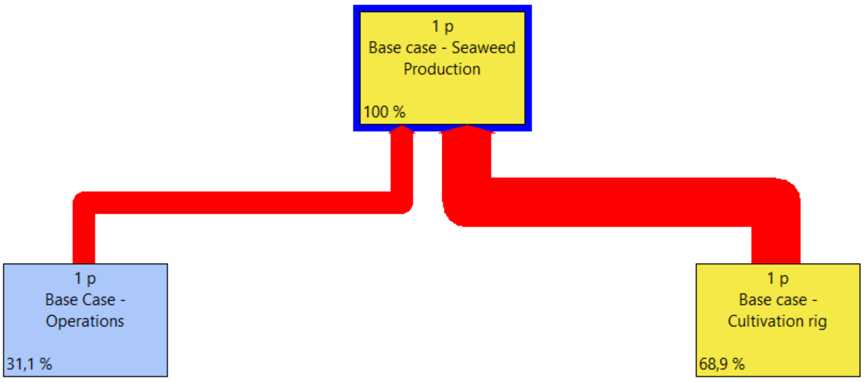


Figure 7.1: Impact distribution between cultivation rig and operations.

The second largest contribution from the rig assembly is the chromium steel, followed by the flows representing the fabrication for the rope and steel components. Vessel operations related to installing and disassembling the rig are below the cut-off limit and hereby, they are not included in this network.

Looking at the network for the operations, the greatest impact contributions come construction and fuel consumption of the MPV. Fuel consumption for the ROV has a smaller but still significant impact. Lastly, electricity for seedling production contributes to only about 2 % of the impacts. In the network, there are four flows coming from diesel production and use. The reason is that the flow is divided between the four operations; harvest, deployment, inspection and maintenance. Here, the two latter are much smaller than the two former ones.

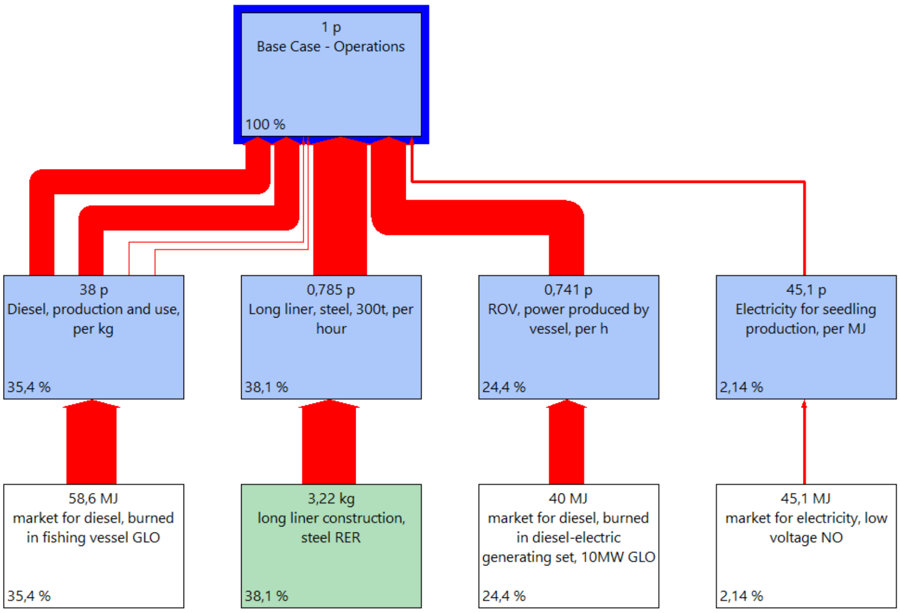


Figure 7.2: Network of the relative impact contributions from the inventory flows to the operate the cultivation rig.

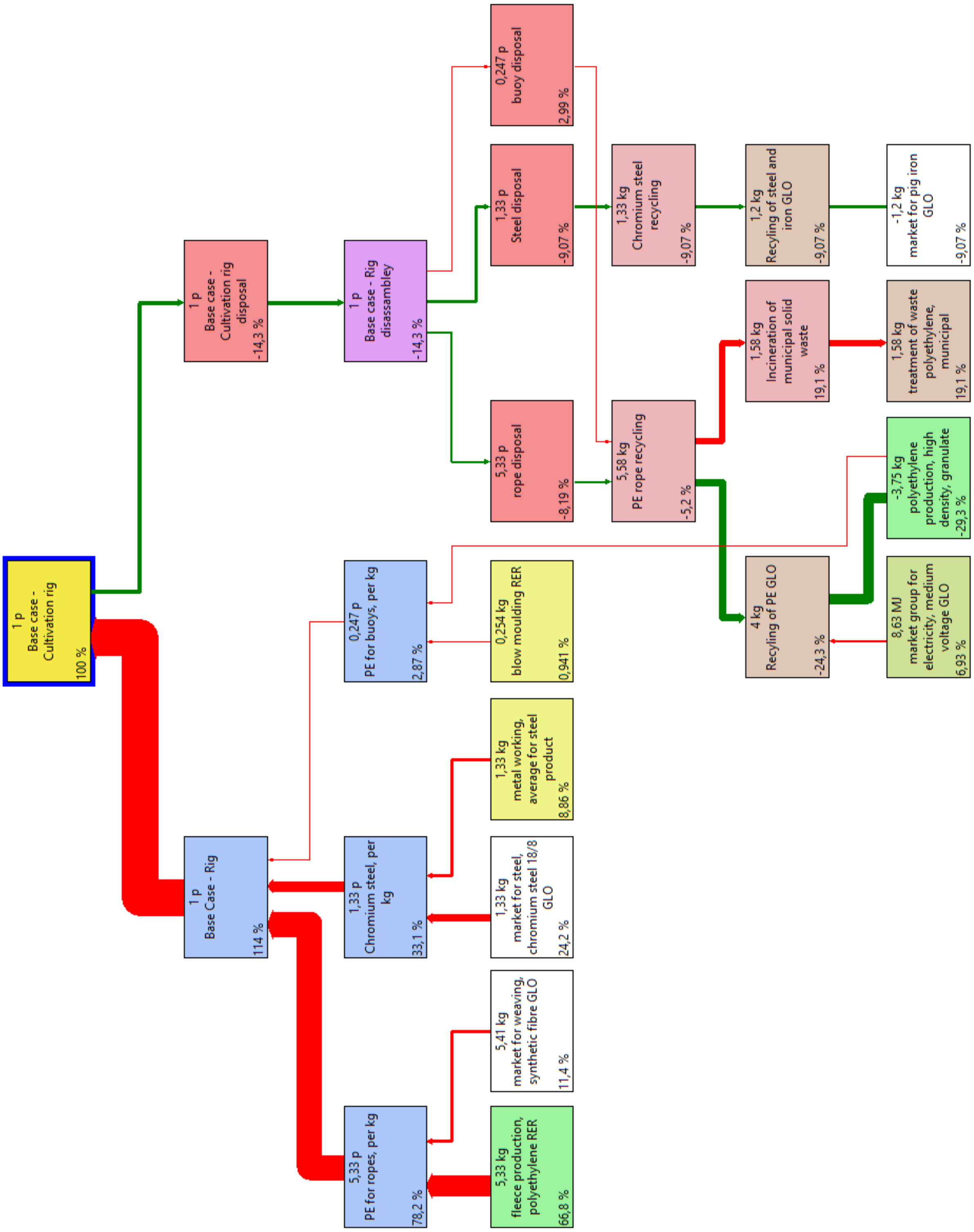


Figure 7.3: Network of the relative impact contributions from the inventory flows to the rig assembly.

Figure 7.4 shows the GWP of the different process and product flows in the kelp cultivation life cycle given in CO_2-equivalents. These results are the combined impact of the life cycle of the cultivation rig and the operation phase, where kelp is produced.

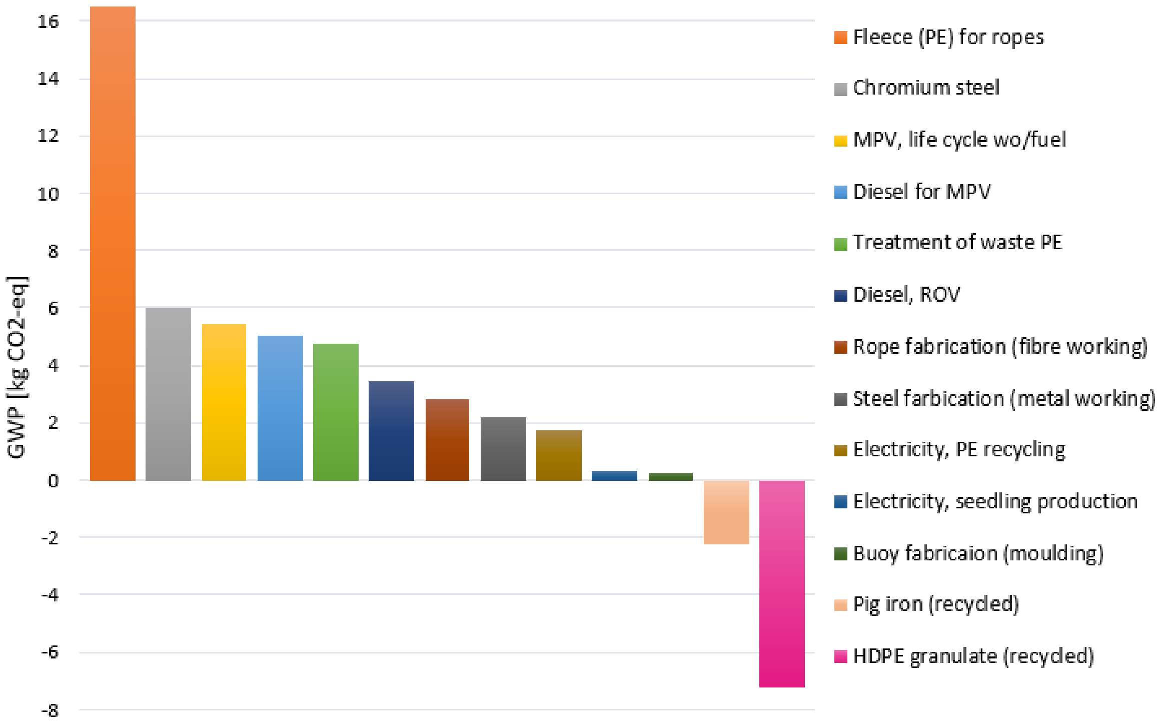


Figure 7.4: GWP the different material and process flows in the base case seaweed cultivation life cycle. A 0.5 % cut off is used.

It is evident that, also for the combined life cycle of the rig and the operation, the PE for the ropes is a hotspot and the recycling process is important to reduce the total impact of the cultivation. Aside from the PE, both steel and steel fabrication, rope fabrication, construction and use of MPV, as well as energy flows related to waste handling, have significant impacts and can be assessed to find reduction potentials. In total, the assessment gives an impact of 38,9 kg CO_2 per ton FW kelp cultivated.

7.1.1 Midpoint Categories: ReCiPe

Results from the LCIA using the ReCiPe midpoint methods can be seen in figure 7.5. Here, midpoint category impact scores are given relative to each other, making it easy to point to the hotspots within the impacts. As seen, freshwater ecotoxicity, marine ecotoxicity and human carcinogenic toxicity have a significantly higher impact than the other categories.

Due to the high impacts in the three categories mentioned above, a closer look into the inventory flows causing the impacts is taken. Figure 7.6 shows how the contribution is shared between the inventory flows, and as seen, a significant impact is related to the MVP, modelled as a long liner. In addition, the PE used for the ropes gives a relatively large contribution to marine and freshwater toxicity while the chromium steel is more significant for human carcinogenic toxicity.

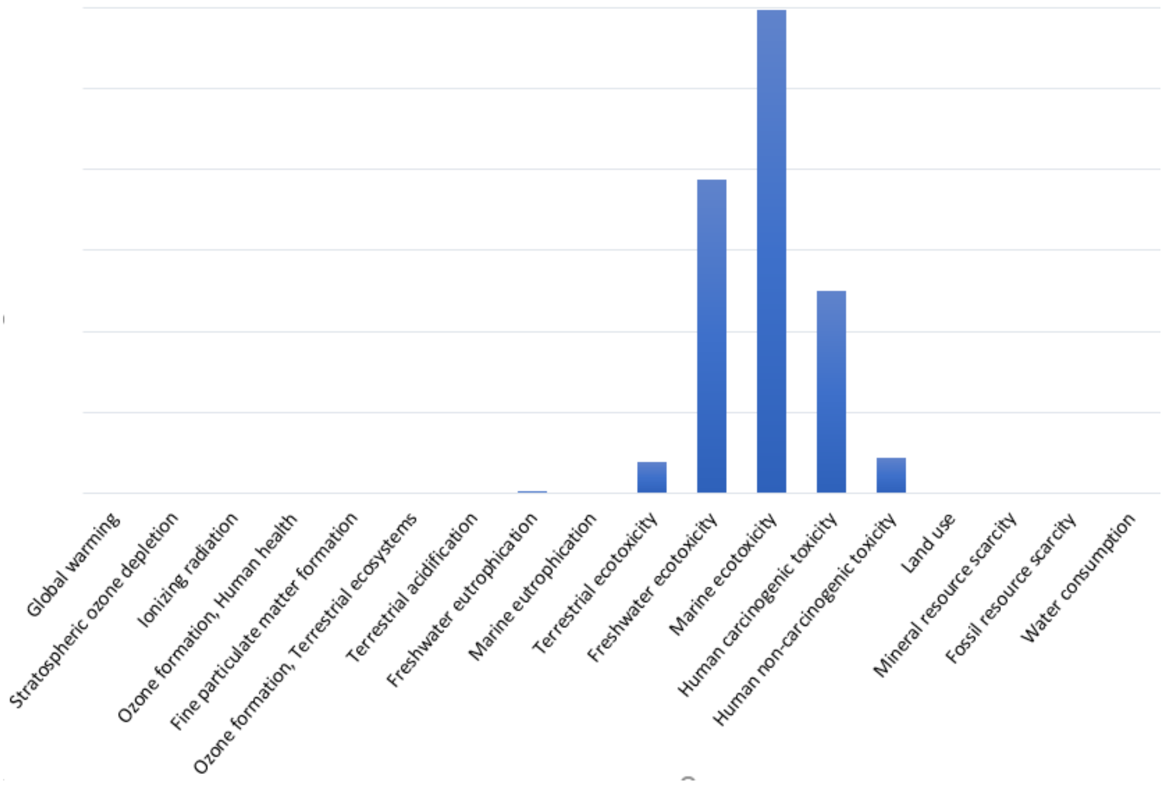


Figure 7.5: Impact of kelp cultivation, given sorted in midpoint categories, calculated by ReCiPe 2016.

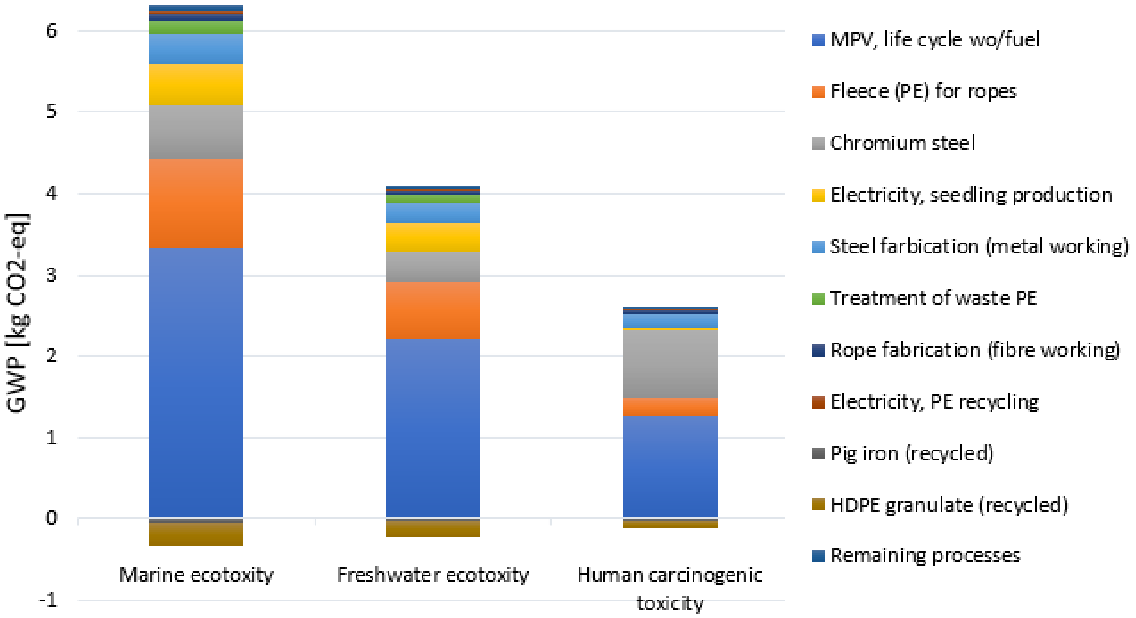


Figure 7.6: Distribution of contributions to marine ecotoxity, freshwater ecotoxity and human carcinogenic toxicity.

7.2 Sensitivity analysis

Results from the assessments of the different test scenarios, as described in 6.4, will be presented here. Outcomes of different biomass yield predictions are presented first before looking into the remaining scenarios.

7.2.1 Biomass Yields

Figure 7.7 shows the resulting GWP for the three different biomass yield scenarios. The impact here will vary opposite proportionally with the growth rate. Among the assessed scenarios, the results from scenarios 1A and 1B represent a worst and best case, respectively.

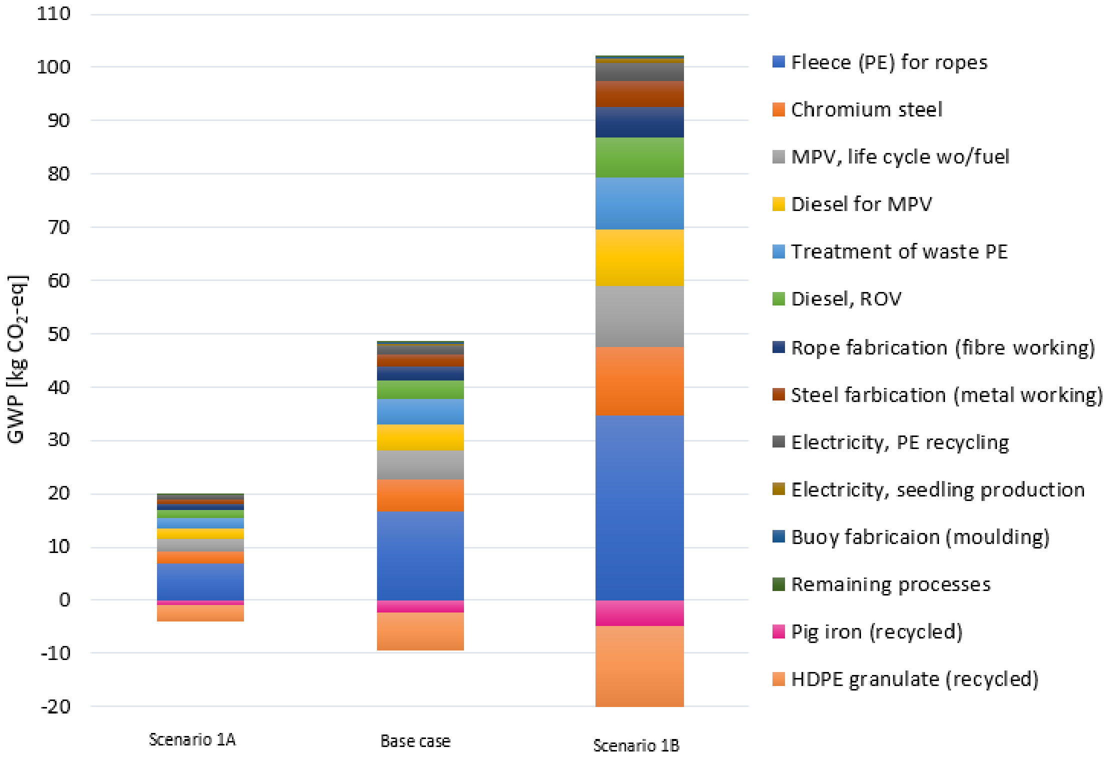


Figure 7.7: GWP contributions of seaweed cultivation using three different biomass yields. A 0.5 % cut off is used.

The GWP related to the three scenarios is summarised in table 7.2. This illustrates the large spread in potential impact due to the variation in measured and expected biomass yield.

Table 7.2: GWP for three chosen biomass yields.

Scenario	Growth rate [t/ha]	GWP[kg CO_2]
Base case	157	38.9
Scenario 1A	383	16.0
Scenario 1B	75	82.0

7.2.2 Scenarios

Resulting GWP when modelling scenario 2-5 is presented i table 7.3. Here, ϵ represents the relative change in GWP relative to the base case value. The numbers indicate a relatively low increase in scenario 2, representing a doubling of the distance from shore. The remaining scenarios give a decreased GWP, where the increased functional life of the ropes is the scenario showing the greatest potential for reducing the GWP relative to the base case scenario.

Table 7.3: Global Warming Potential of seaweed cultivation in the remaining four scenarios. A 0.5 % cut off is used.

Scenario	GWP[kg CO_2]	ϵ
Base Case	38.9	-
2	35.9	-7.7 %
3	39.4	+1.3%
4	34.4	-11.6 %
5	32.4	-16.7 %

Figure 7.8 shows how the different processes contribute to the impacts of the scenarios.

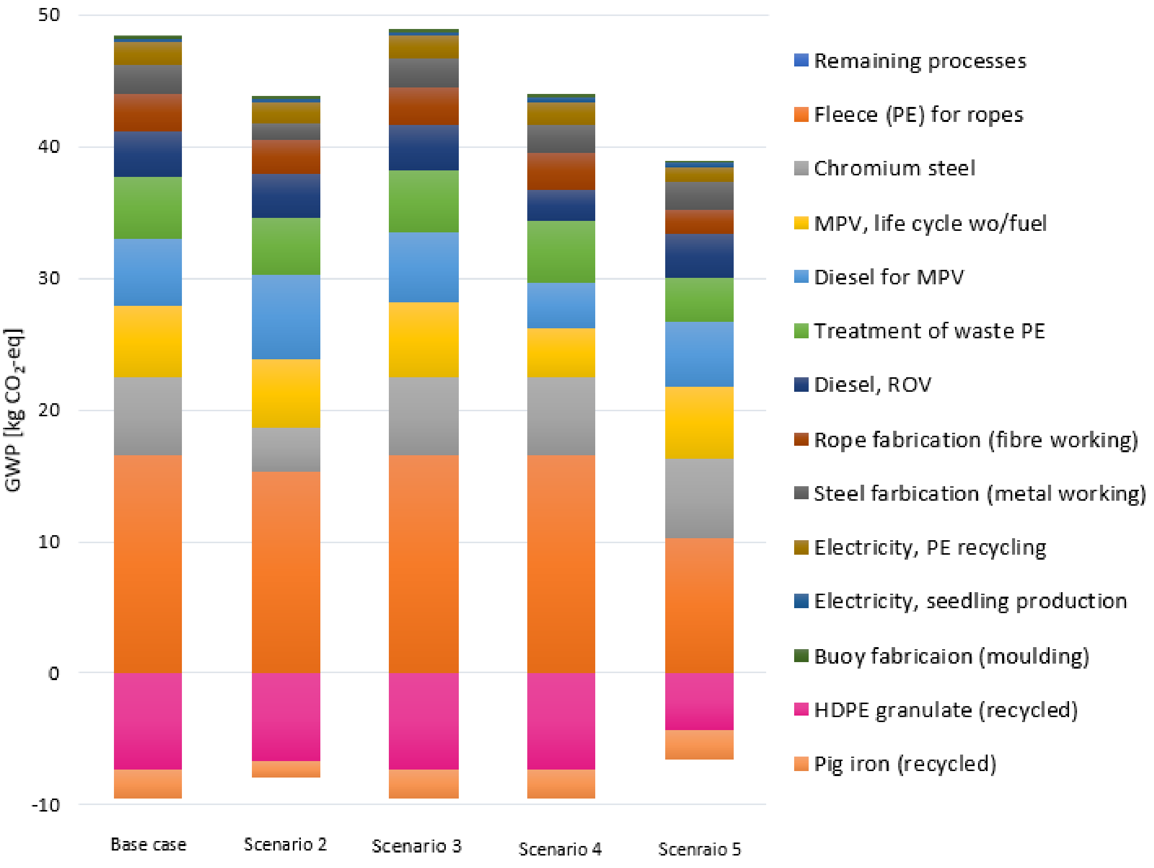


Figure 7.8: GWP contributions of kelp cultivation for scenario 2-5, alongside with the base case GWP. A 0.5 % cut off is used.

Rig size

If the rig size can be scaled up without proportionally increasing the materials used for the mooring system, this will decrease the total impact, but not significantly. Of course, this will depend on the extent of the upscale. In this case, a doubling of the rig size led to a 7.7 % decrease in kelps GWP.

Distance to shore
The calculated increase in GWP due to a doubling of the distance is insignificant. This indicated that the increased transit distance introduced when taking the cultivation facility further from shore will not be a challenge with regard to the GWP of the kelp.

Operational efficiency
Improving the operational efficiency of the deployment and harvesting by 50 % gives an impact cut of 11.6 %, and hence, this scenario gives a lower GWP than the scaled up rig size-scenario.

Functional life of ropes
Of the studied scenarios, the one where the functional life of the cultivation ropes is doubled is the one giving the largest decrease in GWP. Related to the large contribution from the PE in the base case assessment, this is not very unexpected.

7.2.3 Uncertain Parameters

ϵ in table 7.4a gives the relative change in GWP due to a change in ROV efficiency of ± 50 %. ϵ in table 7.4b shows the same when decreasing the recycling grade of PE by 25 and 50 %. Results indicate a small impact variations due to the change in power consumption for the ROV, while the variation due to change in recycling rate is more significant, with a 35.2 % increase if the recycling grade is at 25 %.

(a) Sensitivity scenarios for ROV power consumption.

ROV effect

P[kW]	GWP[kg CO_2]	ϵ
15 (BC)	38.9	-
7.5 (-50 %)	37.2	+4.4 %
22.5 (+50 %)	40.6	-4.4 %

(b) Sensitivity scenarios for PE recycling grade.

PE Recycling grade

Rec. grade	GWP[kg CO_2]	ϵ
75 % (BC)	38.9	-
50 %	46.6	+19.8 %
25 %	52.6	+35.2 %

7.3 Carbon Accounting

To make a carbon accounting, two effects of GWP reduction will be evaluated. These are capture potential due to natural sequestration in the grow out phase and capture potential of bioenergy production and CCS. Detailed data used for the calculations here can be found in appendix E.

7.3.1 Natural Sequestration

Equation 3.1 is used to calculate the mass of sequestrated CO_2 per tonne of cultivated biomass. Based on reviewed research discussed in section 3, and looking at sugar kelp cultivation along the coast of central Norway with a cultivation period from February to August, the following values for carbon mass percentage (α), erosion rate (β) and sequestration rate (γ) are assumed:

Parameter	Low	Average	High
α	0.24	0.27	0.33
β	0.13	0.31	0.49
γ	0.100	0.125	150

Using the values calculated for low, high and average yield per hectare as presented in section 7.2, we then get sequestration levels as presented below. Here, the low value is calculated using the pessimistic estimate for all parameters, including the yield, and similar and with the optimistic estimates for the high value. The kelp GWP presented here is the GWP as presented in the base case of the LCA with the natural sequestration subtracted from the initial result.

	Low	Average	High
Natural sequestrations [t CO_2/ha]	1.7	5.5	18.0
Kelp GWP w/natural sequestrations [t CO_2-eq/ha]	4.4	0.6	-11.9

7.3.2 Utilization of Bioenergy

Methane production potentials from seaweed obtained through the literature review in section 3.2 will be used to estimate the potential GWP reduction due to substitution of fossil fuels. Here, the bioenergy potential is the estimated energy content of methane gas made from one tonne of fresh kelp produced by anaerobic digestion.

To calculate the reduction due to substitution, the GWP of fossil fuel energy corresponding to the energy content of a biofuel produced from one hectare of cultivated kelp is calculated, as shown in equation 7.1. Here, the energy content in the biofuel, biomethane gas, is given per tonne of fresh kelp used to produce it. The fossil fuel used to model the substituted fuel is heavy fuel oil (HFO). GWP used of the HFO is only accounting for the tank to wake impacts, and hence not the impacts related to production. As for the biomethane gas, details from the processing beyond raw material production are not accounted for. Consequently, the result will not reflect the impact difference betweeen producing biomethane from kelp biomass on one hand and raw material extraction and processing for HFO on the other.

$$GWP_{HFO,subs}\left[\frac{t_{CO_2eq}}{MJ}\right] = GWP_{HFO}\left[\frac{t_{CO_2eq}}{MJ}\right]\cdot E_{methane}\left[\frac{MJ}{t_{seaweed}}\right] \tag{7.1}$$

The modelled process is outlined in figure 7.9, where only the flows in the white boxes are taken into account in the calculations. As indicated by the figure, the raw material extraction for the biomethane, which in this case is seaweed cultivation, as well as the energy used during production, is included in the estimates. For HFO, no impacts from the production are included.

Table 7.5 presents the low, average and high estimates of the parameters used to calculate the effect of the substation along with the resulting GWP.

Table 7.5: Fuel characteristics and GWP reduction potential of substitution of HFO.

	Unit	Low	Average	High
Bioenergy potential	$[MJ/t_{seaweed}]$	880E+00	113E+01	138E+01
GWP of HFO	$[CO_2eq./MJ_{HFO}]$*	7.60E-02	9.80E-02	1.19E-01
GWP reduction by substitution	$[CO_2eq./t_{seaweed}]$	-5.70E+00	-1.53E+01	-4.56E+01
GWP reduction by substitution	$[CO_2eq./ha]$	-5.02E+00	-1.35E+01	-4.02E+01

* Tank to wake emissions of HFO using a medium speed combustion engine of 3.61 t CO_2-eq./t, values from Comer and Osipova 2021. Conversion made by using an energy content in HFO of 41800 MJ/t.

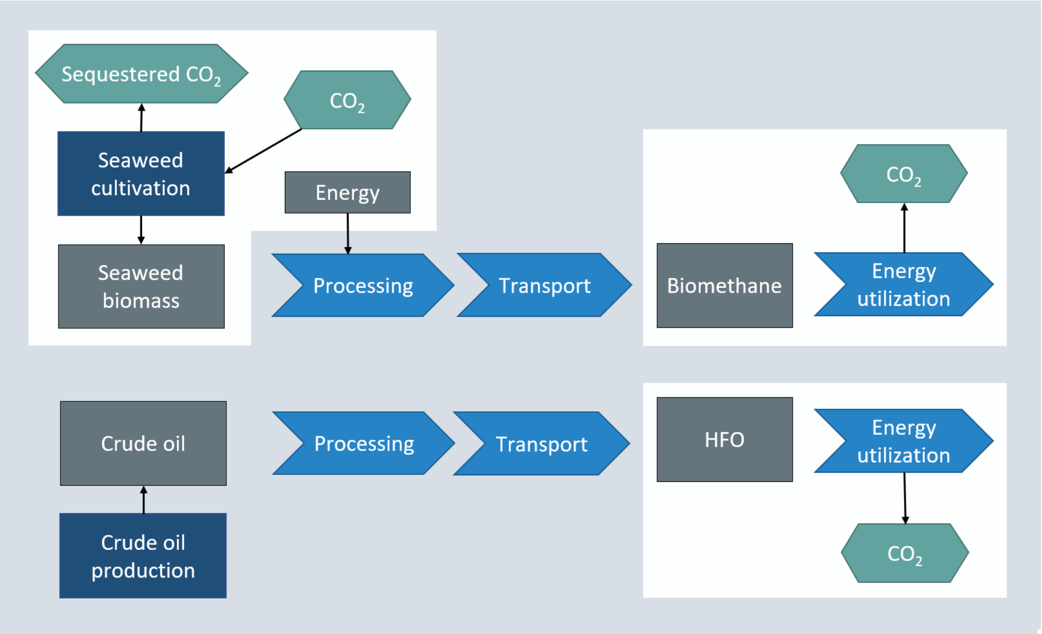


Figure 7.9: Processes in production of biomethane produced from kelp and HFO produced from fossil resources. Highlighted areas are accounted for in this study.

7.3.3 GWP Reduction Potential

Equation 7.2 is used to calculate the total GWP when adding the effect of natural sequestration and substitution of HFO.

$$GWP = GWP_{sc} - NS_{sc} - GWP_{HFO,subs} \tag{7.2}$$

Using the values calculated above we get results as presented below.

	Low	Average	High
GWP [t CO_2/ha]:	-1.31E+00	-1.47E+01	-5.75E+01

The low value gives a worst case scenario using the pessimistic estimate for all parameters, while the high gives a best case using the optimistic ones. Figure 7.10 shows the relative contributions from the modelled life cycle of the seaweed from the LCA, the natural sequestration and the effect of substitution of HFO. As indicated by the graph, a significant amount of the capturing contribution comes from the substitution of HFO. It is also observed that the contribution from the kelp cultivation is small relative to the reduction effect of substitution in bot the average and high capture scenario.

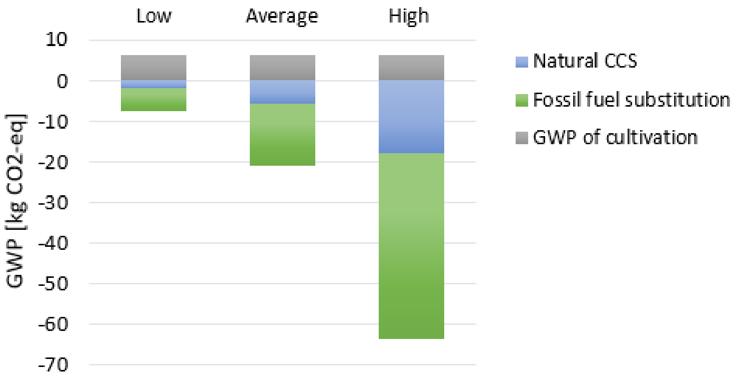


Figure 7.10: GWP reduction potential of kelp.

8 Discussion

The discussion starts with an interpretation of the results from the scenario analysis to identify impact hotspots and improvement potential through the life cycle of the kelp. Thereafter, the results obtained when testing the sensitivity of the ROV effect and PE recycling rate will be evaluated. Moving on from the LCA, the carbon capture potentials calculated will be commented upon before weaknesses and possible improvements of the analysis, both the LCA and the assessment of carbon capture potential, are discussed. Lastly, the relations between the carbon capture potential and cultivation system design and operation will be evaluates.

8.1 Hotspots and GWP Potentials of the Cultivation

Results from the base case scenario showed a significant impact due to raw material used for rope production and thereby also a large potential of recycling the rope. The ropes are the components with the shortest assumed functional life, and thereby, large amounts are used during the functional life of the rig. Doubling the functional life of the ropes decreased the impact of the kelp significantly. However, to be able to use the cultivation ropes for more than one season, more effort may have to be put into rinsing of the ropes during or after cutting of the kelp. Such rinsing activities are assumed to require energy and hence add impact in the form of an energy flow input to the system. This is not accounted for in the assessed scenario and hence, the relative decrease calculated here may be somewhat optimistic.

The possibility of reusing ropes has in principle been outside the scope of the study. However, as this has proven to grant relatively large impact cuts, it would have been interesting to look further into it. Similarly, it could have been interesting to look into the potential of using other ropes than the traditional PE ropes, for instance biodegradable ropes.

Increasing the rig size is primarily motivated by the overall increased yield. Increased biomass production may potentially push the production costs down, which is necessary to produce large volume, low value products. The LCA showed a small impact cut when increasing the amount of cultivation lines relative to the amount of rope and steel used in the mooring system.

Another effect of increasing the cultivation area, which is not taken into account in the LCA, is that the total area used for cultivation will be smaller relative to the actual cultivated area. Assuming that the length of the mooring lines stays unchanged when scaling up the cultivation area. Then, the size of the cultivated area increases relative to the area used for the mooring system. For the two rigs assessed in the LCA, assuming that the cultivation lines extend 200 m horizontally, the relative cultivation area increases from 18.5 % to 55 %, and hence the area occupation per tonne of cultivated kelp decreases significantly.

Scenario 3, which assessed the effect of locating the rig at a longer distance from shore by doubling the distance from the base case, gave a GWP that was marginally higher than the base case results. This indicates that increased distance to shore will not significantly decrease the carbon reduction potential of the farm. In a potential up-scale, to avoid occupying large parts of the nearshore areas and competition with other industries operating along the coastline, requirements to use locations further offshore are expected. Therefore, knowledge about the consequence of an increased transit distance is considered valuable.

The effect of increased operational efficiency did not have an enormous effect on the GWP. In the base case, it was assumed that the deployment and the harvest of a cultivation line would take 6 minutes each. This means that, in scenario 4, the time used for these two operations would be 3 minutes, which is believed to be a rather optimistic estimation considering the methods and equipment used in the industry today.

It has been difficult finding data on operations to use for comparison to the ones modelled for the kelp production. As pointed out, most methods used today are characterized by labor intensive and time consuming work, which is considered not to be feasible for large scale cultivation in exposed locations. By putting more effort into trials or thorough examination of the operations, more exact time and power consumption can be estimated and hence, the uncertainty related to these data will be reduced. However, as results from scenario 4 showed, a 50 % decrease in the duration of deployment and harvest activities gave only a moderate GWP reduction. Therefore, it is believed that uncertainties related to the estimated operation durations will not significantly increase the uncertainty of the GWP calculated for the kelp production cycle. However, even though increasing the operation efficiency did not have a significant effect on the GWP, it has the potential of decreasing the production costs and is therefore of interest for such purposes.

To summarize the discussion of the hotspots found in the LCA, effort should be focused on reducing the use of ropes either by extending their functional life or exploring other options than PE ropes. This is especially important if a low recycling rate is expected for the PE. Further, it is observed that the consequence of increasing the distance from shore to the cultivation locations will not increase the GWP significantly. As for the effect of increased rig size and operational efficiency, this is moderate related to the GWP. However, these are assumed to decrease the overall production costs of the seaweed. Another positive effect of increasing the rig size is that the relative area occupation will decrease.

8.2 Uncertainties and Assessment Weakness

The focus throughout the inventory analysis was the cultivation rig and energy consumption related to operations. It is acknowledged that neglecting the impacts of infrastructure used for seedling production and port facilities, as well as for the ROV construction, can have affected the final result. Due to this, the LCIA results related to the seaweed production phase may be somewhat optimistic compared to the true impact.

Another aspect that, to a large extent has been neglected in the study are impacts of on-shore transport. For instance, transport of the components from fabric to the shore site for installation, transport from the shore site to the recycling facility after the disassembly and transport of cultivation ropes from the hatchery is not included. This is also a reason to believe that the calculated impacts are lower than in reality.

Regarding the two assessed uncertainty parameters, an insignificant sensitivity was found for the ROV power consumption. In contrast, the PE recycling grade was found to have a relatively high impact on the final results. This was also indicated by the base case results, which revealed a large GWP contribution from the PE ropes, and a corresponding large negative contribution from the recycling of the PE. It is unfortunate that there is such a significant uncertainty related to a parameter being this critical for the final result. In addition, in absence of more specific inventory data, the ecoinvent model used to model the recycling process is a generic process based on data for the global market. This process is believed to give higher environmental impacts than a corresponding recycling process based solely on a European or a Norwegian market. A more thorough study of methods and statistics for rope recycling, as well as details related to the recycling process, would be beneficial to obtain more reliable data.

It was early in the inventory analysis concluded that modelling the MPV in SimaPro from scratch would be too time consuming. In addition to the steel body, systems such as propulsion system, accommodation facilities and auxiliary equipment would have to be included, all requiring detailed data to be modelled. Among the vessels modelled in ecoinvent, the long liner is the only one that is a working vessel, i.e. not specialised in transport. A fishing vessel is considered a suitable option due to the reasoning explained in the presentation of the inventory data in section 6.2. However, the unexpected high marine and freshwater ecotoxicity and carcinogenic toxicity were not possible to explain using the available data about the process from ecoinvent. For this reason, it would have been beneficial to model the vessel as a foreground process and not use the long liner background process directly.

Another arguable aspect regarding the vessel use is the method used to allocate the amount of the vessels functional life to the cultivation. Firstly, this allocation requires that vessel is both suited and needed to perform other tasks in its remaining functional life, which is not necessarily the case. Secondly, the calculation of the functional life of the vessel is not based on any real life data, and therefore, great uncertainty is related to this. In further work, the sensitivity of this allocation can be assessed by testing scenarios where either more or all of the vessel's functional life is allocated to the kelp cultivation.

In the LCA, it was aimed to use background processes modelled from a European market or a Norwegian market in cases where this was relevant. However, many ecoinvent processes were only available for global markets, and therefore, it became difficult restricting the inventory data to the European market. Due to differences in electricity sources and waste handling in different parts of the world, this is believed to influence the results significantly. For further work, more efforts should be put into understanding the consequence of the chosen geography for the different processes.

The functionality of the base case rig and the scaled up rig scenario is not validated through any tests or simulations, and limited efforts have been put into calculations of the wave and current forces that the rig will have to withstand out on the cultivation site. This introduces an additional uncertainty in the result of the analysis and it is recommended to put more effort into testing of the rig design, for instance, through simulations.

8.3 Additional Impacts

In the following sections, environmental impacts aside from GWP, will be evaluated. First, the LCIA results using the ReCiPe midpoint method will be assessed and thereafter, ecosystem impacts, which are difficult to model in a typical LCA, will be discussed.

8.3.1 Interpretation of Midpoint Category Impact

The result from the LCIA using the ReCiPe midpoint method indicated that the relative contribution from GWP was negligible compared to freshwater and marine ecotoxicity and human carcinogenic toxicity. This suggests that relative reduction of GWP effects will have a minor effect on the overall environmental impact of the cultivation.

Unfortunately, as the GWP was the impact category focused on in this assessment, little time was allocated to study and understand the impacts given by the midpoint method. However, a short evaluation of the hotspots in the three categories with major impacts showed that a significant contribution came from the vessel used for the operations, followed by the raw materials for ropes and steel. The impacts from the latter two flows were expected to have a significance as large amounts of rope and steel is used during the lifetime of the rig. Though, the large impact from the vessel was unexpected. For further work, more efforts should be put into analyses of the vessel to figure out what caused the large contributions. Alternatively, as suggested earlier, the MPV should be modelled as a foreground process such that one can have better insight in the inventory flow details.

Generally, doing a further assessment of other midpoint categories would build a better foundation to argue on whether an upscale of the Norwegian kelp cultivation is environmentally beneficial or not. Doing further work to explore endpoint category impacts would also be valuable to get an impression of the human and ecosystem impacts related to the cultivation.

8.3.2 Ecosystem impacts

Ecosystem impacts of large scale kelp cultivation have been a topic in several studies, but as of today, there is no consensus on what the full picture of consequences will look like. While some aspects are more straightforward to assess, such as the result of increased nutrient uptake, others, like the impact on seabed biodiversity, are more complicated to predict. Due to this lack of knowledge, such ecosystem impacts can not be quantified and included in an LCA. However, it is considered important not to exclude a discussion of these effects when assessing the environmental effect of kelp cultivation.

One of the most evident effects of the cultivation is the increased seaweed nutrient uptake. Both positive and negative consequences related to this have been reported in research. On one hand, it has been argued that the uptake, and thereby reduction of nutrients and plankton, may reduce marine productivity (Skjermo, Aasen et al. 2014). As well, densely growing seaweed will lead to shading, meaning that less light will reach the areas beneath the rig and hence, the productivity of species in this area will decrease. On the other hand, large scale kelp farms can form artificial ocean forests which may act as habitats and provide nutrition for fish and other organisms (Skjermo, Aasen et al. 2014;Buschmann et al. 2017).

Further, while the eroded biomass creates a potential CCS effect, the material sinking to the seabed will affect the seabed ecosystems as well. Skjermo, Aasen et al. 2014 mentions potential de-oxygenation of sediments and increased nutrition for animals living in or near the seabed as possible consequences. Other studies have shown cases of decreased biodiversity as a consequence of the erosion of seaweed settling on the seabed (Hancke et al. 2021). Camplbell et al. 2019 rates "Potential release of reproductive materials", "Facilitation of disease parasites and non-native species","Absorption of kinetic energy" and "Addition of cultivation systems" as impacts with highest risk, the first two ones being more difficult to mitigate than the latter.

Quantifying these effects requires is believed to require a more specific framework than what the LCA framework currently provides. This is particularly difficult for long term ecosystem impacts. Long term impacts are not very well covered by the literature, and this is believed to be because of absence of good methods of estimating these. One way to get an impression of these effects is to simulate the ecosystem and check the sensitivity of different parameters. Developing such simulation models requires extensive knowledge about ecosystem interactions.

8.4 Comparison with Reviewed Assessments

It is decided not to compare the specific GWP to that found in other LCAs as there are too many aspects of the assessments that can differ, for instance in forms of which processes that are included, the geography of the production and LCIA methods used. To do a fair comparison with other assessments, the results should be based on the same boundaries, methods and assumptions. Nevertheless, it is interesting to compare the more qualitative results, especially the hotspots within the cultivation process, as this can give an indication of processes that have been under or overestimated in the assessment.

From the studies reviewed and presented in section 4.3, none mentioned the components of the cultivation rig as the largest impact hotspot amount the impact flows. It should though be mentioned that most of the assessments included biomass processing and production of specific products and many found hotspots within the preservation and processing stages. Others, such as Taelman et al. 2015, found that impacts from the fuel used in transport were large relative to others, implying that the neglecting of transport activities may have a significant effect on the results in this thesis. Although, this impact is highly dependent on the location of the different production and fabrication facilities.

8.5 Global Warming Mitigation Potential

The assessment of the GWP mitigation potential shows results in a range of 1.31 to 57.5 t CO_2-eq/ha, which is quite a large spread. For the parameters related to the natural sequestration, it is observed that the span in the sequestration rate is caused by uncertainty and the span of carbon content of the kelp is assumed to be caused by genetic variation and local environmental differences. The erosion rate, on the other hand, can, to some extent, be managed. This parameter, which is highly dependent on harvest time, can be pushed towards the higher value by extending the grow out phase and harvest later in the summer. Nevertheless, this will probably reduce the total yield and hence reduce the potential for biofuel production, which in the end will decrease the effect of fossil fuel substitution. As seen through the study, the two parameters causing the largest variations in the result are in fact the biomass yield and the erosion rate. Finding a location giving ideal growth conditions and the time of the grow out period when the biomass peaks, i.e. before erosion rates exceeds growth rate, it should be possible to steer the GWP mitigation potential towards the upper estimated values.

Ideally, more literature regarding the sequestration rate should have been reviewed and compared due to the uncertainty in all the different processes that this rate depends on. However, it was difficult to find thorough studies on the topic, and many of the available assessments are qualitative and do hence not provide any concrete data. The uncertainty related to the sequestration rate increases the uncertainty related to the calculated natural sequestration. As for the carbon content of the biomass, results from Sharma et al. 2018 shows a higher content for plants cultivated at 3 meter than at 8 meters depth, while Fieler et al. 2021 observed a higher rate in central Norway than for northern Norway. There are hence some indicators that can be evaluated to find a more specific estimate for this ratio.

Many studies assessing impacts of bioenergy production, have been conducted. Most with focus on costs, and many with biomass from terrestrial plants. The methods for producing biofuels were not thoroughly studied in this thesis due to the limited time frame. For further work, more effort should be put into studying one or more methods of producing biofuels and adding this stage to the LCA. This way, more precise calculations of the energy yield from the biomass could have been obtained, along with a foundation to uncover hotspots and improvement potentials of the production process. In addition, even though anaerobic digestion was reported to be the currently most feasible way to produce fuel from seaweed biomass, other pathways should not necessarily be excluded.

By adding up the average cases from the LCA of the kelp, the natural sequestration and the substituted HFO give an average case GWP for the kelp of 14.7 t CO_2-eq/ha. To put this number into context, the yearly emission from all Norwegian passenger cars are, which is 4.1 million tonnes of CO_2-equivalents (Statistisk sentralbyrå 2020), is used. With a mitigation potential of 14.7 t CO_2-eq/ha, about 280 000 hectares would thereby have to be cultivated to compensate for the emissions from the Norwegian passenger car traffic. This corresponds to an area just below 0.4 % of the whole Norwegian economic zone.

Adding a negative impact as an effect of substitution is, as mentioned in section 3, mainly a way of rewarding the biofuel in comparison with other options. In reality, fuels based on CCS are carbon neutral and will not actually reduce carbon levels in the atmosphere. As indicated by IEA's CCS outlook, presented in figure 3.2, it is believed that processes providing net negative emissions, such as BECCS, will play a role in the future in addition to carbon neutral fuel production and use. By excluding the effect of fossil fuel substitution from the assessment, leaving the positive impacts from inventories related to the cultivation and the negative ones from natural sequestration, the average case will result in a net positive GWP, as shown in section 7.3.1. Hence, the chances are that there will be no real net carbon capture effect of the kelp unless parameters affecting the natural sequestration and growth rate are optimized, or additional CCS-efforts are put into the energy utilization process to make it a BECCS.

8.6 Relation Between Carbon Uptake Potential the and Cultivation System

By combining the results from the LCA with the study of carbon capture and kelp cultivation potential, it is observed that two major factors affect the potential of capturing carbon through kelp cultivation. The first is the biomass yield and the second is the time of year in which the kelp is deployed and harvested.

Optimizing the kelp growth rate and hereby the biomass yield will contribute to the carbon capture potential in two ways: Firstly, as more biomass will be harvested, a greater bioenergy yield will follow and hence, fossil fuel substitution potential. Secondly, the erosion rate increases as the yield increases, suggesting that more biomass will be sequestrated in the ocean during the grow out phase. Rig design parameters that will affect the growth rate are, in particular, the depth and density of the kelp.

An optimal cultivation management with regards to the time of deployment is also important to optimise the biomass yields. In addition, the time of harvest will to a large extent decide the erosion rate of the kelp. The erosion rate increases during spring and summer, and at some point, the erosion rate will exceed the erosion rate. From this point, the biomass rate will decrease. When the kelp is being used for bioenergy purposes, it is assumed that the quality of the plants is not a critical parameter, such as when the kelp is harvested for food purposes. In this case, the biomass peek point when the erosion rate exceeds is considered the optimal harvesting point. If the harvest is not done at this point, the effect of natural sequestration of the kelp may increase, but the GWP contribution of this is not believed to be more valuable than the value of the harvested biomass, both with regard to the GWP value and the economic value.

As for the aspects related to rig design and operational management studied in the LCA, the importance of these turned out insignificant to the carbon capture potential relative to the two discussed above. In the case with the highest yield, the impacts of the total cultivation process are insignificant. This indicates that the cultivation system should be designed with a main focus on optimising the yields and not minimising impacts from itself. As a second priority, PE usage should be reduced and efforts to increase the rope recycling rate should be increased.

The fact that the distance from shore to the rig does not increase the GWP significantly is good news for an upscale where offshore farms may become relevant. And as indicated from the results, major areas will be needed if the carbon capture effect is going to be significant for mitigating climate change. However, this applies primarily to a moderate increase in distance from shore. Further investigation of consequences should be assessed if the distance is significantly increased from the case assessed in this LCA.

9 Conclusion

Through this thesis, an LCA was carried out to evaluate the global warming potential of large scale exposed kelp cultivation. A case of cultivation of sugar kelp at a location outside central Norway was studied. The LCA was used to explore the impacts of rig design and operational management of the kelp cultivation and to find GWP reduction potentials through the kelp cultivation cycle. Further, the carbon capture effect of kelp cultivation was evaluated, and the results from this, along with LCA results were used to calculate a net GWP of the kelp and thereby its potential to reduce atmospheric carbon levels.

Due to large variations in observed growth rates for kelp, a high, low and average result were assessed. Results from the LCA give a GWP in the range of 16.0 to 82.0 kg CO_2-equivalents per tonne of fresh harvested sugar kelp, while the estimated average growth rate gave a GWP of 38.9 kg CO_2-equivalents per tonne of fresh harvested sugar kelp.

In the inventory analysis, the cultivation rig was modelled as an individual life cycle while the operations carried out to produce kelp, i.e. to operate the cultivation system, were added as processes through the kelp production cycle. The results show that about 70 % of the impact is related to the farm, and the remaining 30 % to the operations. Further, a significant contribution to the GWP comes from the PE used for rope production and a significant impact reduction is given by the HDPE granulate which is output from the recycling of ropes and buoys. It is therefore recommended for further studies to increase the focus on the material used for ropes or efforts to reduce the overall use of ropes.

In addition to the GWP assessment, the ReCiPe midpoint method was used to get an idea of the more general environmental impact of the cultivation and to find the GWP contribution relative to other impact categories. This assessment indicates that the impacts of the cultivation mainly affect three midpoint categories marine ecotoxicity, freshwater ecotoxicity and human carcinogenic ecotoxicity. Impacts assigned to the GWP are negligible in comparison with these three. Further studies of these impacts are hence necessary to be able to evaluate the general environmental effect of kelp cultivation.

Results from the cultivation system assessment show a moderate cut in the GWP due to increased rig size and decreased operational efficiency, indicating that such efforts will help decrease the carbon footprint, but not significantly. As for the functional life of cultivation ropes, this has a somewhat larger impact on the final result. In the studied case, the functional life is increased from one to two, but it is believed that there are possibilities for extending their life even further. Therefore, it is recommended for further studies to evaluate the feasibility of reusing cultivation ropes as this can contribute to significant impact reduction. Lastly, results show that the consequence of increased distances to the cultivation locations is minor related to the GWP of the cultivation, which indicates that farming further offshore will not be problematic due to the transit distance.

Using results from the LCA and an assessment of the sequestration potential and bioenergy yield of biofuels produced from seaweed, the GWP mitigation potential is estimated to range from 1.31 CO_2-equivalents to 57.5 CO_2-equivalents per cultivated hectare. The huge span in the results is due to a span in observed and estimated values, primarily related to erosion rate, growth rate and energy yield in the biofuels.

On average, the results show a sequestration potential of 5.5 t CO_2 per hectare during the grow out phase, while the estimated GWP reduction due to substitution of heavy fuel oil is 13.5 t CO_2-equivalents per hectare. In total, the GWP reduction potential using average estimates for all parameters, including the GWP of the cultivation, is 14.7 t CO_2-eq/ha.

Through the study, it is observed that the biomass yield, which is decided by the growth rate of the kelp and the harvesting time, is the parameter that should be in focus to optimize the climate mitigation potential of the kelp. Based on this, the primary focus when planning for kelp cultivation is to design the rig and manage operations such that the biomass yield is optimized. Here, factors such as depth and plant density will have an impact, but it is believed that the impact of harvesting at the right time of the season is even more important.

Regarding the parameters assessed in this study, their impact on the carbon capture potential was insignificant in comparison with the biomass yield. However, considering the results from the midpoint category impacts, it is believed that rig design and operations can be more critical when looking into other impact categories than GWP. Further studies of this are therefore recommended.

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Appendix

A Inventory data

Base Case

General

Ocean depth [m]	110	**Farm length [m]**	500
Substrate depth [m]	10	**Farm breadth [m]**	200
Distance to shore [m]	5000	**Farm size [ha]**	10
Transit speed MPV [m/s]	7	**Number of anchoring points**	16
Inspection freq. [n/year]	2	**Number of frame buoys**	12
Planned maintenance freq.[n/year]	1	**Number of cult.lines**	5477
Lifetime of farm [y]	20	**Length, cult. line [m]**	10
Max operation duration	12	**Tot. Length, cult. lines [m]**	54770
EXP yield [t WW over lfetime]	31433,3	**Length, mooring line [m]**	200

Operation durations

Operation	**Fleet**	**Duration [h]**	**Comments**
Transit	MPV	0,40	Rountrip
Anchor installation	MPV + ROV	2,00	Per unit
Frame/mooring connection	MPV + ROV	0,50	Per connection
Deployment	MPV + ROV	0,10	Per cult. rope
Harvesting	MPV + ROV	0,10	Per cult. rope
Inspection	MPV + ROV	2,00	Per hectare
Maintenance	MPV + ROV	1,00	Per hectare
ROV deployment+retrieval	MPV + ROV	0,50	

Component specifications

Component	**Material**	**MBL base case**	**Density**		**Specs**	**MBL Actual**	**N[m//units]**	**Mass[kg]**	**S. life[y]**	**kg per ww t sw**
Anchor chain	Cr steel	27,6 tonn	1,84E+01	kg/m**	Scale, 30 mm	47,6 tonn	1,60E+03	2,94E+04	2,00E+01	9,35E-01
Anchors	Cr steel	5,5 tonn	7,00E+02	kg	Scale, 700 kg plough anchor	700*20 tonn	1,60E+01	1,12E+04	2,00E+01	3,56E-01
Connection plate/ring	Cr steel	11,0 tonn	3,80E+01	kg per	Scale, 40 mm, 8 holes	?	1,20E+01	4,56E+02	2,00E+01	1,45E-02
Thimbles	Cr steel	16,6 tonn	2,40E+00	kg per	Guess /Half of the shackles	?	7,00E+01	1,68E+02	2,00E+01	5,34E-03
Shackles (A: 60t)	Cr steel	11,0 tonn	4,80E+00	kg per	Mørenot, RedPin Bow shackle	72 tonn	3,20E+01	1,54E+02	2,00E+01	4,89E-03
Shackles (B: 40t)	Cr steel	11,0 tonn	4,80E+00	kg per	Mørenot, RedPin Bow shackle	72 tonn	5,80E+01	2,78E+02	2,00E+01	8,86E-03
Buoy shackle	Cr steel	6,2 tonn	1,70E+00	kg per	Mørenot, RedPin Bow shackle	39 tonn	1,20E+01	2,04E+01	2,00E+01	6,49E-04
Mooring rope	PE, fleece	16,6 tonn	1,04E+00	kg/m	Mørenot, 3-strand, 48 mm	36,6 tonn	3,20E+03	3,33E+03	5,00E+00	4,23E-01
Cultivation rope	PE, fleece	3,1 tonn	1,15E-01	kg/m	Mørenot, 3-strand, 16 mm	25,7 tonn	5,48E+04	6,30E+03	1,00E+00	4,01E+00
Frame rope	PE, fleece	16,6 tonn	1,04E+00	kg/m	Mørenot, 3-strand, 48 mm	36,6 tonn	6,70E+03	6,97E+03	5,00E+00	8,87E-01
Buoy rope	PE, fleece	6,2 tonn	7,20E-01	kg/m	Mørenot, 3-strand, 40 mm	25,7 tonn	1,20E+02	8,64E+01	5,00E+00	1,10E-02
Buoys, cultivation lines	PE	13 kg (buoyance)	1,15E+00	kg per	Eiva-safetec polyform A-1 buoy	13 kg	5,48E+03	6,30E+03	2,00E+01	2,00E-01
Buoys, mooring frame	PE	CB 1800	1,23E+02	kg	Mørenot, CB 1800	1800 tonn	1,20E+01	1,48E+03	2,00E+01	4,70E-02

Operation specifications

Operation	**Duration[h]**	**Transit duration**	**Duration[h/life]**	**M.eng.cap.[kW]**	**Load**	**Load[kW]**	**SFC[kg/kWh]**	**E. cons.[kWh]**	**Fuel cons.[kg]**	**Load ROV[kW]**	**ROV use**	**ROV use[h]**
Transit (roundtrip) MPV				7,50E+02	80,00 %	6,00E+02	1,80E-01	2,38E+02	4,29E+01	-		
Transit (roundtrip) Barge				7,50E+02	80,00 %	6,00E+02	1,80E-01	1,20E+03	0,00E+00	-		
Anchor installation (per unit)	3,25E+01	3,97E-01	3,29E+01	7,50E+02	30,00 %	2,25E+02	2,10E-01	1,58E+03	1,58E+03	1,50E+01	10 %	3,25E+00
Frame/mooring connection	8,50E+00	3,97E-01	8,90E+00	7,50E+02	30,00 %	2,25E+02	2,10E-01	4,73E+01	4,44E+02	1,50E+01	100 %	8,50E+00
Installation total			**4,18E+01**	-	-	-	-	**1,63E+03**	**2,02E+03**			**1,18E+01**
Deployment	5,71E+02	1,90E+01	1,18E+04	7,50E+02	30,00 %	2,25E+02	2,10E-01	2,80E+06	5,80E+05	1,50E+01	100 %	1,14E+04
Harvesting	5,71E+02	1,90E+01	1,18E+04	7,50E+02	30,00 %	2,25E+02	2,10E-01	2,80E+06	5,80E+05	1,50E+01	100 %	1,14E+04
Inspection [per ha]	2,10E+01	7,94E-01	8,72E+02	7,50E+02	30,00 %	2,25E+02	2,10E-01	1,04E+05	2,16E+04	1,50E+01	100 %	4,20E+02
Maintenance	1,05E+01	3,97E-01	2,18E+02	7,50E+02	30,00 %	2,25E+02	2,10E-01	5,20E+04	1,08E+04	1,50E+01	20 %	4,20E+01
Operation total			**2,47E+04**					**5,75E+06**	**1,19E+06**			**2,33E+04**

Scenario 2: XXL rig

General

Ocean depth [m]	110	**Farm length [m]**	500
Substrate depth [m]	10	**Farm breadth [m]**	400
Distance to shore [m]	5000	**Farm size [ha]**	20
Transit speed MPV [m/s]	7	**Number of anchoring points**	18
Inspection freq. [n/year]	2	**Number of frame buoys**	18
Planned maintenance freq.[n/year]	1	**Number of cult.lines**	10479
Lifetime of farm [y]	20	**Length of cultivation line [m]**	10
Max operation duration	12	**Tot length of cultivation lines [ı**	104790
EXP yield [t WW over lfietime]	62866,7	**Lengt of mooring line [m]**	200

Operation durations

Operations	Fleet	Duration [h]	Comments
Transit	MPV	0,40	Rountrip
Anchor installation	MPV + ROV	2,00	Per unit
Frame/mooring connection	MPV + ROV	0,50	Per connection
Deployment	MPV + ROV	0,10	Per cultivation rope
Harvesting	MPV + ROV	0,10	Per cultivation rope
Inspection	MPV + ROV	2,00	Per hectare
Maintenance	MPV + ROV	1,00	Per hectare
ROV deployment+retrieval	MPV + ROV	0,50	

Component specifications

Component	Material	MBL base case	Density	Specs	MBL Actual	N[m//units]	Mass[kg]	S. life[y]	kg per ww t sw
Anchor chain	Cr steel	27,6 tonn	1,84E+01 kg/m**	Scale, 30 mm	47,6 tonn	1,80E+03	3,30E+04	2,00E+01	5,26E-01
Anchors	Cr steel	5,5 tonn	7,00E+02 kg	Scale, 700 kg plough anchor	700*20 tonn	1,80E+01	1,26E+04	2,00E+01	2,00E-01
Connection plate/ring	Cr steel	11,0 tonn	3,80E+01 kg per	Scale, 40 mm, 8 holes	?	1,40E+01	5,32E+02	2,00E+01	8,46E-03
Mooring/frame rope thimble	Cr steel	16,6 tonn	2,40E+00 kg per	Guess /Half of the shackles	?	9,40E+01	2,26E+02	2,00E+01	3,59E-03
Shackles (A: 60t)	Cr steel	11,0 tonn	4,80E+00 kg per	Mørenot, RedPin Bow shackle	72 tonn	3,60E+01	1,73E+02	2,00E+01	2,75E-03
Shackles (B: 40t)	Cr steel	11,0 tonn	4,80E+00 kg per	Mørenot, RedPin Bow shackle	72 tonn	7,60E+01	3,65E+02	2,00E+01	5,80E-03
Buoy shackle	Cr steel	6,2 tonn	1,70E+00 kg per	Mørenot, RedPin Bow shackle	39 tonn	1,80E+01	3,06E+01	2,00E+01	4,87E-04
Mooring rope	PE, fleece	16,6 tonn	1,04E+00 kg/m	Mørenot, 3-strand, 48 mm	36,6 tonn	3,60E+03	3,74E+03	5,00E+00	2,38E-01
Cultivation rope	PE, fleece	3,1 tonn	1,15E-01 kg/m	Mørenot, 3-strand, 16 mm	25,7 tonn	1,05E+05	1,21E+04	1,00E+00	3,83E+00
Frame rope	PE, fleece	16,6 tonn	1,04E+00 kg/m	Mørenot, 3-strand, 48 mm	36,6 tonn	1,29E+04	1,34E+04	5,00E+00	8,54E-01
Buoy rope	PE, fleece	6,2 tonn	7,20E-01 kg/m	Mørenot, 3-strand, 40 mm	25,7 tonn	1,80E+02	1,30E+02	5,00E+00	8,25E-03
Buoys, cultivation lines	PE	13 kg (buoyance)	1,15E+00 kg per	Eiva-safetec polyform A-1 garnblåse	13 kg	1,05E+04	1,21E+04	2,00E+01	1,92E-01
Buoys, mooring frame	PE	CB 1800	1,23E+02 kg	Mørenot, CB 1800	1800 tonn	1,80E+01	2,21E+03	2,00E+01	3,52E-02

Operation specifications

Operation	Duration[h]	Transit duration	Duration[h/life]	M.eng.cap.[kW]	Load	Load[kW]	SFC[kg/kWh]	E. cons.[kWh]	Fuel cons.[kg]	Load ROV[kW]	ROV use	ROV use[h]
Transit (roundtrip) MPV				1,00E+03	80,00 %	8,00E+02	1,80E-01	3,17E+02	5,71E+01	-		
Transit (roundtrip) Barge				1,00E+03	80,00 %	8,00E+02	1,80E-01	1,60E+03	0,00E+00	-		
Anchor installation (per unit)	3,65E+01	3,97E-01	3,69E+01	1,00E+03	30,00 %	3,00E+02	2,10E-01	2,36E+03	2,36E+03	1,50E+01	10 %	3,65E+00
Frame/mooring connection	9,50E+00	3,97E-01	9,90E+00	1,00E+03	30,00 %	3,00E+02	2,10E-01	6,30E+01	6,56E+02	1,50E+01	100 %	9,50E+00
Installation total			**4,68E+01**	-	-	-	-	**2,42E+03**	**3,01E+03**			**1,32E+01**
Connecting cult. ropes	1,09E+03	3,61E+01	2,26E+04	1,00E+03	30,00 %	3,00E+02	2,10E-01	7,13E+06	1,48E+06	1,50E+01	100 %	2,18E+04
Disconnecting and harvesting	1,09E+03	3,61E+01	2,26E+04	1,00E+03	30,00 %	3,00E+02	2,10E-01	7,13E+06	1,48E+06	1,50E+01	100 %	2,18E+04
Inspection [per ha]	4,20E+01	1,59E+00	1,74E+03	1,00E+03	30,00 %	3,00E+02	2,10E-01	2,77E+05	5,49E+04	1,50E+01	100 %	8,40E+02
Maintenance	2,10E+01	7,94E-01	4,36E+02	1,00E+03	30,00 %	3,00E+02	2,10E-01	1,39E+05	2,75E+04	1,50E+01	20 %	8,40E+01
Operation total			**4,73E+04**					**1,47E+07**	**3,04E+06**			**4,46E+04**

Scenario 3: Increased distance to shore

General

Ocean depth [m]	110	**Farm length [m]**	500
Substrate depth [m]	10	**Farm breadth [m]**	200
Distance to shore [m]	10000	**Farm size [ha]**	10
Transit speed MPV [m/s]	7	**Number of anchoring points**	16
Inspection freq. [n/year]	2	**Number of frame buoys**	12
Planned maintenance freq.[n/year]	1	**Number of cult.lines**	5477
Lifetime of farm [y]	20	**Length of cultivation line [m]**	10
Max operation duration	12	**Tot length of cultivation lines [ı**	54770
EXP yield [t WW over lfietime]	31433,3	**Lengt of mooring line [m]**	200

Operation durations

Operations	Fleet	Duration [h]	Comments
Transit	MPV	0,79	Rountrip
Anchor installation	MPV + ROV	2,00	Per unit
Frame/mooring connection	MPV + ROV	0,50	Per connection
Connecting cult. Ropes	MPV + ROV	0,10	Per cultivation rope
Disconnecting and harvesting	MPV + ROV	0,10	Per cultivation rope
Inspection	MPV + ROV	2,00	Per hectare
Maintenance	MPV + ROV	1,00	Per hectare
ROV deployment+retrieval	MPV + ROV	0,50	

Component specifications

Component	Material	MBL base case	Density		Specs	MBL Actual	N[m//units]	Mass[kg]	S. life[y]	kg per ww t sw
Anchor chain	Cr steel	27,6 tonn	1,84E+01	kg/m**	Scale, 30 mm	47,6 tonn	1,60E+03	2,94E+04	2,00E+01	9,35E-01
Anchors	Cr steel	5,5 tonn	7,00E+02	kg	Scale, 700 kg plough anchor	700*20 tonn	1,60E+01	1,12E+04	2,00E+01	3,56E-01
Connection plate/ring	Cr steel	11,0 tonn	3,80E+01	kg per	Scale, 40 mm, 8 holes	?	1,20E+01	4,56E+02	2,00E+01	1,45E-02
Thimbles	Cr steel	16,6 tonn	2,40E+00	kg per	Guess /Half of the shackles	?	7,00E+01	1,68E+02	2,00E+01	5,34E-03
Shackles (A: 60t)	Cr steel	11,0 tonn	4,80E+00	kg per	Mørenot, RedPin Bow shackle	72 tonn	3,20E+01	1,54E+02	2,00E+01	4,89E-03
Shackles (B: 40t)	Cr steel	11,0 tonn	4,80E+00	kg per	Mørenot, RedPin Bow shackle	72 tonn	5,80E+01	2,78E+02	2,00E+01	8,86E-03
Buoy shackle	Cr steel	6,2 tonn	1,70E+00	kg per	Mørenot, RedPin Bow shackle	39 tonn	1,20E+01	2,04E+01	2,00E+01	6,49E-04
Mooring rope	PE, fleece	16,6 tonn	1,04E+00	kg/m	Mørenot, 3-strand, 48 mm	36,6 tonn	3,20E+03	3,33E+03	5,00E+00	4,23E-01
Cultivation rope	PE, fleece	3,1 tonn	1,15E-01	kg/m	Mørenot, 3-strand, 16 mm	25,7 tonn	5,48E+04	6,30E+03	1,00E+00	4,01E+00
Frame rope	PE, fleece	16,6 tonn	1,04E+00	kg/m	Mørenot, 3-strand, 48 mm	36,6 tonn	6,70E+03	6,97E+03	5,00E+00	8,87E-01
Buoy rope	PE, fleece	6,2 tonn	7,20E-01	kg/m	Mørenot, 3-strand, 40 mm	25,7 tonn	1,20E+02	8,64E+01	5,00E+00	1,10E-02
Buoys, cultivation lines	PE	13 kg (buoyance)	1,15E+00	kg per	Eiva-safetec polyform A-1 garnblåse	13 kg	5,48E+03	6,30E+03	2,00E+01	2,00E-01
Buoys, mooring frame	PE	CB 1800	1,23E+02	kg	Mørenot, CB 1800	1800 tonn	1,20E+01	1,48E+03	2,00E+01	4,70E-02

Operation specifications

Operation	Duration[h]	Transit duration	Duration[h/life]	M.eng.cap.[kW]	Load	Load[kW]	SFC[kg/kWh]	E. cons.[kWh]	Fuel cons.[kg]	Load ROV[kW]	ROV use	ROV use[h]
Transit (roundtrip) MPV				7,50E+02	80,00 %	6,00E+02	1,80E-01	4,76E+02	8,57E+01	-		
Transit (roundtrip) Barge				7,50E+02	80,00 %	6,00E+02	1,80E-01	1,20E+03	0,00E+00	-		
Anchor installation (per unit)	3,25E+01	7,94E-01	3,33E+01	7,50E+02	30,00 %	2,25E+02	2,10E-01	1,62E+03	1,62E+03	1,50E+01	10 %	3,25E+00
Frame/mooring connection	8,50E+00	7,94E-01	9,29E+00	7,50E+02	30,00 %	2,25E+02	2,10E-01	4,73E+01	4,87E+02	1,50E+01	100 %	8,50E+00
Installation total			**4,26E+01**	-	-	-	-	**1,67E+03**	**2,11E+03**			**1,18E+01**
Deployment	5,71E+02	3,81E+01	1,22E+04	7,50E+02	30,00 %	2,25E+02	2,10E-01	3,03E+06	6,22E+05	1,50E+01	100 %	1,14E+04
Harvesting	5,71E+02	3,81E+01	1,22E+04	7,50E+02	30,00 %	2,25E+02	2,10E-01	3,03E+06	6,22E+05	1,50E+01	100 %	1,14E+04
Inspection [per ha]	2,10E+01	1,59E+00	9,03E+02	7,50E+02	30,00 %	2,25E+02	2,10E-01	1,14E+05	2,33E+04	1,50E+01	100 %	4,20E+02
Maintenance	1,05E+01	7,94E-01	2,26E+02	7,50E+02	30,00 %	2,25E+02	2,10E-01	5,68E+04	1,16E+04	1,50E+01	20 %	4,20E+01
Operation total			**2,55E+04**					**6,22E+06**	**1,28E+06**			**2,33E+04**

Scenario 4: Increased efficiency

General

Ocean depth [m]	110	**Farm length [m]**	500
Substrate depth [m]	10	**Farm breadth [m]**	200
Distance to shore [m]	5000	**Farm size [ha]**	10
Transit speed MPV [m/s]	7	**Number of anchoring points**	16
Inspection freq. [n/year]	2	**Number of frame buoys**	12
Planned maintenance freq.[n/year]	1	**Number of cult.lines**	5477
Lifetime of farm [y]	20	**Length of cultivation line [m]**	10
Max operation duration	12	**Tot length of cultivation lines [ı**	54770
EXP yield [t WW over lfietime]	31433,3	**Lengt of mooring line [m]**	200

Operation durations

Operations	**Fleet**	**Duration [h]**	**Comments**
Transit	MPV	0,397	Rountrip
Anchor installation	MPV + ROV	2,000	Per unit
Frame/mooring connection	MPV + ROV	0,500	Per connection
Connecting cult. ropes	MPV + ROV	0,067	Per cultivation rope
Disconnecting and harvesting	MPV + ROV	0,067	Per cultivation rope
Inspection	MPV + ROV	2,000	Per hectare
Maintenance	MPV + ROV	1,000	Per hectare
ROV deployment+retrieval	MPV + ROV	0,500	

Component specifications

Component	**Material**	**MBL base case**	**Density**		**Specs**	**MBL Actual**	**N[m//units]**	**Mass[kg]**	**S. life[y]**	**kg per ww t sw**
Anchor chain	Cr steel	27,6 tonn	1,84E+01	kg/m**	Scale, 30 mm	47,6 tonn	1,60E+03	2,94E+04	2,00E+01	9,35E-01
Anchors	Cr steel	5,5 tonn	7,00E+02	kg	Scale, 700 kg plough anchor	700*20 tonn	1,60E+01	1,12E+04	2,00E+01	3,56E-01
Connection plate/ring	Cr steel	11,0 tonn	3,80E+01	kg per	Scale, 40 mm, 8 holes	?	1,20E+01	4,56E+02	2,00E+01	1,45E-02
Thimbles	Cr steel	16,6 tonn	2,40E+00	kg per	Guess /Half of the shackles	?	7,00E+01	1,68E+02	2,00E+01	5,34E-03
Shackles (A: 60t)	Cr steel	11,0 tonn	4,80E+00	kg per	Mørenot, RedPin Bow shackle	72 tonn	3,20E+01	1,54E+02	2,00E+01	4,89E-03
Shackles (B: 40t)	Cr steel	11,0 tonn	4,80E+00	kg per	Mørenot, RedPin Bow shackle	72 tonn	5,80E+01	2,78E+02	2,00E+01	8,86E-03
Buoy shackle	Cr steel	6,2 tonn	1,70E+00	kg per	Mørenot, RedPin Bow shackle	39 tonn	1,20E+01	2,04E+01	2,00E+01	6,49E-04
Mooring rope	PE, fleece	16,6 tonn	1,04E+00	kg/m	Mørenot, 3-strand, 48 mm	36,6 tonn	3,20E+03	3,33E+03	5,00E+00	4,23E-01
Cultivation rope	PE, fleece	3,1 tonn	1,15E-01	kg/m	Mørenot, 3-strand, 16 mm	25,7 tonn	5,48E+04	6,30E+03	1,00E+00	4,01E+00
Frame rope	PE, fleece	16,6 tonn	1,04E+00	kg/m	Mørenot, 3-strand, 48 mm	36,6 tonn	6,70E+03	6,97E+03	5,00E+00	8,87E-01
Buoy rope	PE, fleece	6,2 tonn	7,20E-01	kg/m	Mørenot, 3-strand, 40 mm	25,7 tonn	1,20E+02	8,64E+01	5,00E+00	1,10E-02
Buoys, cultivation lines	PE	13 kg (buoyance)	1,15E+00	kg per	Eiva-safetec polyform A-1 garnblåse	13 kg	5,48E+03	6,30E+03	2,00E+01	2,00E-01
Buoys, mooring frame	PE	CB 1800	1,23E+02	kg	Mørenot, CB 1800	1800 tonn	1,20E+01	1,48E+03	2,00E+01	4,70E-02

Operation specifications

Operation	**Duration[h]**	**Transit duration**	**Duration[h/life]**	**M.eng.cap.[kW]**		**Load**	**Load[kW]**	**SFC[kg/kWh]**	**E. cons.[kWh]**	**Fuel cons.[kg]**	**Load ROV[kW]**	**ROV use**	**ROV use[h]**
Transit (roundtrip) MPV				7,50E+02		80,00 %	6,00E+02	1,80E-01	2,38E+02	4,29E+01	-		
Transit (roundtrip) Barge				7,50E+02		80,00 %	6,00E+02	1,80E-01	1,20E+03	0,00E+00	-		
Anchor installation (per unit)	3,25E+01	3,97E-01	3,29E+01	7,50E+02		30,00 %	2,25E+02	2,10E-01	1,58E+03	1,58E+03	1,50E+01	10 %	3,25E+00
Frame/mooring connection	8,50E+00	3,97E-01	8,90E+00	7,50E+02		30,00 %	2,25E+02	2,10E-01	4,73E+01	4,44E+02	1,50E+01	100 %	8,50E+00
Installation total			**4,18E+01**	-	-		-	-	**1,63E+03**	**2,02E+03**			**1,18E+01**
Deployment	3,81E+02	1,27E+01	7,87E+03	7,50E+02		30,00 %	2,25E+02	2,10E-01	1,87E+06	3,87E+05	1,50E+01	100 %	7,61E+03
Harvesting	3,81E+02	1,27E+01	7,87E+03	7,50E+02		30,00 %	2,25E+02	2,10E-01	1,87E+06	3,87E+05	1,50E+01	100 %	7,61E+03
Inspection [per ha]	2,10E+01	7,94E-01	8,72E+02	7,50E+02		30,00 %	2,25E+02	2,10E-01	1,04E+05	2,16E+04	1,50E+01	100 %	4,20E+02
Maintenance	1,05E+01	3,97E-01	2,18E+02	7,50E+02		30,00 %	2,25E+02	2,10E-01	5,20E+04	1,08E+04	1,50E+01	20 %	4,20E+01
Operation total			**1,68E+04**						**3,89E+06**	**8,07E+05**			**1,57E+04**

Scenario 5: Extended functional life of ropes

General

Ocean depth [m]	110	**Farm length [m]**	500
Substrate depth [m]	10	**Farm breadth [m]**	200
Distance to shore [m]	5000	**Farm size [ha]**	10
Transit speed MPV [m/s]	7	**Number of anchoring points**	16
Inspection freq. [n/year]	2	**Number of frame buoys**	12
Planned maintenance freq.[n/year]	1	**Number of cult.lines**	5477
Lifetime of farm [y]	20	**Length of cultivation line [m]**	10
Max operation duration	12	**Tot length of cultivation lines [ı**	54770
EXP yield [t WW over lfetime]	31433,3	**Lengt of mooring line [m]**	200

Operation durations

Operations	Fleet	Duration [h]	Comments
Transit	MPV	0,40	Rountrip
Anchor installation	MPV + ROV	2,00	Per unit
Frame/mooring connection	MPV + ROV	0,50	Per connection
Connecting cult. Ropes	MPV + ROV	0,10	Per cultivation rope
Disconnecting and harvesting	MPV + ROV	0,10	Per cultivation rope
Inspection	MPV + ROV	2,00	Per hectare
Maintenance	MPV + ROV	1,00	Per hectare
ROV deployment+retrieval	MPV + ROV	0,50	

Component specifications

Component	Material	MBL base case	Density		Specs	MBL Actual	N[m//units]	Mass[kg]	S. life[y]	kg per ww t sw
Anchor chain	Cr steel	27,6 tonn	1,84E+01	kg/m**	Scale, 30 mm	47,6 tonn	1,60E+03	2,94E+04	2,00E+01	9,35E-01
Anchors	Cr steel	5,5 tonn	7,00E+02	kg	Scale, 700 kg plough anchor	700*20 tonn	1,60E+01	1,12E+04	2,00E+01	3,56E-01
Connection plate/ring	Cr steel	11,0 tonn	3,80E+01	kg per	Scale, 40 mm, 8 holes	?	1,20E+01	4,56E+02	2,00E+01	1,45E-02
Thimbles	Cr steel	16,6 tonn	2,40E+00	kg per	Guess /Half of the shackles	?	7,00E+01	1,68E+02	2,00E+01	5,34E-03
Shackles (A: 60t)	Cr steel	11,0 tonn	4,80E+00	kg per	Mørenot, RedPin Bow shackle	72 tonn	3,20E+01	1,54E+02	2,00E+01	4,89E-03
Shackles (B: 40t)	Cr steel	11,0 tonn	4,80E+00	kg per	Mørenot, RedPin Bow shackle	72 tonn	5,80E+01	2,78E+02	2,00E+01	8,86E-03
Buoy shackle	Cr steel	6,2 tonn	1,70E+00	kg per	Mørenot, RedPin Bow shackle	39 tonn	1,20E+01	2,04E+01	2,00E+01	6,49E-04
Mooring rope	PE, fleece	16,6 tonn	1,04E+00	kg/m	Mørenot, 3-strand, 48 mm	36,6 tonn	3,20E+03	3,33E+03	5,00E+00	4,23E-01
Cultivation rope	PE, fleece	3,1 tonn	1,15E-01	kg/m	Mørenot, 3-strand, 16 mm	25,7 tonn	5,48E+04	6,30E+03	2,00E+00	2,00E+00
Frame rope	PE, fleece	16,6 tonn	1,04E+00	kg/m	Mørenot, 3-strand, 48 mm	36,6 tonn	6,70E+03	6,97E+03	5,00E+00	8,87E-01
Buoy rope	PE, fleece	6,2 tonn	7,20E-01	kg/m	Mørenot, 3-strand, 40 mm	25,7 tonn	1,20E+02	8,64E+01	5,00E+00	1,10E-02
Buoys, cultivation lines	PE	13 kg (buoyance)	1,15E+00	kg per	Eiva-safetec polyform A-1 garnblåse	13 kg	5,48E+03	6,30E+03	2,00E+01	2,00E-01
Buoys, mooring frame	PE	CB 1800	1,23E+02	kg	Mørenot, CB 1800	1800 tonn	1,20E+01	1,48E+03	2,00E+01	4,70E-02

Operation specifications

Operation	Duration[h]	Transit duration	Duration[h/life]	M.eng.cap.[kW]	Load	Load[kW]	SFC[kg/kWh]	E. cons.[kWh]	Fuel cons.[kg]	Load ROV[kW]	ROV use	ROV use[h]
Transit (roundtrip) MPV				7,50E+02	80,00 %	6,00E+02	1,80E-01	2,38E+02	4,29E+01	-		
Transit (roundtrip) Barge				7,50E+02	80,00 %	6,00E+02	1,80E-01	1,20E+03	0,00E+00	-		
Anchor installation (per unit)	3,25E+01	3,97E-01	3,29E+01	7,50E+02	30,00 %	2,25E+02	2,10E-01	1,58E+03	1,58E+03	1,50E+01	10 %	3,25E+00
Frame/mooring connection	8,50E+00	3,97E-01	8,90E+00	7,50E+02	30,00 %	2,25E+02	2,10E-01	4,73E+01	4,44E+02	1,50E+01	100 %	8,50E+00
Installation total			**4,18E+01**	-	-	-	-	**1,63E+03**	**2,02E+03**			**1,18E+01**
Deployment	5,71E+02	1,90E+01	1,18E+04	7,50E+02	30,00 %	2,25E+02	2,10E-01	2,57E+06	5,80E+05	1,50E+01	100 %	1,14E+04
Harvesting	5,71E+02	1,90E+01	1,18E+04	7,50E+02	30,00 %	2,25E+02	2,10E-01	2,57E+06	5,80E+05	1,50E+01	100 %	1,14E+04
Inspection [per ha]	2,10E+01	7,94E-01	8,72E+02	7,50E+02	30,00 %	2,25E+02	2,10E-01	9,45E+04	2,16E+04	1,50E+01	100 %	4,20E+02
Maintenance	1,05E+01	3,97E-01	2,18E+02	7,50E+02	30,00 %	2,25E+02	2,10E-01	4,73E+04	1,08E+04	1,50E+01	20 %	4,20E+01
Operation total			**2,47E+04**					**5,28E+06**	**1,19E+06**			**2,33E+04**

B Simapro Input Flows

	BASE CASE					
	Materials/processes	**Comp./Operations**	**Source**	**Amount**	**Unit**	**/t WW seaweed**
Farm	Fleece, polyethylene {GLO}| market for | APOS, S	Rope	Ecoinvent		kg	5,33E+00
	Weaving, synthetic fibre {GLO}| market for weaving, synthetic fibre | APOS, S	Rope	Ecoinvent		kg	5,33E+00
	Steel, low-alloyed, hot rolled {GLO}| market for | APOS, S	Chain/Anchor	Ecoinvent		kg	1,33E+00
	Metal working, average for metal product manufacturing {GLO}| market for | APOS, S	Chain/Anchor	Ecoinvent		kg	1,33E+00
	Polyethylene, high density, granulate {RER}| production | APOS, S	Bouy	Ecoinvent		kg	2,47E-01
	Blow moulding {RER}| blow moulding | APOS, S	Bouy	Ecoinvent		kg	2,47E-01
Vessels/fuel	MPV (longliner)	MPV, installation	Ecoinvent	4,18E+01	hours	1,33E-03
	MPV (longliner)	MPV, disassembley	Ecoinvent	4,18E+01	hours	1,33E-03
	MPV (longliner)	MPV, Operation	Ecoinvent	2,47E+04	hours	7,85E-01
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, installation, MPV	Ecoinvent	2,02E+03	kg	6,44E-02
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, disassambley,MPV	Ecoinvent	2,02E+03	kg	6,44E-02
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, deployment, MPV	Ecoinvent	5,80E+05	kg	1,85E+01
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, harvest, MPV	Ecoinvent	5,80E+05	kg	1,85E+01
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, inspection, MPV	Ecoinvent	2,16E+04	kg	6,86E-01
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, maintenance, MPV	Ecoinvent	1,08E+04	kg	3,43E-01
	Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Powe, ROV, installation	Ecoinvent	1,18E+01	hours	3,74E-04
	Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Powe, ROV, disassembly	Ecoinvent	1,18E+01	hours	3,74E-04
	Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Power, ROV, operation	Ecoinvent	2,33E+04	hours	7,41E-01
	Electricity, low voltage {NO}| market for | APOS, S	Electricity, hatchery	Ecoinvent	4,51E+01	MJ	4,51E+01

	Scenario 1A				
	Cultivated yearly [WW, t]	3830,00			
	Cultivated over lifetime [WW, t]	76600,00			
	Materials/processes	**Comp./Operations**	**Source**	**Unit**	**/t WW seaweed**
Farm	Fleece, polyethylene {GLO}| market for | APOS, S	Rope	Ecoinvent	kg	2,19E+00
	Weaving, synthetic fibre {GLO}| market for weaving, synthetic fibre | APOS, S	Rope	Ecoinvent	kg	5,44E-01
	Steel, low-alloyed, hot rolled {GLO}| market for | APOS, S	Chain/Anchor	Ecoinvent	kg	2,19E+00
	Metal working, average for metal product manufacturing {GLO}| market for | APOS, S	Chain/Anchor	Ecoinvent	kg	5,44E-01
	Polyethylene, high density, granulate {RER}| production | APOS, S	Bouy	Ecoinvent	kg	1,01E-01
	Blow moulding {RER}| blow moulding | APOS, S	Bouy	Ecoinvent	kg	1,01E-01
Vessels/fuel	MPV (longliner)	MPV, installation	Ecoinvent	hours	5,46E-04
	MPV (longliner)	MPV, disassembley	Ecoinvent	hours	5,46E-04
	MPV (longliner)	MPV, Operation	Ecoinvent	hours	3,22E-01
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, installation, MPV	Ecoinvent	kg	2,64E-02
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, disassambley,MPV	Ecoinvent	kg	2,64E-02
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, deployment, MPV	Ecoinvent	kg	7,58E+00
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, harvest, MPV	Ecoinvent	kg	7,58E+00
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, inspection, MPV	Ecoinvent	kg	2,81E-01
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, maintenance, MPV	Ecoinvent	kg	1,41E-01
	Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Powe, ROV, installation	Ecoinvent	hours	1,53E-04
	Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Powe, ROV, disassembly	Ecoinvent	hours	1,53E-04
	Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Power, ROV, operation	Ecoinvent	hours	3,04E-01
	Electricity, low voltage {NO}| market for | APOS, S	Electricity, hatchery	Ecoinvent	MJ	1,85E+01

	Scenario 1B				
	Cultivated yearly [WW, t]	750,00			
	Cultivated over lifetime [WW, t]	15000,00			
	Materials/processes	**Comp./Operations**	**Source**	**Unit**	**/t WW seaweed**
Farm	Fleece, polyethylene {GLO}| market for | APOS, S	Rope	Ecoinvent	kg	1,12E+01
	Weaving, synthetic fibre {GLO}| market for weaving, synthetic fibre | APOS, S	Rope	Ecoinvent	kg	2,78E+00
	Steel, low-alloyed, hot rolled {GLO}| market for | APOS, S	Chain/Anchor	Ecoinvent	kg	1,12E+01
	Metal working, average for metal product manufacturing {GLO}| market for | APOS, S	Chain/Anchor	Ecoinvent	kg	2,78E+00
	Polyethylene, high density, granulate {RER}| production | APOS, S	Bouy	Ecoinvent	kg	5,18E-01
	Blow moulding {RER}| blow moulding | APOS, S	Bouy	Ecoinvent	kg	5,18E-01
Vessels/fuel	MPV (longliner)	MPV, installation	Ecoinvent	hours	2,79E-03
	MPV (longliner)	MPV, disassembley	Ecoinvent	hours	2,79E-03
	MPV (longliner)	MPV, Operation	Ecoinvent	hours	1,65E+00
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, installation, MPV	Ecoinvent	kg	1,35E-01
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, disassambley,MPV	Ecoinvent	kg	1,35E-01
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, deployment, MPV	Ecoinvent	kg	3,87E+01
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, harvest, MPV	Ecoinvent	kg	3,87E+01
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, inspection, MPV	Ecoinvent	kg	1,44E+00
	Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, maintenance, MPV	Ecoinvent	kg	7,19E-01
	Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Powe, ROV, installation	Ecoinvent	hours	7,83E-04
	Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Powe, ROV, disassembly	Ecoinvent	hours	7,83E-04
	Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Power, ROV, operation	Ecoinvent	hours	1,55E+00
	Electricity, low voltage {NO}| market for | APOS, S	Electricity, hatchery	Ecoinvent	MJ	9,45E+01

Scenario 2					
Materials/processes	**Comp./Operations**	**Source**	**Amount**	**Unit**	**kg/t WW seaweed**
Fleece, polyethylene {GLO}| market for | APOS, S	Rope	Ecoinvent		kg	4,93E+00
Weaving, synthetic fibre {GLO}| market for weaving, synthetic fibre | APOS, S	Rope	Ecoinvent		kg	4,93E+00
Steel, low-alloyed, hot rolled {GLO}| market for | APOS, S	Chain/Anchor	Ecoinvent		kg	7,47E-01
Metal working, average for metal product manufacturing {GLO}| market for | APOS, S	Chain/Anchor	Ecoinvent		kg	7,47E-01
Polyethylene, high density, granulate {RER}| production | APOS, S	Bouy	Ecoinvent		kg	2,27E-01
Blow moulding {RER}| blow moulding | APOS, S	Bouy	Ecoinvent		kg	2,27E-01
MPV (longliner)	MPV, installation	Ecoinvent	4,68E+01	hours	7,44E-04
MPV (longliner)	MPV, disassembley	Ecoinvent	4,68E+01	hours	7,44E-04
MPV (longliner)	MPV, Operation	Ecoinvent	4,73E+04	hours	7,52E-01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, installation, MPV	Ecoinvent	3,01E+03	kg	4,79E-02
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, disassambley,MPV	Ecoinvent	3,01E+03	kg	4,79E-02
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, deployment, MPV	Ecoinvent	1,48E+06	kg	2,35E+01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, harvest, MPV	Ecoinvent	1,48E+06	kg	2,35E+01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, inspection, MPV	Ecoinvent	5,49E+04	kg	8,74E-01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, maintenance, MPV	Ecoinvent	2,75E+04	kg	4,37E-01
Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Powe, ROV, installation	Ecoinvent	1,32E+01	hours	2,09E-04
Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Powe, ROV, disassembly	Ecoinvent	1,32E+01	hours	2,09E-04
Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Power, ROV, operation	Ecoinvent	4,46E+04	hours	7,09E-01
Electricity, low voltage {NO}| market for | APOS, S	Electricity, hatchery	Ecoinvent	4,51E+01	MJ	4,51E+01

Scenario 3					
Materials/processes	**Comp./Operations**	**Source**	**Amount**	**Unit**	**kg/t WW seaweed**
Fleece, polyethylene {GLO}| market for | APOS, S	Rope	Ecoinvent		kg	5,33E+00
Weaving, synthetic fibre {GLO}| market for weaving, synthetic fibre | APOS, S	Rope	Ecoinvent		kg	5,33E+00
Steel, low-alloyed, hot rolled {GLO}| market for | APOS, S	Chain/Anchor	Ecoinvent		kg	1,33E+00
Metal working, average for metal product manufacturing {GLO}| market for | APOS, S	Chain/Anchor	Ecoinvent		kg	1,33E+00
Polyethylene, high density, granulate {RER}| production | APOS, S	Bouy	Ecoinvent		kg	2,47E-01
Blow moulding {RER}| blow moulding | APOS, S	Bouy	Ecoinvent		kg	2,47E-01
MPV (longliner)	MPV, installation	Ecoinvent	4,26E+01	hours	1,35E-03
MPV (longliner)	MPV, disassembley	Ecoinvent	4,26E+01	hours	1,35E-03
MPV (longliner)	MPV, Operation	Ecoinvent	2,55E+04	hours	8,11E-01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, installation, MPV	Ecoinvent	2,11E+03	kg	6,71E-02
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, disassambley,MPV	Ecoinvent	2,11E+03	kg	6,71E-02
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, deployment, MPV	Ecoinvent	6,22E+05	kg	1,98E+01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, harvest, MPV	Ecoinvent	6,22E+05	kg	1,98E+01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, inspection, MPV	Ecoinvent	2,33E+04	kg	7,40E-01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, maintenance, MPV	Ecoinvent	1,16E+04	kg	3,70E-01
Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Powe, ROV, installation	Ecoinvent	1,18E+01	hours	3,74E-04
Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Powe, ROV, disassembly	Ecoinvent	1,18E+01	hours	3,74E-04
Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Power, ROV, operation	Ecoinvent	2,33E+04	hours	7,41E-01
Electricity, low voltage {NO}| market for | APOS, S	Electricity, hatchery	Ecoinvent	4,51E+01	MJ	45,11

Scenario 4					
Materials/processes	**Comp./Operations**	**Source**	**Amount**	**Unit**	**kg/t WW seaweed**
Fleece, polyethylene {GLO}| market for | APOS, S	Rope	Ecoinvent		kg	5,33E+00
Weaving, synthetic fibre {GLO}| market for weaving, synthetic fibre | APOS, S	Rope	Ecoinvent		kg	5,33E+00
Steel, low-alloyed, hot rolled {GLO}| market for | APOS, S	Chain/Anchor	Ecoinvent		kg	1,33E+00
Metal working, average for metal product manufacturing {GLO}| market for | APOS, S	Chain/Anchor	Ecoinvent		kg	1,33E+00
Polyethylene, high density, granulate {RER}| production | APOS, S	Bouy	Ecoinvent		kg	2,47E-01
Blow moulding {RER}| blow moulding | APOS, S	Bouy	Ecoinvent		kg	2,47E-01
MPV (longliner)	MPV, installation	Ecoinvent	4,18E+01	hours	1,33E-03
MPV (longliner)	MPV, disassembley	Ecoinvent	4,18E+01	hours	1,33E-03
MPV (longliner)	MPV, Operation	Ecoinvent	1,68E+04	hours	5,35E-01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, installation, MPV	Ecoinvent	2,02E+03	kg	6,44E-02
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, disassambley,MPV	Ecoinvent	2,02E+03	kg	6,44E-02
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, deployment, MPV	Ecoinvent	3,87E+05	kg	1,23E+01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, harvest, MPV	Ecoinvent	3,87E+05	kg	1,23E+01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, inspection, MPV	Ecoinvent	2,16E+04	kg	6,86E-01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, maintenance, MPV	Ecoinvent	1,08E+04	kg	3,43E-01
Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Powe, ROV, installation	Ecoinvent	1,18E+01	hours	3,74E-04
Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Powe, ROV, disassembly	Ecoinvent	1,18E+01	hours	3,74E-04
Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Power, ROV, operation	Ecoinvent	1,57E+04	hours	4,99E-01
Electricity, low voltage {NO}| market for | APOS, S	Electricity, hatchery	Ecoinvent	4,51E+01	MJ	45,11

Scenario 5					
Materials/processes	**Comp./Operations**	**Source**	**Amount**	**Unit**	**kg/t WW seaweed**
Fleece, polyethylene {GLO}| market for | APOS, S	Rope	Ecoinvent		kg	3,32E+00
Weaving, synthetic fibre {GLO}| market for weaving, synthetic fibre | APOS, S	Rope	Ecoinvent		kg	3,32E+00
Steel, low-alloyed, hot rolled {GLO}| market for | APOS, S	Chain/Anchor	Ecoinvent		kg	1,33E+00
Metal working, average for metal product manufacturing {GLO}| market for | APOS, S	Chain/Anchor	Ecoinvent		kg	1,33E+00
Polyethylene, high density, granulate {RER}| production | APOS, S	Bouy	Ecoinvent		kg	2,47E-01
Blow moulding {RER}| blow moulding | APOS, S	Bouy	Ecoinvent		kg	2,47E-01
MPV (longliner)	MPV, installation	Ecoinvent	4,18E+01	hours	1,33E-03
MPV (longliner)	MPV, disassembley	Ecoinvent	4,18E+01	hours	1,33E-03
MPV (longliner)	MPV, Operation	Ecoinvent	2,47E+04	hours	7,85E-01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, installation, MPV	Ecoinvent	2,02E+03	kg	6,44E-02
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, disassambley,MPV	Ecoinvent	2,02E+03	kg	6,44E-02
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, deployment, MPV	Ecoinvent	5,80E+05	kg	1,85E+01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, harvest, MPV	Ecoinvent	5,80E+05	kg	1,85E+01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, inspection, MPV	Ecoinvent	2,16E+04	kg	6,86E-01
Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | APOS, S	Fuel, maintenance, MPV	Ecoinvent	1,08E+04	kg	3,43E-01
Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Powe, ROV, installation	Ecoinvent	1,18E+01	hours	3,74E-04
Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Powe, ROV, disassembly	Ecoinvent	1,18E+01	hours	3,74E-04
Diesel, burned in diesel-electric generating set {GLO}| market for | APOS, S	Power, ROV, operation	Ecoinvent	2,33E+04	hours	7,41E-01
Electricity, low voltage {NO}| market for | APOS, S	Electricity, hatchery	Ecoinvent	4,51E+01	MJ	45,11

C Growth rate and Carbon content of Sugar Kelp

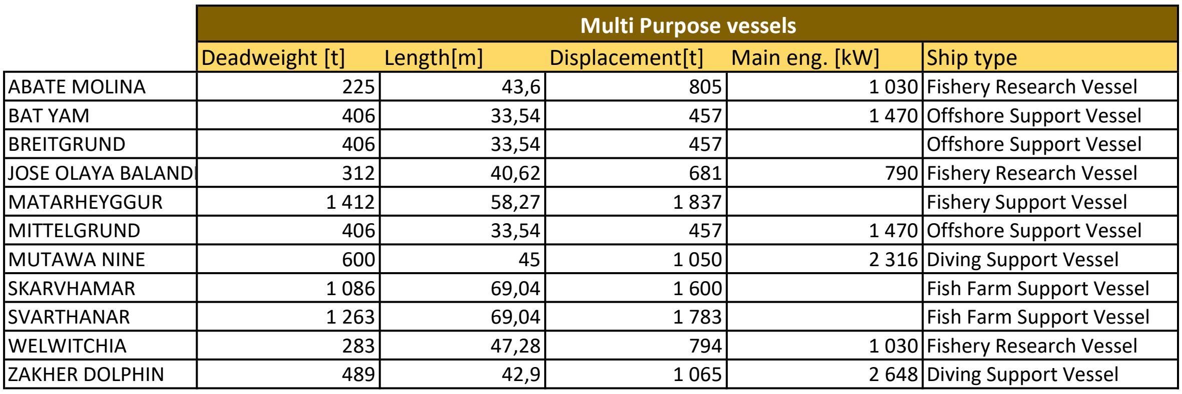
Kelp Growth Rates

Art	t WW/ha	Location	Remarks	Source
S. latissima	220	Scotland	Upscaled from small scale field trials in Integrated Multi-trophic Aquaculture (IMTA)	Sanderson et al., 2012
S. latissima	35	Galicia		Peteiro and Freire 2013
S. latissima	95	Eastern Canada	Recalculated by the present authors from a yield of 19.95 t per 0.21 ha	Reid et al., 2013
S. latissima	200	Norway	Upscaled by present authors	Matsson et al., 2015
S. latissima	10	Limfjorden, Den	Upscaled by present authors from biomass yields m−1 vertical rope culture, 2.5 deep, assuming 2,000 ropes ha−1	Seghatta et al. 2016
S. latissima	25,05	Sweeden	Upscaled from small scale field trials by present authors	Pechsiri et al., 2016
S. latissima	383	Central Norway	Upscaled by the present authors from reports on a production of 38.3 kg m−2 from February to June	Sharma et al., 2018
S. latissima	75	Norway	Model based estimate for average within entire Norwegian baseline.	Broch et al.,
S. latissima	230	Norway	Model based estimate for maximal potential within entire Norwegian baseline with deployment in September.	Broch et al.,
S. latissima	30	Norway	SES, shallow depths, horizontal ropes	Bale, 2017
S. latissima	62,5	Ireland	AtSeaNova, sheets	Bale, 2017
S. latissima	25	Norway	Bulandet 10, horizontal ropes	Bale, 2017
	115,88	AVERAGE		
	157,17	AVERAGE, Norway		
	383	BEST CASE		

Carbon content Saccharina l.

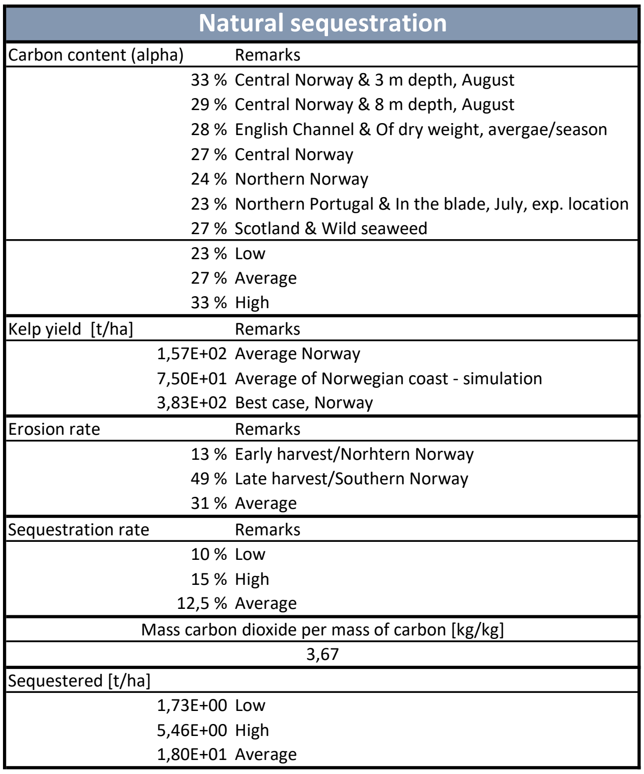
Art	avg C-content	Location	Remarks	Source
S. latissima	27,7 %	eastern English Channel	Of dry weight, avergae over a season	Gevaert_2001
S. latissima	26,6 %	Frøya	-	Fieler_2021
S. latissima	23,8 %	Tromsø	-	Fieler_2021
S. latissima	23,3 %	Northern Portugal	In the blade, july, exopsed location	Azevedo_2019
S. latissima	26,5 %	Isle of Seil, Scotland	Wild seaweed	Schiener_2015
S. latissima	32,7 %	Frøya	3 m, August	Sharma_2018
S. latissima	28,60 %	Frøya	8 m, August	Sharma_2018
	27,02 %	AVERAGE		
	27,93 %	AVERAGE, Norway		

D Reference vessels



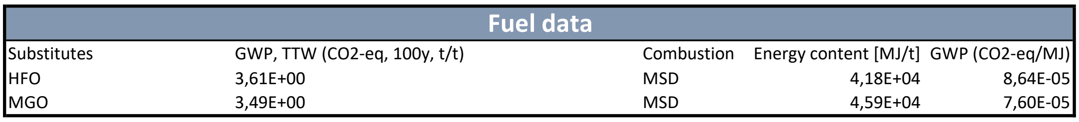
	Multi Purpose vessels				
	Deadweight [t]	Length[m]	Displacement[t]	Main eng. [kW]	Ship type
ABATE MOLINA	225	43,6	805	1 030	Fishery Research Vessel
BAT YAM	406	33,54	457	1 470	Offshore Support Vessel
BREITGRUND	406	33,54	457		Offshore Support Vessel
JOSE OLAYA BALAND	312	40,62	681	790	Fishery Research Vessel
MATARHEYGGUR	1 412	58,27	1 837		Fishery Support Vessel
MITTELGRUND	406	33,54	457	1 470	Offshore Support Vessel
MUTAWA NINE	600	45	1 050	2 316	Diving Support Vessel
SKARVHAMAR	1 086	69,04	1 600		Fish Farm Support Vessel
SVARTHANAR	1 263	69,04	1 783		Fish Farm Support Vessel
WELWITCHIA	283	47,28	794	1 030	Fishery Research Vessel
ZAKHER DOLPHIN	489	42,9	1 065	2 648	Diving Support Vessel

E Sequestration Data and Calculations



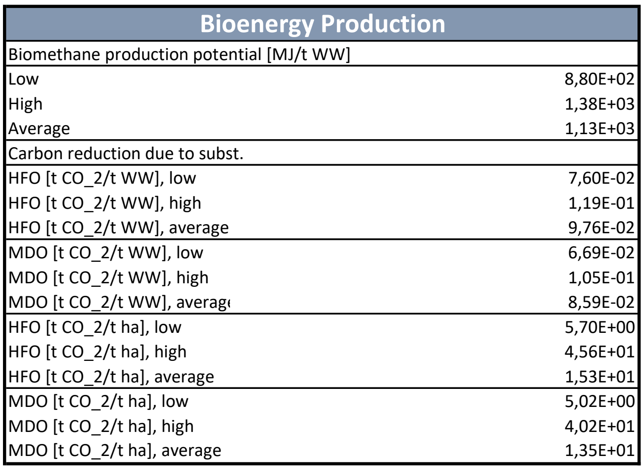
Natural sequestration

Carbon content (alpha)	Remarks
33 %	Central Norway & 3 m depth, August
29 %	Central Norway & 8 m depth, August
28 %	English Channel & Of dry weight, avergae/season
27 %	Central Norway
24 %	Northern Norway
23 %	Northern Portugal & In the blade, July, exp. location
27 %	Scotland & Wild seaweed
23 %	Low
27 %	Average
33 %	High
Kelp yield [t/ha]	Remarks
1,57E+02	Average Norway
7,50E+01	Average of Norwegian coast - simulation
3,83E+02	Best case, Norway
Erosion rate	Remarks
13 %	Early harvest/Norhtern Norway
49 %	Late harvest/Southern Norway
31 %	Average
Sequestration rate	Remarks
10 %	Low
15 %	High
12,5 %	Average
Mass carbon dioxide per mass of carbon [kg/kg]	
3,67	
Sequestered [t/ha]	
1,73E+00	Low
5,46E+00	High
1,80E+01	Average



Fuel data

Substitutes	GWP, TTW (CO2-eq, 100y, t/t)	Combustion	Energy content [MJ/t]	GWP (CO2-eq/MJ)
HFO	3,61E+00	MSD	4,18E+04	8,64E-05
MGO	3,49E+00	MSD	4,59E+04	7,60E-05



Bioenergy Production

Biomethane production potential [MJ/t WW]	
Low	8,80E+02
High	1,38E+03
Average	1,13E+03
Carbon reduction due to subst.	
HFO [t CO_2/t WW], low	7,60E-02
HFO [t CO_2/t WW], high	1,19E-01
HFO [t CO_2/t WW], average	9,76E-02
MDO [t CO_2/t WW], low	6,69E-02
MDO [t CO_2/t WW], high	1,05E-01
MDO [t CO_2/t WW], averag	8,59E-02
HFO [t CO_2/t ha], low	5,70E+00
HFO [t CO_2/t ha], high	4,56E+01
HFO [t CO_2/t ha], average	1,53E+01
MDO [t CO_2/t ha], low	5,02E+00
MDO [t CO_2/t ha], high	4,02E+01
MDO [t CO_2/t ha], average	1,35E+01

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