Bachelor's project

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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# Economic analysis of microalgae production in by-product from biogas plant by installation of rotating biofilm reactors

Bachelor's project in Renewable Energy, Engineering
Supervisor: Kristian M. Lien

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# Bachelor thesis

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# Preface

This bachelor thesis is written by group FEN1905 at Norwegian University of Science and Technology (NTNU), in the spring of 2019. The group consists of three students from the study programme Renewable Energy under the department of Energy and Process Engineering. The bachelor thesis is the final part of the study programme and leads to 20 credits in the subject TFNE3001 and the degree of bachelor, engineer.

The purpose of the thesis was to investigate the possibility to install a microalgae cultivation plant at Biokraft AS at Skogn in Trøndelag, Norway. It was examined whether it would be a profitable, sustainable and beneficial investment, according to market potential and future prospects.

The authors would like to thank supervisor Kristian M. Lien, associate professor at Department of Energy and Process Engineering, for helpful advice and guidance throughout the project period. Thanks to the external supervisor Olivier Bernard, for valuable help. We appreciate you both for always being available for questions and suggestions. Many thanks to Jan Helge Ekeren from Norske Varmeleveranser AS who has contributed with calculations regarding investment costs, and to Anna Synnøve Røstad Norgård from Biokraft who has given information about the digestate composition. A special thanks to Espen Forseth Westrum for illustrating the microalgae cultivation methods. We would also like to thank fellow students and our families for feedback during the process.

Through the process of preparing and carrying out the assignment, we have gained professional knowledge of thesis writing and solution-oriented approach of problem solving. We have also learned useful and important experiences regarding teamwork and project management.

Trondheim, 24.05.2019

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# Abstract

The interest for microalgae cultivation is growing, and the fields of applications are numerous. Microalgae have high growth rate and high lipid content including essential omega–3 fatty acids and high value pigments. There is a growing demand for new sustainable fish feed ingredients in the aquaculture. As algae is a part of the natural fish diet, it has a potential to replace current ingredients in the aquaculture feed. The biogas production at Biokraft AS in Trøndelag, Norway, creates a by-product which is rich in nitrogen and phosphorus. These nutrients are essential for microalgal growth, and will together with the accessible $CO_2$ from the biogas production enable microalgae cultivation.

By conducting a profit and loss (**P&L**) analysis, two different scenarios were analyzed to determine the profitability of investing in a microalgae production plant. Both scenarios were based on a production from April to September, an area of 1 ha and using rotating biofilm reactors. Scenario 1 was based on using algae paste of *Phaeodactylum tricornutum* as an omega–3 rich ingredient in fish feed. Scenario 2 was based on cultivation of *Haematococcus pluvialis* to extract the high value pigment astaxanthin. In addition, this scenario gave a remaining defatted biomass, consisting of valuable nutrients.

The results from the analysis showed that the semiannual production for algae paste and astaxanthin could be 57.5 t and 1.4 t of dry weight (**DW**), respectively. The production cost of the paste was calculated to be 84 NOK $kg^{-1}$ DW, and would be profitable if sold at a price higher than 180 NOK $kg^{-1}$ DW. This is too high a price to compete as a bulk ingredient in fish feed, but might be a potential feed supplement. The extracted astaxanthin was calculated to have a production cost of 4,155 NOK $kg^{-1}$ DW, which is almost half the production cost of synthetic astaxanthin at 8,100 NOK $kg^{-1}$ DW. The astaxanthin should be sold at a price higher than 4,800 NOK $kg^{-1}$ to be profitable. This is a great advantage as the current market price is at 20,000–57,000 NOK $kg^{-1}$. This enables the great potential of producing natural astaxanthin in Trøndelag. The analysis showed that the investment of the microalgae production plant will be profitable if the algae is sold as a high value product.

# Abstract in Norwegian

Interessen for dyrking av mikroalger er voksende, og bruksområdene er mange. Mikroalger har høy vekstrate og høyt lipidinnhold, derav essensielle omega–3 fettsyrer og høyverdipigmenter. Det er et økende behov for nye bærekraftige ingredienser til fiskefôr for oppdrettsfisk. Siden alger er en naturlig del av kostholdet til fisk, har de potensiale til å erstatte nåværende ingredienser i oppdrettsfôret. Biogassproduksjonen til Biokraft AS i Trøndelag danner et biprodukt som er rikt på nitrogen og fosfor. Disse næringsstoffene er essensielle for mikroalgevekst, og vil sammen med tilgjengelig $CO_2$ fra biogassproduksjonen gjøre det mulig å gro mikroalger.

For å vurdere mulighetene for mikroalgeproduskjon, ble det utført en økonomisk analyse av to ulike scenarioer. Begge scenarioene baserte seg på produksjon fra April til September, med et utgangspunkt i et produksjonsareal på 1 ha, samt bruk av roterende biofilmreaktorer. Scenario 1 så på muligheten av å bruke *Phaeodactylum tricornutum*-pasta som en ingrediens i fiskefôr. Scenario 2 vurderte muligheten for dyrking av *Haematococcus pluvialis*, for å ekstrahere det verdifulle pigmentet astaxanthin. I tillegg ga dette scenarioet et interessant restprodukt, med gunstig næringsinnhold.

Resultatene fra analysen viste at den halvårlige produksjonen av algepasta og astaxanthin kan bli henholdsvis 57.5 t og 1.4 t, på tørrvektbasis (**DW**). Produksjonskostnaden for pastaen ble regnet ut til å bli 84 NOK $kg^{-1}$ DW, og vil bli lønnsom dersom den blir solgt for en høyere pris enn 180 NOK $kg^{-1}$ DW. Dette er en høy pris å konkurrere med som en bulkingrediens til fiskefôr, men kan ha potensiale som tilsetningsstoff i fôr. Den ekstraherte astaxanthinen ble regnet til å få en produksjonskostnad på 4,155 NOK $kg^{-1}$ DW, som er nesten halvparten av den syntetiske produksjonskostnaden på 8,100 NOK $kg^{-1}$ DW. Astaxanthinen må bli solgt for en pris over 4,800 NOK $kg^{-1}$ DW for å være lønnsom. Dette er en klar fordel, siden den nåværende markedsprisen ligger på 20,000–57,000 NOK $kg^{-1}$ DW. Dette viser et spennende potensiale som ligger til rette for å produsere naturlig astaxanthin i Trøndelag. Analysen viste at investeringen av mikroalgeproduksjonsanlegget vil være lønnsom dersom algene blir solgt som et høyverdiprodukt.

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# List of Abbreviations

| | |
|---|---|
| ALA | Alpha-linolenic acid |
| ARA | Arachidonic acid |
| CAD | Cash available for distribution |
| CAPEX | Capital expenditures |
| DHA | Docosahexaenoic acid |
| DW | Dry weight |
| EAT | Earnings after tax |
| EBIT | Earnings before interest and taxes |
| EBITDA | Earnings before interest, taxes, depreciation and amortization |
| EBT | Earnings before taxes |
| EFA | Essential fatty acid |
| EPA | Eicosapentaenoic acid |
| GRAS | Generally recognized as safe |
| LA | Linoleic acid |
| OPEX | Operational expenditures |
| P&L | Profit and loss |
| PBR | Photobioreactor |
| PUFA | Polyunsaturated fatty acid |
| ROI | Return on investment |
| TSS | Total suspended solid |
| WNDS | Weighted nutrient density score |

# 1 Introduction

## 1.1 Thesis statement

Microalgae are microorganisms that have the potential to make bioproducts for a wide range of applications. Cultivation of microalgae is an area-efficient, high-productive method, and by using sunlight as an energy source the microalgae is of great interest as a more sustainable replacement for current products. Nutrients in wastewater can enable microalgae growth, and by this utilize resources already available. There are numerous reasons to do research on microalgae cultivation as a step towards a more sustainable society with focus on circular economy.

This thesis examines the profitability and possibility to cultivate microalgae in a by-product from a biogas plant at Skogn in Trøndelag, Norway. There were questions raised ahead of the research and calculations regarding market potential, opportunities and challenges. Will there be a market potential which can meet the value of the algae product? What could the algae product offer to outperform the already existing product? What are the opportunities for growing microalgae at Skogn? What are the advantageous conditions that will be present, compared to other research and already developed projects?

## 1.2 Biokraft at Skogn

Biokraft AS at Skogn in Trøndelag produces liquid biogas from waste and by-products from other nearby industries, such as aquaculture, food industry and the paper factory Norske Skog Skogn. The raw materials are transformed into biogas in digestive tanks by anaerobic decomposition. The purified liquid biogas produced at Skogn is used as fuel in buses, heavy goods vehicle, vans, ferries and hopefully trains in the future.[1]

The production of biogas creates a by-product, or digestate, which contains nutrients, including nitrogen and phosphorus among others. The by-product is currently used as a biofertilizer for agriculture. Nitrogen and phosphorus are necessary for plant growth and must be supplied to the soil. The by-product is concentrated by a factor of 10 in an evaporator prior to shipping to the farmers. Both the evaporation process and the transport of the fertilizer require energy. Another possibility is to utilize the by-product on-site and avoid transport. Biokraft does research on how to increase the profitability and the utilization, and refining of the digestate. This is done through the research project Complete, in collaboration with SINTEF, Norwegian University of Science and Technology (NTNU) and Norwegian Institute of Bioeconomy Research (NIBIO).[2]

## 1.3 Scope of the thesis

The thesis focuses on feed for Atlantic salmon due to Norway's large aquaculture industry and the growing need for sustainable fish feed. Feeding salmon with feed originating from salmon waste may be an issue with the Norwegian Food Safety Authority, due to awareness of mad cow disease. It has been chosen to disregard this issue in this thesis.

The French company Inalve develops microalgae cultivation reactors, and one of the preconditions for this thesis was to use their cultivation method. The thesis does not consider the methods for supplying of nitrogen, phosphorus and $CO_2$. They are assumed to be accessible for the algae reactors.

## 1.4 Outline of the thesis

The thesis is divided into seven chapters. After this introduction and problem formulation, Chapter 2 surveys major lines of research and literature on microalgae production, market potential and species. Chapter 3 presents the implementation of the methods used and how the study was done. In Chapter 4, the results of the study are presented. In Chapter 5 the results are discussed and analyzed. The final conclusion is given in Chapter 6. Suggestions for further work are attached in Chapter 7. Lastly, a section of appendices are attached. They give information that supports the analysis but is not essential to its explanation.

# 2 Microalgae production

Microalgae are unicellular, typically photoautotrophic microorganisms, and are able to convert light and $CO_2$ to chemical energy stored as organic carbon sources, such as carbohydrates and lipids. Microalgae are a large and diverse group containing approximately 200,000 species, and they have many unique properties. They have many applications including human food and animal feed, bioenergy and wastewater treatment.[3] A major advantageous property is the high growth rate. During exponential growth the biomass doubling times are commonly as short as 3.5 h.[4] Microalgae production leaves a small geo-footprint as it occupies minimal land area and water consumption compared to agriculture [5]. It can also be cultivated on marginal land, where it does not compete with food production and it causes less environmental and social impacts. Another benefit of microalgae is the possibility to fix $CO_2$ from streams derived from industrial processes [6].

Microalgae also has a high photosynthetic efficiency, the ratio between chemical energy stored in a plant and solar energy incident upon the plant, compared to other plants [7]. A photosynthetic efficiency of 3–5 % is a realistic, practically obtainable estimate for microalgae [2, 8], while terrestrial crops typically have an efficiency of 1 % [7].

## 2.1 Content and growth conditions

There is a wide variation in algal chemical composition, depending on species, strains, growth condition, cultivation duration and growth medium composition [5]. Microalgae contain proteins, carbohydrates, lipids, pigments, vitamins, minerals, antioxidants and ashes [5, 9]. On average, microalgae contain 10–40 % proteins, 10–30 % lipids and 5–30 % carbohydrates, on a dry weight (**DW**) basis [10].

The lipids contain fatty acids, waxes, ketones, hydrocarbons, sterols and pigments [11]. Fatty acids are carbon chains and are divided into three groups depending on the degree of unsaturation. The amount of double bonds between the carbons separates these groups. The ones with no double bonds are called saturated, while monounsaturated have one double bond and polyunsaturated have two or more double bonds. Omega–3 and omega–6 belong to the polyunsaturated group, and must be added to the food and feed for both mammals and fish. This is because they cannot synthesize these themselves, hence the name **essential** fatty acids (**EFA**).[12]

Microalgae are the primary producers of the marine omega–3 long chained polyunsaturated fatty acids (**PUFA**) docosahexaenioc acid (**DHA**) (C22:6 n–3) and eicosapentaenoic acid (**EPA**) (C20:5 n–3). These PUFAs are particularly important as a supply to feed and food, for fish and humans [13–15]. The lipid name (C22:6 n–3) indicates 22 carbons and six double bonds, where the first one is on the third carbon. This explains the names omega–3 and omega–6, where it refers to the position of its first double bond.[12] Depending on the microalgae species, there are variations in the content of these PUFAs [13]. EPA and DHA contribute to many health benefits for fish, such as development and functionality of the brain, vision and nervous system, and also for its survivability, growth and resistance to disease and stress [12]. Humans get these EFAs mainly through consumption of fish with high fat content, such as salmon, and by omega–3 supplements [13, 14]. Research has shown that EPA and DHA could play an important role for human health [16].

The three most important nutrients for algal growth are carbon, nitrogen and phosphorus, and their supply is central to algal biotechnology. On a molar basis, microalgae require 7 times more carbon than nitrogen, and 16 times more nitrogen than phosphorus to grow; a ratio known as the Redfield ratio.[17]

To make the algae biomass more suitable for its application, it is possible to enhance the content by increasing or decreasing the nutrient levels in the growth medium. There is a positive correlation between the protein level in the algae and the concentration of available nitrogen. Moreover, there will be less lipids and carbohydrates produced in nitrogen-rich media. Based on this, nitrogen starvation can be used to achieve higher levels of lipids or carbohydrates. The protein synthesis is shifted to either lipid or carbohydrate synthesis, depending on the species. Other stressors such as phosphorus starvation, light, temperature, pH and salinity are other factors that can impact the lipid accumulation.[5, 11, 18, 19]

In general, more research is needed to understand the most suitable nutrient levels. Fields et al. [19] have collected the current literature on the use of nutrient deprivation and other conditions to control and optimize microalgal culture growth in the context of cell and lipid accumulation.

## 2.2 Cultivation methods

Microalgae can be grown in open or closed systems. The open systems are commonly raceway ponds, in which nutrients, algae and water are regulated along in a circular pond. The raceway ponds have cheap construction and operation costs, but have low biomass productivity, due to limited light transmission, temperature fluctuation and low $CO_2$ transfer, among others.[20]

The closed systems, also called photobioreactors (**PBR**), operate in a more controlled environment. The parameters, including $CO_2$ level, water supply, culture density, pH level, aeration rate and mixing pattern can be controlled and customized according to the species requirement. If the PBR is placed indoors, temperature and light intensity are also controllable parameters. The biomass productivity is higher than for the open systems, but in addition the construction and operation costs are a lot higher. For both the raceway ponds and PBRs the algal cells are suspended in liquid.[20]

The French company Inalve is developing a rotating biofilm reactor. The microalgae are attached on the surface of a fabric, making a biofilm. The biofilm rotates as it alternates between being in the light and being submerged in the water, where it gets supplied nutrients. This improves the uptake of nutrients compared to traditional microalgae cultivation methods. The need for maintenance is low, and only involves a change of the fabric every second year.[21] The three cultivation methods are illustrated in Figure 1.

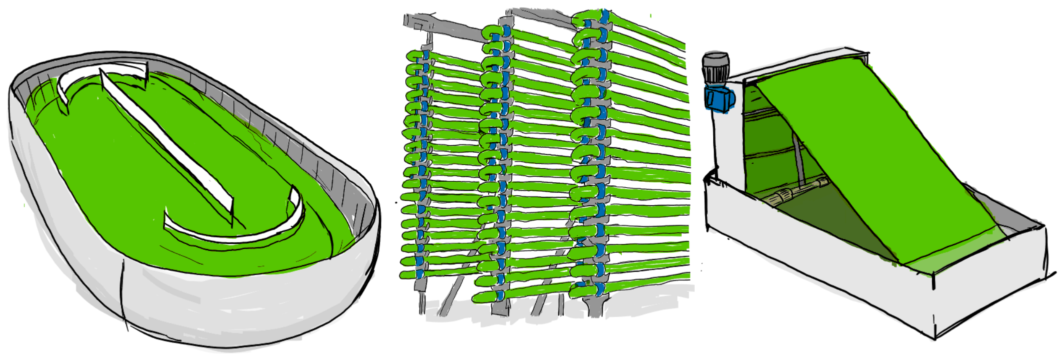

***Figure 1:*** *Illustrations of microalgae cultivation methods.*
*From left: Raceway pond, photobioreactor and rotating biofilm reactor.*

## 2.3 Harvesting methods

The microalgae paste from Inalve's reactor is easily harvested by scraping, and it consists of about 80 % water, hence 20 % of total suspended solids (**TSS**). In comparison, the harvested biomass has a much higher water content for traditional cultivation methods, since the algae is grown in aqueous suspension. The TSS for the harvested biomass varies from 0.02–0.05 % for raceway ponds and from 0.1–0.5 % for tubular PBRs [22]. To proceed, these methods require a centrifugation process, which typically gives an algal cake comprising of 15–25 % TSS [22, 23]. When using Inalve's reactor, centrifugation is not required.[21]

The necessary operations to concentrate the biomass for the traditional cultivation systems are expensive and time consuming. It has been reported that water removal can cover up to 30 % of the total capital and operating costs, and that harvesting can contribute to 21 % of total capital costs in an open pond system.[24]

## 2.4 Extraction and purification methods

Microalgae cells are small and some species have strong and layered cell walls. These walls have to be disrupted to extract the wanted fractions of the algae and maximize the product recovery. There are many different cell disruption techniques such as bead milling, chemical solvents, ultrasound, high pressure steaming, microwaving and combinations of several techniques.[25] Bead milling is the preferred method for microalgal cell disruption in industries, since it is effective and energy efficient [22, 26]. The bead miller mechanically disrupts the cell walls by spherical beads colliding and trapping the microalgae cells. The stress from the collision breaks the cells and the compounds inside are released.[23]

After the cell disruption, the next step is to dry the biomass [23]. The drying leads to better recovery of high value products from the microalgae and increases the durability. Microalgae are typically dried using spray drying, drum drying, freeze drying or solar drying. Spray drying is considered a good method for high value products.[27, 28] This method atomizes the paste into a flowing stream of hot air, and converts it to a dry powder [27]. As a result, the biomass now contains 5 % water compared to 80 % after harvesting [6].

In order to recover the desired microalgae product, liquid solvents and supercritical fluids are generally applied. A commonly used method for extraction of high value products is supercritical $CO_2$ extraction with ethanol as a co-solvent.[22, 23] The principle behind supercritical fluid extraction is to utilize the fluid properties when its pressure and temperature gets higher than its critical point. Phase changes do not occur by changing pressure or temperature over its critical point.[29] Based on this, the fluid takes advantages of both liquid and gas properties. Solvation property of liquids and high diffusivity of gases gets combined, which enables the extraction. This technique has an extraction recovery of 97 %.[23]

$CO_2$ is a beneficial fluid to use for fluid extraction, because it is nontoxic. Furthermore, its moderate critical temperature and pressure are 31.1 ℃ and 7.4 MPa, which are relatively low compared to other fluids. When using ethanol as a co-solvent, it is usually used a temperature of 60 ℃ and pressure of 30 MPa to extract. $CO_2$ could get recycled after the extraction.[23]

## 2.5 Market potential

The interest for production of microalgae has been high the last years for many reasons. Due to its properties and chemical composition, the microalgae has a wide range of applications. It can be used as feed for fish and animals, colour pigments, cosmetics, pharmaceuticals and nutraceuticals. In addition, it can serve as wastewater treatment and for bioplastic production.[6, 30, 31] Furthermore, it can be used as a raw material for production of bioenergy, which will contribute as a more sustainable alternative than using terrestrial plants. However, microalgae cultivation solely for bioenergy is not economically feasible yet.[22] A Swedish research project is using microalgae to improve the efficiency of solar panels, and has achieved an enhancement of 60 % [32]. A group from NTNU is researching the use of microalgae in batteries, and has confirmed that this type of battery has a capacity up to 40 % higher than commercially available batteries [33]. There are a lot of opportunities, but due to the report's main focus on salmon, the markets of interest were restricted to fish feed ingredients and additives.

### 2.5.1 Traditional fish feed

The world's population is constantly increasing, which again increases the demand for fish as a food resource. At the same time people are becoming more aware of the health benefits of eating fish. This results in a higher demand from the aquaculture sector. A part of the ingredients in the fish feed is covered by pelagic fisheries, which has a limited availability.[5, 18] This is challenging due to the higher need of fish feed, as well as the competition from other markets, such as the emerging omega–3 market. These factors are contributing to drive the prices upwards, and force new alternatives for the fish feed ingredients to be developed.[18, 34] The feed alternatives have to be sustainable and give a positive health effect for the fish, and this is supported by the desire among both consumers and manufacturers.[35, 36]

In Norwegian aquaculture, the marine ingredients accounted for about 90 % of the salmon diet in 1990. This content has significantly decreased the recent years, and was about 30 % in 2018 [37]. Today, the feed typically consists of 50 % vegetal protein, 19 % vegetal oil, 11 % fish oil and 17 % fishmeal [38]. Figure 2 shows the development of the composition of raw materials in fish feed in Norway in the period 1990–2014. The marine ingredients have been replaced by terrestrial plant-derived ingredients, such as plant oil and plant protein. This has led to lower levels of EFAs in the fish feed, especially regarding EPA and DHA, which adversely affect the fish health and performance.[12, 34] The vegetal raw materials include soybean, sunflower, wheat, corn, beans, peas and rapeseed oil.[39] These typically have to be shipped long distances. 94 % of the soy protein concentrate used in Norway today originates from Brazil.[40]

Fish oil is the provider of the fatty acids EPA and DHA to the fish feed. Today, 80 % of the global market of fish oil is produced from Peruvian anchoveta in Peru and Chile [18]. The current global availability of fish oil is 1,000,000 t $y^{-1}$, and 70 % of this is used in feed production in the aquaculture [13]. The price of fish oil fluctuates a lot, and the current price is about 1,550 USD $t^{-1}$, which corresponds to about 13 NOK $kg^{-1}$ [39]. In recent years there has been an increase in the fish oil price, as it in 2005 fluctuated between 300–800 USD $t^{-1}$.[13, 18] The assumed content of EPA and DHA that is needed in the fish feed for good growth is above 2.7 % of the lipids. In 2017 in Norway the average EPA and DHA share was 6 % of the lipids. In addition to the supply of EPA and DHA in the fish feed, it is also essential to include linoleic acid (**LA**) (C18:2 n–6) and alpha-linolenic acid (**ALA**) (C18:3 n–3) [41]. Some studies have shown that arachidonic acid (**ARA**) (C20:4 n–6) also can be beneficial for salmon, especially during periods of stress.[42]

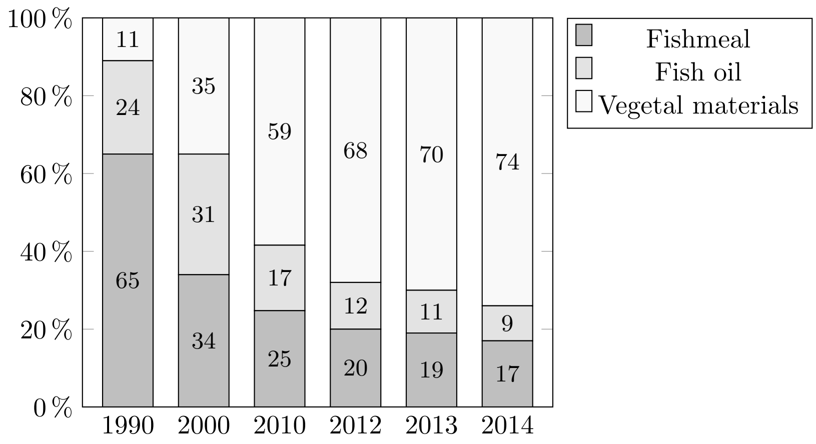


***Figure 2:*** *Development of the composition of raw materials in fish feed in Norway.[39]*

Fishmeal contains proteins, which ensure all the essential amino acids, and minerals.[38, 43] Globally in 2014, 15.8 Mt fish were caught to produce both fish oil and fishmeal [44]. This is mostly pelagic fish [5]. The price for fishmeal is about 1,505 USD $t^{-1}$, which corresponds to about 12 NOK $kg^{-1}$ [45].

The Norwegian salmon production in 2017 was 1.2 Mt, which is 95 % of the total Norwegian aquaculture [46]. The total fish feed consumption was 1.7 Mt [42]. The same year it was exported 1 Mt salmon, which makes Norway the world's leading exporter of salmon [47, 48]. A salmon needs 1.2 kg feed to grow 1 kg [39]. The feeding patterns change throughout the salmon life, and Table 1 shows a typical feeding pattern. The feed price per kg fish is about NOK 14 [49], which makes the price per kg feed about NOK 12. The Norwegian government is hoping to fivefold the aquaculture by 2050 [50]. This will require new food sources that microalgae might be an important part of [51].

***Table 1:*** *Typical feeding patterns throughout the salmon growth cycle [39].*

| Fish growth intervals | 0.1–0.2 kg | 0.2–1 kg | 1–2 kg | 2–3 kg | 3–4 kg | 4–5 kg |
|---|---|---|---|---|---|---|
| Feed consumption | 0.08 kg | 0.75 kg | 1.00 kg | 1.05 kg | 1.10 kg | 1.20 kg |
| Time [months] | 2 | 4 | 4 | 3 | 2 | 2 |

### 2.5.2 Microalgae in fish feed

Some species of microalgae can be good substitutes for ingredients in fish feed, due to their contents of proteins, vitamins, minerals, natural antioxidants, amino acids and EFAs, especially considering EPA and DHA [5, 18]. The nutritional value of the microalgae are similar to fishmeal and fish oil. Microalgae in fish feed have shown benefits on immunity, stress resistance and improved survival of larvae.[52, 53] Microalgae are at the lowest step of the aquatic food chain, which reduces the length of the chain compared to the use of anchoveta. The microalgae are also favourable due to the less needs for water and space, compared to terrestrial plants.[5] These factors ensure sustainability in the aquaculture, by reducing the remaining dependency on the limited anchoveta and not using arable land.

The main components of the salmon feed are lipids and proteins, which are the primary energy sources [12]. In addition, carbohydrates can contribute with a limited amount of energy, and provide a good water holding capacity. Even though lipids and proteins are the most important components, carbohydrates are important to ensure a technical good feed.[42] As protein synthesis could shift to either lipid or carbohydrate synthesis, it is desirable to avoid microalgae species which accumulate carbohydrates [5].

There are different ways of using the microalgae as a fish feed ingredient. The unprocessed raw material could be used directly in the feed production, if the digestibility and nutritional value have been maintained. The feed production technology has some requirements which the raw material must meet. The physical quality is mostly influenced by the ingredient composition, and should ensure high feed intake and an effective digestion. Both an appropriate size and texture are desirable to achieve this.[18]

In addition to EPA and DHA, other fatty acids such as ARA, LA and ALA are also present in some microalgae. Fish are able to convert plant derived ALA into small amounts of longer PUFAs [13, 41]. ALA can be converted to some DHA and EPA, while LA can be converted to ARA [12]. The total amount of EPA and DHA in farmed salmon is therefore a result from both the direct supply from fish oil or algae oil and the small amount from the conversion of ALA [41].

For the aquaculture industry, algae pastes are mainly used as protein supplement for the fish larvae, bivalves and shrimps, among others [54]. De Rosbo et al. [55] give a market price for biomass for aquaculture in the range of 50–150 USD $kg^{-1}$ DW. It corresponds to about 400–1,200 NOK $kg^{-1}$ DW.

To customize the biomass, different parts of the microalgae could be used separately by extraction. Supposed that the lipids are extracted for algal oil or omega-fatty acid production, the remaining defatted biomass could consist of valuable nutrients that could be used as animal or fish feed. These nutrients could contain proteins, carbohydrates, water-soluble vitamins and minerals. The protein content could be used as a substitute for fishmeal protein or as an additive ingredient in the feed.[56] This defatted biomass has a market price of 10–20 EUR $kg^{-1}$ [21], which correspond to about 95–195 NOK $kg^{-1}$.

A study by Kiron et al. [34] added defatted biomass from the species *Desmodesmus sp.* to salmon feed. The study reported that an inclusion level of 20 % defatted biomass is possible. This did not make any significant differences from the original fish feed, considering the specific growth rate, protein efficiency, fish health and composition of the fish. Another study by Ju et al. [56] has shown the possibility of using defatted *Haematoccocus pluvialis* meal in shrimp feed. In the study different content rations of 3, 6, 9 and 12 % of algae meal was added to the feed to replace fish meal and vegetal ingredients. The replacement of 12 % did not have any negative effects on the shrimp. The shrimp fed the diet with 3 % defatted algae had a higher growth rate than the control diet and the other diets containing algae.

### 2.5.3 High value colour pigment

One of the high value microalgal products is the carotenoid pigment astaxanthin [11]. It is naturally synthesized by some microalgae, yeast, plants and bacteria, and through the natural food chains it is present in some fishes, birds and crustaceans. Astaxanthin has high antioxidant activity and has a wide range of important applications in the feed, food, nutraceuticals, pharmaceutical and cosmetics sector. It is mostly used in the aquaculture and as a dietary supplement.[28, 57]

Astaxanthin is best known for the pinkish-red colour that it provides in salmons, shrimps, lobsters and crayfish. It is important for the embryo development, cell reproduction, as a precursor of vitamin A and plays an important role for their immune system.[11, 22] Wild fish get astaxanthin through eating crustaceans and algae, while the aquaculture adds astaxanthin to the feed [18]. The upper limit of accepted astaxanthin levels in fish feed is 100 mg astaxanthin per kg fish feed, and it is not allowed to add astaxanthin to fish under six months. In 2016 in Norway the average level in grower diets was 54 mg astaxanthin per kg fish feed.[58]

The world market is dominated by synthetic astaxanthin derived from petrochemicals, which contributes to over 95 % of the market. This is because of its low production costs relative to natural astaxanthin.[22] It has been reported that the synthetic astaxanthin can have 20 times lower antioxidant capacity than its natural counterpart [28]. There are also some concerns about the syntetic astaxanthin's food safety, pollution and unsustainability due to its origin from petrochemical sources. This limits the utilization of the synthetic pigment to only aquacultural applications, as other animal feeds and human consumption has not been approved.[22, 57]

The growing awareness of health benefits from natural astaxanthin, and the increasing use of natural products in nutraceutical, food and cosmetic markets, has increased the demand for natural astaxanthin [28]. In addition, the increase in aquaculture creates a greater demand of the fish feed contents [34]. These factors provide the opportunity for natural astaxanthin production.

In 2014 the global astaxanthin market for both synthetic and natural, was around 280 t. This is expected to increase to 670 t by 2020.[28] The current market value of astaxanthin varies from 2,500–7,000 USD $kg^{-1}$ to about 15,000 USD $kg^{-1}$, depending on its application and purity [28]. These prices correspond to about 20,000–57,000 NOK $kg^{-1}$ and 122,000 NOK $kg^{-1}$, respectively. The production cost of synthetic astaxanthin is around 1,000 USD $kg^{-1}$ [22], which corresponds to about 8,100 NOK $kg^{-1}$. Li et al. [57] have shown a potential for a lower production cost and a possible profitable production of natural algae-derived astaxanthin. With a combination of photobioreactors and raceway ponds they predicted the production cost of 718 USD $kg^{-1}$ DW astaxanthin (5,841 NOK $kg^{-1}$).

## 2.6 Microalgae species

There is a large variation in algal chemical composition between microalgae species, as well as from strain to strain. The market potentials of microalgae fatty acids and colour pigment, make the species *Phaeodactylum tricornutum* and *Haematococcus pluvialis* promising for their high content of respectively EPA and astaxanthin.

### 2.6.1 *Phaeodactylum tricornutum*

*P. tricornutum* is a microalgae with a high EPA content. Due to the need for EPA in the fish feed industry, this algae is a potential source of fatty acids in fish feed. Table 2 shows the composition of *P. tricornutum*. The values for proteins, lipids, carbohydrates and ashes are average values [59]. The amount of the fatty acids are from the study by Steinrücken et al. [60] where *P. tricornutum* was grown in flat panel photobioreactors outdoors in Bergen, Norway. Three different strains were grown simultaneously for a period of six months, 25.04.2016–28.10.2016, and the EPA content was found to be averagely 4.4, 3.2 and 3.1 % of DW for the different strains. The researchers found this to be higher than earlier reported values at 2.6–3.1 %. LA and ARA are also listed in the table. The contents of DHA and ALA were examined as well, but because it was under 2 % of the fatty acids, the results were not stated.[60]

The optimum growth temperature for *P. tricornutum* is 20 ℃ [61]. Physiological variables can be adjusted to induce lipid accumulation and change the composition [18]. For instance it has been reported that the EPA + DHA content could increase with 120 % when the temperature gets lowered from 25 ℃ to 10 ℃ [61].

Using *P. tricornutum* as feed has been successfully tested by adding it as an unprocessed, raw ingredient in the feed for Atlantic salmon. The protein digestibility reached 80 %, and the lipid digestibility got as

***Table 2:*** *Typical composition of P. tricornutum, with a selection of interesting fatty acids.*

| Content (% of DW) | | References |
|---|---|---|
| Proteins | 36.4 | [59] |
| Lipids | 18.0 | [59] |
| Fatty acids [1] | 6.3–18.1 | [60] |
| C18:2 n–6 (LA)[2] | 1.9–3.4 | [60] |
| C20:4 n–6 (ARA)[2] | 0.2–6.5 | [60] |
| C20:5 n–3 (EPA)[2] | 22.4–31.4 | [60] |
| Carbohydrates | 26.1 | [59] |
| Ashes | 15.9 | [59] |

[1] % of total
[2] % of fatty acids

high as around 96 %.[18]

### 2.6.2 *Haematococcus pluvialis*

*Haematococcus pluvialis* is a green freshwater algae and is considered the best source of the pigment astaxanthin found in nature [28]. Astaxanthin is produced inside the thick, multi-layered cell walls of the algae. These walls are strong and robust, and needs to be destroyed to be able to extract the astaxanthin.[25]

A typical composition, focusing on astaxanthin and EFAs, is shown in Table 3. Based on the varying content of carotenoids, the percentage of astaxanthin in the DW biomass varies between 1.5–4.0 % [62]. The astaxanthin content is the most relevant and interesting component in *H. pluvialis.* The share of LA and ALA are also relative high.

***Table 3:*** *Typical composition H. pluvialis biomass in green and red cultivation stages, with a selection of interesting fatty acids and pigments, n.d: not detected.*

| Content (% of DW) | Green stage | Red stage | References |
|---|---|---|---|
| Proteins | 29–45 | 17–25 | [62] |
| Lipids | 20–25 | 32–37 | [62] |
| Carotenoids[1] | 0.5 | 2–5 | [28] |
| Astaxanthin[2] | n.d | 81.2 | [28] |
| Fatty acids | | | |
| C18:2 n–6 (LA)[3] | – | 20.8 | [28] |
| C18:3 n–3 (ALA)[3] | – | 12.8 | [28] |
| C20:4 n–6 (ARA)[3] | – | 1.4 | [28] |
| C20:5 n–3 (EPA)[3] | – | 0.6 | [28] |
| C22:6 n–3 (DHA)[3] | – | n.d | [28] |
| Carbohydrates | 15–17 | 36-40 | [62] |
| Ashes | 29–30 | 3.8–4.2 | [63] |

[1] % of total
[2] % of carotenoids
[3] % of fatty acids

The optimum growth temperature of *H. pluvialis* is between 15–20 ℃ [64]. To get a high astaxanthin content, it is first grown with optimal growth conditions with rich nitrogen and phosphorus levels to get a high volume of biomass. Then the algae are inflicted stress factors like nitrogen starvation, increased temperature or high light irradiance, and the green cells become red [65]. The colour change in a *H. pluvialis* culture is striking when the astaxanthin is accumulated.[66] The content of astaxanthin is clearly changing from the red to the green phase, as shown in Table 3.

Supercritical $CO_2$ extraction extracts the lipids, resulting in a semi-solid substance called oleoresin which contains 10–20 % astaxanthin [22]. Astaxanthin extracted from *H. pluvialis* has been granted generally recognized as safe (**GRAS**) status. It is therefore the preferred source for high-end products, since there are concerns using synthetic astaxanthin for human consumption.[28]

In the aforementioned feeding study by Ju et al. [56] the defatted *H. pluvialis* had 0.05 % remaining astaxanthin. When 12 % of the shrimp feed was replaced with defatted algae, the astaxanthin content was estimated to be 60 mg astaxanthin per kg feed. With this level there will be no need to add any extra astaxanthin, as the average astaxanthin content in Norway is 54 mg per kg salmon feed[42].

# 3 Methodology

In order to find the most suitable microalgae species to examine, different scenarios were considered. The potential scenarios are briefly presented in this chapter. Furthermore, the calculation steps to find the final production cost per kg algae are described, along with the steps in the profitability analysis. The uncertainties of the economic parameters are taken into consideration to conduct a sensitivity analysis.

## 3.1 Scenario decision

Different microalgae scenarios were considered. The scenario decision was based on market potential of the final product, feasibility in relation to required growth conditions, as well as the profitability and viability of the investment. The final microalgae product should have a current demand, and ideally have a reliable and steady customer, which should preferably be located close to Biokraft. The access to nitrogen, phosphorus and $CO_2$ at Biokraft makes it favourable to cultivate microalgae. The access of $CO_2$ is also beneficial to use for supercritical $CO_2$ extraction.

The scenario evaluation resulted in two scenarios. Scenario 1 would be based on cultivation of the microalgae species *Phaeodactylum tricornutum*. Scenario 2 would be based on cultivation of the microalgae species *Haematococcus pluvialis*. Both *P. tricornutum* and *H. pluvialis* have the right preconditions to be grown at Skogn. Scenario 1 would produce a fresh algae paste to be used for fish feed. For scenario 2, the products would be extracted astaxanthin and a defatted biomass. The unselected scenarios were unsuitable for cultivation at Skogn due to required growth conditions, lack of market potential or other criteria that could not be met. The shelved scenarios are briefly explained below.

The possibility to not extract the astaxanthin from *H. pluvialis*, but to sell the biomass as a powder with a small percentage of astaxanthin was considered. This would not require the supercritical $CO_2$ extraction facility, and would lead to lower investment and electricity costs. However, it would result in a less pure product, hence a lower price of the final product. In addition, the defatted biomass would not be utilized.

Another considered scenario was to cultivate the microalgae *Botryococcus braunii*. It is a suitable species to use for bioplastic production due to its high hydrocarbon content, but the optimum growth temperature is 40 ℃ [30], which makes it an unsuitable species to grow at Skogn. In addition, there is not existing any bioplastic producers nearby Biokraft.

Researchers from the Department of Materials Science and Engineering at NTNU have researched using microalgae *Cosinudiscus sp.* in batteries [33]. The possibility to collaborate with the novel innovation was considered. After contacting the researchers, it was revealed that it was too early to give any clear price estimate, and the scenario was eliminated.[67]

Due to the increasing demand for new EPA and DHA sources in fish feed, a search for a species with a high DHA level was done. The species *Schizochytrium sp.* seemed to be a microalgae with high DHA content. But it became clear that it is a *Thraustochytriaceae*, which are incapable of photosynthesis, and is not really an algae.[68] This seems to be a common misconception, and is explained as a microalgae in various scientific articles. Because it needs sugar as an energy source, instead of the sun, it does not work with the Inalve reactors.[21] This scenario was therefore excluded.

## 3.2 Base calculations

The two selected scenarios for algae cultivation were analyzed with a technological and economic approach. Both were based on production from April to September, with a cultivation area of 1 ha. The cultivation period was chosen based on the solar irradiance and hours of daylight at Skogn which is shown in Table 4. The solar irradiance at Skogn from April to September is averagely 679 kWh $m^{-2}$ which represents 85 % of the annual solar irradiance. Calculations for a pilot plant of 100 $m^2$ were also carried out, the results can be found in Appendix A.

***Table 4:*** *Average solar irradiance for each month from 2010 to 2016 [69] and the average hours of daylight each day by month [70].*

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Des |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Solar irradiance [kWh $m^{-2}$] | 4.93 | 20.1 | 55.8 | 97.7 | 141 | 137 | 131 | 109 | 63.2 | 30.7 | 7.49 | 1.59 |
| Daylight [h $d^{-1}$] | 5.5 | 8.6 | 12 | 15 | 18 | 20 | 19 | 15 | 13 | 9.8 | 6.7 | 4.6 |

The biogas production at Skogn makes a gas consisting of mainly 60 % $CH_4$ and 40 % $CO_2$. The $CO_2$ is removed from the $CH_4$ by a treatment plant, and will be available to use to grow algae. The production capacity at Biokraft is 125 GWh $CH_4$ annually.[2, 71] This result in an amount of 6.14 kt $CO_2$ during half a year. The amounts of nitrogen and phosphorus in the digestate were given by Anna Synnøve Røstad Norgård at Biokraft [72] and can be found in Appendix B. It was calculated that from April to September the average nitrogen production would be 1,035 t and the phosphorus production would be 51 t. Based on the Redfield ratio, carbon will be the limiting reagent. Phosphorus and nitrogen will be excessive and the ratio of the available to the required compounds is shown in Table 5.

***Table 5:*** *The amount of the available and required compounds to grow microalgae with carbon as the limited reagent, and the ratio of the available to the required amount.*

| | Produced [Mmol] | Required [Mmol] | Ratio |
|---|---|---|---|
| Carbon | 140 | 140 | 1.0 |
| Nitrogen | 74 | 20 | 3.7 |
| Phosphorus | 1.7 | 1.3 | 1.3 |

The productivity is the grown biomass per area per time. This was calculated as shown in Equation (1), based on the relationship between the absorbed solar energy and the energy density. The absorbed solar energy is the photosynthetic efficiency multiplied with the solar irradiance, where the photosynthetic efficiency was assumed to be 5 % [2]. It is assumed that all losses from solar energy to energy in the microalgae are contained in the photosynthetic efficiency. The energy density was calculated based on the amount of proteins, lipids and carbohydrates in the species, shown in Table 2 and 3 in Chapter 2.6. Lipids contain 900 kcal per 100 g, and proteins and carbohydrates contains 400 kcal per 100 g [2].

$$\text{Productivity} = \frac{\text{Solar irradiance} \times \text{Photosynthetic efficiency}}{\text{Energy density}} \tag{1}$$

A rough estimate of the maximum cultivation area was calculated based on the assumption that all the available $CO_2$ from the biogas production from April to September was used. The amount of $CO_2$ which actually will be available for the algae was found to be 4.6 kt, by including a loss of 25 % [21]. The potential biomass production was found using the available $CO_2$ and the assumption that carbon is 50 % of DW biomass. The corresponding area was calculated by dividing the mass with the calculated productivity.

Both scenarios include the use of Inalve's biofilm reactor, which is described in Chapter 2.2. The active cultivation area, $A_{\text{active cultivation}}$ was assumed to be 80 % of the footprint area of the reactor, $A_{\text{footprint}}$ [21]. This is shown in Equation (2) and was used to find the footprint area.

$$A_{\text{active cultivation}} = A_{\text{footprint}} \times 80\,\% \tag{2}$$

## 3.3 Scenario descriptions

In scenario 1, *P. tricornutum* is cultivated and sold as a fresh paste with high EPA content, to be used as an ingredient in fish feed. The microalgae are harvested once a week. The harvested paste contains 80 % water, and has a durability of about a week when stored in a refrigerator at a temperature of about 5 ℃ [21]. Figure 3 shows the production process of scenario 1.

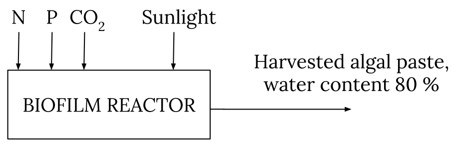


***Figure 3:*** *Flow chart of the main components for the production process of scenario 1.*

In scenario 2, *H. pluvialis* is cultivated. The microalgae are deprived of nitrogen at the end of the cultivation process to get a high astaxanthin content. The harvested paste is transferred on a conveyor belt to a bead miller for disruption. Another conveyor belt brings the biomass to a spray dryer. The lipids are extracted from the dried biomass, using supercritical $CO_2$ extraction. The extracted astaxanthin is estimated to be 2.5 % of the total dried biomass, and 10–20 % of the final lipid product. Both the astaxanthin and the remaining defatted biomass are stored in tanks, before sold to fish feed manufacturers. To the authors' knowledge defatted *H. pluvialis* has not been tested as salmon feed. In this thesis it is assumed that *H. pluvialis* will contribute positively in feed, as other species has been successfully tested on salmon. A flow chart of the main components for the production process is shown in Figure 4.

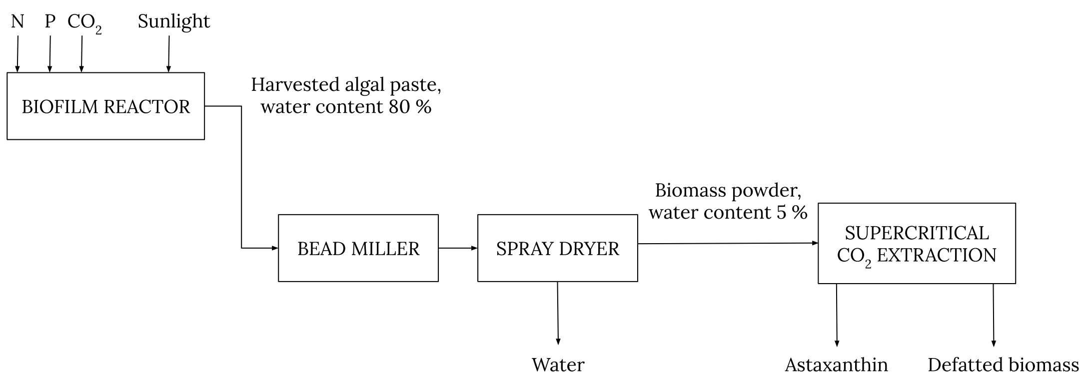


***Figure 4:*** *Flow chart of the main components for the production process of scenario 2.*

For both scenarios, the reactors are placed inside a greenhouse where the temperature is kept at 15–20 ℃. The temperature is regulated using district heating that exploits wastewater, having a temperature of 35–40 ℃, from Norske Skog Skogn.[2]

## 3.4 Economic analysis

To analyze the profitability, a profit and loss (**P&L**) analysis was carried out. The analysis and the table-layout were based on the methods used by Zgheib et al. [23] and G. Panis and J. Rosales Carreon [22]. The goal of the analysis is to find the payback time and return on investment (**ROI**), and this method is often used as an evaluation of risky projects in the initial phases. Neither payback time nor ROI takes the discount rate into account.[73] Since the prices used in the analysis are international marked prices, value added tax is not taken into account. The currency exchange rates used in the analysis are 8.1351 for USD and 9.6033 for EUR, which were the average rates for 2018 [74].

In scenario 1 the applied prices of DW algae paste were 180, 250, 400, 800 and 1,200 NOK $kg^{-1}$. In scenario 2 the prices of 4,800, 8,000, 10,000, 20,000 and 57,000 NOK $kg^{-1}$ were used for DW astaxanthin and 145 NOK $kg^{-1}$ was used as the DW defatted biomass price. Calculations with a varying defatted biomass price between 0–195 NOK $kg^{-1}$ and a fixed astaxanthin price of 20,000 NOK $kg^{-1}$ was carried out, and the results can be found in Appendix C.

To conduct the P&L analysis, a calculation of the investment costs was needed. A list of the major equipment and the corresponding costs in NOK is shown in Table 6. The future target price used in the analysis for the reactors was stated to be 100 EUR $m^{-2}$ (960 NOK $m^{-2}$), compared to today's price of 800 EUR $m^{-2}$ (7,686 NOK $m^{-2}$) [21].

Based on the similar production quantity from a study done by Zgheib et al. [23], some equipment values and sizes were found here. Respectively, the price for bead miller was USD 64,800, spray dryer was USD 30,000, for both conveyor belts it was USD 32,000 and for each storage tank it was USD 4,871. A refrigerator with an appropriate size had the price of USD 3,755 [75]. The cost of the supercritical $CO_2$ extraction facility was EUR 85,000, and was found from G. Panis and J. Rosales Carreon [22]. A price for a 100 $m^2$ greenhouse was estimated to be NOK 80,000 [76]. The cost of the 1 ha greenhouse was calculated based on the upscaling ratio of $\frac{2}{3}$, as showed in Equation (3) [2]. The fraction in the equation shows the ratio between the two sizes 1 ha and 100 $m^2$. The investment cost of the district heating system was found to be around NOK 1,500,000, based on estimated prices given by Jan Helge Ekeren from Norske Varmeleveranser AS [77]. His calculations can be found in Appendix D.

$$\mathrm{Cost}_{1\ \mathrm{ha}} = \mathrm{Cost}_{100\ \mathrm{m}^2} \times \left(\frac{10,000\,\mathrm{m}^2}{100\,\mathrm{m}^2}\right)^{\frac{2}{3}} \tag{3}$$

***Table 6:*** *The major equipment with corresponding prices and total major equipment costs.*

| Item | Scenario 1 [NOK] | Scenario 2 [NOK] | References |
|---|---|---|---|
| Biofilm reactors | 9,603,300 | 9,603,300 | [21] |
| Bead miller | – | 527,154 | [23] |
| Spray dryer | – | 244,053 | [23] |
| Supercritical $CO_2$ facility | – | 816,281 | [22] |
| Conveyor belts | – | 260,323 | [23] |
| Storage tanks | – | 79,525 | [23] |
| Refrigerator | 30,913 | – | [75] |
| Greenhouse | 1,723,548 | 1,723,548 | [76] |
| District heating system | 1,500,000 | 1,500,000 | [77] |
| Major equipment costs | 12,857,761 | 14,753,911 | |

In addition to the major equipment cost, there are other costs needed to be considered before the facility is ready to operate. These are costs such as installation, instrumentation and piping. These costs can be estimated by multiplying the major equipment cost by their corresponding Lang factors. These factors vary for different processes [78]. The factors used in this analysis were based on values for a microalgae production plant used by Acién et al. [78], located in Almería, Spain. The major equipment costs and the additional factor costs give the total investment costs. These costs are often referred to as capital expenditure (**CAPEX**) [22]. Depreciation is 10 % of CAPEX. This rate is used for industrial installations.[18, 79]

The operational expenditures (**OPEX**) are all the direct production costs; including raw material, utilities, labour and land rent [22]. For this thesis, raw material is solely ethanol for scenario 2, since the other raw materials are available from Biokraft for free. Utilities will only include electricity, where the industrial electricity price of 0.40 NOK $kWh^{-1}$ is used [2]. The energy use of the machines are showed in Table 7. It is estimated that scenario 1 will need two technicians and a 15 % engineer position, and scenario 2 will need one extra technician [21]. The land rent is assumed to be NOK 200,000 each year [2]. The total annual production costs are the sum of the OPEX and depreciation [78], as shown in Equation 4.

$$\text{Total production cost} = \text{OPEX} + \text{Depreciation} \tag{4}$$

***Table 7:*** *The electricity consumption for the machines for the production period of six months.*

| Item | Scenario 1 [kWh] | Scenario 2 [kWh] | References |
|---|---|---|---|
| Biofilm reactors | 1,317,600 | 1,317,600 | [21] |
| Bead miller | – | 388,228 | [22] |
| Spray dryer | – | 143,788 | [22] |
| Supercritical $CO_2$ facility | – | 287,576 | [22] |
| Refrigerator | 1,260 | – | [75] |
| Total electricity consumption | 1,318,860 | 2,137,192 | |

Earnings before interest, taxes, depreciation and amortization (**EBITDA**) is a good tool for comparing and analyzing an industry's profitability, because it eliminates the effects of financing, accounting decisions and CAPEX [80]. Earnings before interest and taxes (**EBIT**) is EBITDA subtracted by depreciation as shown in Equation (5).

$$\text{EBIT} = \text{EBITDA} - \text{Depreciation} \tag{5}$$

It is assumed that half of the investment is covered by economic subsidy, and the other half is covered by a loan [2]. Earnings before taxes (**EBT**) is EBIT subtracted by the interest rates on the loan as shown in Equation (6). The interest rates on the loan was found using a loan calculator for businesses [81]. Interest on capital is not included in this analysis. When taxes are subtracted from EBT the result is earnings after tax (**EAT**) as given by Equation (7).[22, 23]

$$\text{EBT} = \text{EBIT} - \text{Interest} \tag{6}$$

$$\text{EAT} = \text{EBT} - \text{Tax} \tag{7}$$

The annual ROI is given in percent. It is found by taking the ratio between cash available for distribution (**CAD**) and CAPEX, as shown in Equation (8) [22]. ROI shows the feasibility from a business point of view. CAD is the subtraction between EBITDA and taxes and is shown in Equation (9).

$$\text{ROI} = \frac{\text{CAD}}{\text{CAPEX}} \times 100\ \% \tag{8}$$

$$\text{CAD} = \text{EBITDA} - \text{TAX} \tag{9}$$

The payback time is the ratio between CAPEX and EAT, as shown in Equation (10). The payback time gives information about when the production starts to generate profit. The biofilm reactors are assumed to have a lifetime of 10 years [21]. Based on this, a payback time less than 10 years is desirable.

$$\text{Payback time} = \frac{\text{CAPEX}}{\text{EAT}} \tag{10}$$

## 3.5 Sensitivity analysis

A sensitivity analysis was carried out in order to find the most economic impacting parameters with regards to the production cost per kg DW microalgae. The parameters were: CAPEX, electricity demand, labour, land rent cost, photosynthetic efficiency, energy density of the algae and solar irradiance. The individual parameters were varied from the established base value over a reasonable range.

As the price for the biofilm reactor was an uncertain value, the parameter range for the CAPEX was determined based on change in the reactor cost. By changing the reactor cost from 100 EUR $m^{-2}$ to 200 EUR $m^{-2}$, there were about a 65 % increase in CAPEX for scenario 2, and 75 % for scenario 1. The reactor price was not considered to be lower than the given price, but there may be lower investment costs for the other equipment. In addition, the Lang factors used are based on a production plant in Spain, and these might be different in Norway. A range of +50 % and -20 % for the CAPEX was considered reasonable.

Similarly as for investment costs, there will be uncertainty regarding operation costs. The overall electricity demand, the manpower demand and the land rent cost are uncertain values. For the electricity demand, a ±30 % uncertainty was included to the base case values. There is also an uncertainty regarding the required number of employees. The assumption of 2 technicians and a 15 % engineer position was used as a base case for scenario 1 and one extra technician for scenario 2. For scenario 1, an increase to 4 technicians and a 30 % engineer position was added as a worst case, and 5 technicians and a 30 % engineer position for scenario 2. It was not added any best case, as the given required employees was not expected to be lower. The land rent cost was suggested to be 200,000 NOK $m^{-2}$, but the reference indicated it could be higher. Uncertainty ranges of +40 % and -20 % were therefore chosen.

Energy density varies between species and strains. Keeping the photosynthetic efficiency constant, a high energy density will correspond to a lower productivity. The energy density was found based on the contents of the specific algae species. The contents of the species were based on average values. It was considered to use the uncertainty ranges of ±30 %, because the energy density is very dependent on the strain. The productivity also depends on the photosynthetic efficiency. A photosynthetic efficiency of 5 % was used for base calculations, 7 % was used as a best case value and 3 % was used as a worst case value. These are, as presented in Chapter 2.1, realistic, practically obtainable estimates for microalgae.

The microalgae production also depends on the weather. The solar irradiance at a place varies from year to year, and in years with lower solar irradiance there will be less algae production. In this thesis, mean values from 2010 to 2016 for Skogn were used. The maximum solar irradiance for these years was from 2015, with the value of 733 kWh $m^{-2}$ $y^{-1}$. The minimum value was from 2014, which had 640 kWh $m^{-2}$ $y^{-1}$. These values refer to a change on the mean value of 679 kWh $m^{-2}$ $y^{-1}$ of +8 % and -6 %, respectively. A ±10 % range was selected as a reasonable uncertainty, to cover years that may have a wider variety of weather.

The photosynthetic efficiency and solar irradiance affect each other, and their influence together was interesting to predict. The best and worst case values of these two parameters were taken into account and the results were combined. The overall total best and worst case were also found, by combining the best and worst case values of all the single parameters.

The best, base and worst case values for each parameter used in the sensitivity analysis are listed in Table 8 and 9 for scenario 1 and 2, respectively.

***Table 8:*** *The best and worst case values for each parameter, along with the base values, for scenario 1.*

| | Best | Base | Worst |
|---|---|---|---|
| Photosynthetic efficiency [%] & Solar irradiance [kWh $m^{-2}$] | 7 & +10 % | 5 & 679 | 3 & -10 % |
| Photosynthetic efficiency [%] | 7 | 5 | 3 |
| CAPEX [MNOK] | -20 % | 34 | +50 % |
| Energy density in microalgae [kJ $g^{-1}$] | -30 % | 17 | +30 % |
| Labour [technicians + engineers] | 2 + 0.15 | 2 + 0.15 | 4 + 0.30 |
| Solar irradiance [kWh $m^{-2}$ $y^{-1}$] | +10 % | 679 | -10 % |
| Electricity demand [GWh $y^{-1}$] | -30 % | 1.3 | +30 % |
| Land rent cost [MNOK $y^{-1}$] | -20 % | 0.2 | +40 % |

***Table 9:*** *The best and worst case values for each parameter, along with the base values, for scenario 2.*

| | Best | Base | Worst |
|---|---|---|---|
| Photosynthetic efficiency [%] & Solar irradiance [kWh $m^{-2}$] | 7 & +10 % | 5 & 679 | 3 & -10 % |
| Photosynthetic efficiency [%] | 7 | 5 | 3 |
| CAPEX [MNOK] | -20 % | 39 | +50 % |
| Energy density in microalgae [kJ $g^{-1}$] | -30 % | 17 | +30 % |
| Labour [technicians + engineers] | 3 + 0.15 | 3 + 0.15 | 5 + 0.30 |
| Solar irradiance [kWh $m^{-2}$] | +10 % | 679 | -10 % |
| Electricity demand [GWh] | -30 % | 2.1 | +30 % |
| Land rent cost [MNOK] | -20 % | 0.2 | +40 % |

# 4 Results

In this chapter, all the results are presented. First, the base calculations are given, followed by the results from the economic analysis including CAPEX, OPEX, depreciation and production costs. Furthermore, the results from the sensitivity analysis are presented and combined in tornado plots.

## 4.1 Base calculations

The energy density was calculated to be 17 kJ $g^{-1}$ for both species of microalgae. This caused the microalgae productivity to be 39.3 g $m^{-2}$ $d^{-1}$ which corresponds to 7.19 kg $m^{-2}$ $y^{-1}$. If all the $CO_2$ is used, 3.4 kt DW microalgae will be produced annually, and the required footprint area for this production is 0.6 $km^2$. In scenario 2, the annually production of astaxanthin will be 84 t DW. This is 12.5 % of the expected global astaxanthin marked in 2020.

For a footprint size of 1 ha, the annual production is 57.5 t DW biomass. Cultivation of *H. pluvialis* will produce 1.4 t DW astaxanthin, which can contribute to cover the astaxanthin need for 26,630 t fish feed with the inclusion rate of 54 ppm. During the half year of production the microalgae will fix 105 t $CO_2$, which is 0.86 % of Biokraft's annual $CO_2$ emissions. Based on the Redfield ratio, the microalgae will need 4.8 t nitrogen and 662 kg phosphorus.

## 4.2 Economic analysis

The calculated CAPEX and depreciation are shown in Table 10. CAPEX was MNOK 34 for scenario 1, and MNOK 39 for scenario 2. Scenario 2 has higher equipment costs than scenario 1, and a description of the individual equipment costs are given in Table 6 in Chapter 3.4.

***Table 10:*** *CAPEX and depreciation found using the major equipment costs and Lang factors.*

| Item | Lang factor | Scenario 1 [NOK] | Scenario 2 [NOK] |
|---|---|---|---|
| Major equipment costs | 1 | 12,857,761 | 14,753,911 |
| Installation costs | 0.20 | 2,571,552 | 2,950,782 |
| Instrumentation and control | 0.15 | 1,928,664 | 2,213,087 |
| Piping | 0.20 | 2,571,552 | 2,950,782 |
| Electrical | 0.10 | 1,285,776 | 1,475,391 |
| Buildings | 0.23 | 2,957,285 | 3,393,400 |
| Yard improvement | 0.12 | 1,542,931 | 1,770,469 |
| Service facilities | 0.20 | 2,571,552 | 2,950,782 |
| Engineering and supervision | 0.30 | 3,857,328 | 4,426,173 |
| Construction expenses | 0.05 | 642,888 | 737,696 |
| Contractor's fee | 0.03 | 385,733 | 442,617 |
| Contingency | 0.08 | 1,028,621 | 1,180,313 |
| CAPEX | | 34,201,645 | 39,245,403 |
| Depreciation | | 3,420,165 | 3,924,540 |

The production costs for both scenarios include depreciation, labour, electricity and land rent. Ethanol for the $CO_2$ extraction facility is also included for scenario 2. The total production costs per year are given in Table 11. The OPEX, the production costs excluding depreciation, is MNOK 1.4 for scenario 1 and MNOK 2.1 for scenario 2.

***Table 11:*** *The annual production costs.*

| Item | Scenario 1 [NOK] | Scenario 2 [NOK] |
|---|---|---|
| Depreciation | 3,420,164 | 3,924,540 |
| Labour | 628,500 | 958,500 |
| Electricity | 527,544 | 854,877 |
| Land | 200,000 | 200,000 |
| Ethanol | – | 36,771 |
| Total production costs | 4,806,208 | 5,974,688 |

Figure 5 shows a percentage distribution of the values in Table 11. For both scenarios depreciation is the major contribution. Even though the depreciation is higher for scenario 2, the percentage share is smaller than scenario 1. This is because the labour and electricity costs are much higher.

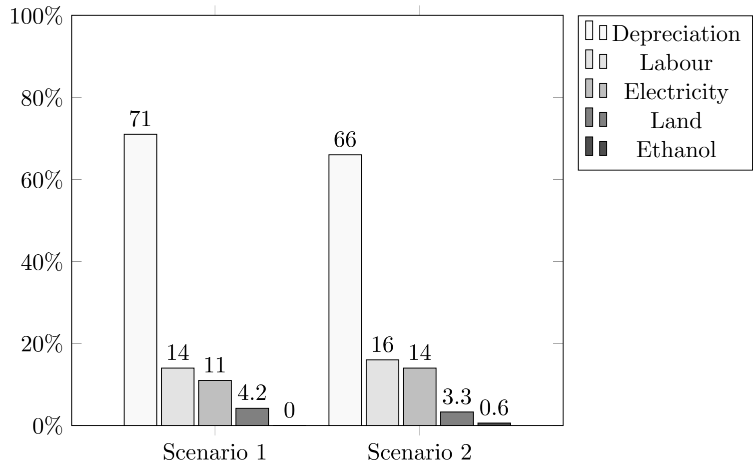


***Figure 5:*** *Percentage distribution of the production costs.*

It was of interest to find the total costs per kg DW produced. The total costs vary for the different algae products, and it is shown in Table 12. Because of the high production cost the price per kg DW biomass is higher for scenario 2 than scenario 1.

***Table 12:*** *The production cost per kg DW of algae product.*

| | Scenario 1 | Scenario 2 | |
|---|---|---|---|
| Product | Paste | Total biomass | Astaxanthin |
| Cost per kg DW [NOK] | 83.56 | 103.90 | 4,155 |

The P&L analyses given in Table 13 and 14 show the values of possible payback time and ROI with varying selling prices. The price to the far left is the lowest price which still gives the payback time below 10 years. The other prices are based on the marked price ranges described in Chapter 2.5. In scenario 2, the price of 145 NOK $kg^{-1}$ defatted biomass was used for all astaxanthin prices. A table with the results of a set astaxanthin price and varying biomass price can be found in Appendix C.

***Table 13:*** *P&L analysis for scenario 1.*

| | [NOK] | [NOK] | [NOK] | [NOK] | [NOK] |
|---|---|---|---|---|---|
| Price per kg DW biomass | 180 | 250 | 400 | 800 | 1,200 |
| Biomass DW [kg] | 57,515 | 57,515 | 57,515 | 57,515 | 57,515 |
| Revenue | 10,352,753 | 14,378,824 | 23,006,118 | 46,012,235 | 69,018,353 |
| OPEX | 1,386,044 | 1,386,044 | 1,386,044 | 1,386,044 | 1,386,044 |
| EBITDA | 8,966,709 | 12,992,780 | 21,620,074 | 44,626,191 | 67,632,309 |
| Depreciation | 3,420,164 | 3,420,164 | 3,420,164 | 3,420,164 | 3,420,164 |
| EBIT | 5,546,545 | 9,572,615 | 18,199,909 | 41,206,027 | 64,212,145 |
| Interest expense dept | 1,113,620 | 1,113,620 | 1,113,620 | 1,113,620 | 1,113,620 |
| Interest income on cash | – | – | – | – | – |
| EBT | 4,432,925 | 8,458,995 | 17,086,289 | 40,092,407 | 63,098,525 |
| Tax (22 %) | 975,243 | 1,860,979 | 3,758,984 | 8,820,330 | 13,881,675 |
| EAT | 3,457,681 | 6,598,016 | 13,327,306 | 31,272,077 | 49,216,849 |
| CAD | 7,991,466 | 11,131,801 | 17,861,090 | 35,805,862 | 53,750,634 |
| CAPEX | 34,201,645 | 34,201,645 | 34,201,645 | 34,201,645 | 34,201,645 |
| ROI [%] | 23.4 | 32.6 | 52.2 | 105 | 157 |
| Payback time [years] | 9.9 | 5.2 | 2.6 | 1.1 | 0.7 |

***Table 14:*** *P&L analysis for scenario 2.*

| | [NOK] | [NOK] | [NOK] | [NOK] | [NOK] |
|---|---|---|---|---|---|
| Astaxanthin: | | | | | |
| Price per kg DW | 4,800 | 8,000 | 10,000 | 20,000 | 57,000 |
| Produced DW [kg] | 1,438 | 1,438 | 1,438 | 1,438 | 1,438 |
| Defatted biomass: | | | | | |
| Price per kg DW | 145 | 145 | 145 | 145 | 145 |
| Produced DW [kg] | 37,385 | 37,385 | 37,385 | 37,385 | 37,385 |
| Revenue | 12,322,652 | 16,923,875 | 19,799,640 | 34,178,464 | 87,380,111 |
| OPEX | 2,050,148 | 2,050,148 | 2,050,148 | 2,050,148 | 2,050,148 |
| EBITDA | 10,272,504 | 14,873,727 | 17,749,492 | 32,128,316 | 85,329,963 |
| Depreciation | 3,924,540 | 3,924,540 | 3,924,540 | 3,924,540 | 3,924,540 |
| EBIT | 6,347,964 | 10,949,187 | 13,824,952 | 28,203,775 | 81,405,422 |
| Interest expense dept | 1,277,837 | 1,277,837 | 1,277,837 | 1,277,837 | 1,277,837 |
| Interest income on cash | – | – | – | – | – |
| EBT | 5,070,127 | 9,671,350 | 12,547,115 | 26,925,938 | 80,127,585 |
| Tax (22 %) | 1,115,428 | 2,127,697 | 2,760,365 | 5,923,706 | 17,628,069 |
| EAT | 3,954,699 | 7,543,653 | 9,786,750 | 21,002,232 | 62,499,517 |
| CAD | 9,157,076 | 12,746,030 | 14,989,127 | 26,204,609 | 67,701,894 |
| CAPEX | 39,245,403 | 39,245,403 | 39,245,403 | 39,245,403 | 39,245,403 |
| ROI [%] | 23.3 | 32.5 | 38.2 | 66.8 | 173 |
| Payback time [years] | 9.9 | 5.2 | 4.0 | 1.9 | 0.6 |

## 4.3 Sensitivity analysis

It is important to evaluate how the single process parameters influence the overall production cost. This is best captured and illustrated through a tornado plot. The tornado plot gives an illustration of the overall best and worst case outcome and how much the different parameters affects the production cost. It becomes clear which parameters affect the uncertainty of the production cost the most. This tornado plot is an essential part for an investor.

The individual parameters were varied from the established base value over a reasonable range, as described in Chapter 3.5. The results are shown in Figure 6 and 7, for scenario 1 and 2, respectively. The vertical base lines show the production cost in NOK $kg^{-1}$ DW for the base calculations. For scenario 1, the production cost was 84 NOK $kg^{-1}$ DW for the paste. For scenario 2, the production cost was 4,155 NOK $kg^{-1}$ DW for the astaxanthin. Here, the defatted biomass was not included, since the astaxanthin was the main economic impacting factor in this scenario. Each of the parameters show the change in production cost compared to these values.

In addition to the single process parameters, the total best and worst case were included to the tornado plot. Here, all of the best and worst case values from the single parameters were inserted and combined. The total worst case is higher than all the single worst case values added together. Photosynthetic efficiency and solar irradiance were also included as a combined parameter.

The tornado plots indicate that photosynthetic efficiency, CAPEX and electricity demand are the most significant single parameters regarding production cost. The increase of labour led to an increase in the production cost about the same as the -10 % change in solar irradiance. The ±30 % change in electricity demand and the change in land rent barely affect the production costs.

The parameter and units for the symbols for Figure 6 and 7 are described in the list below.

| Symbol: | Parameter: | Unit: |
|---|---|---|
| PE | Photosynthetic efficiency | % |
| CAPEX | Investment cost | MNOK |
| ED | Energy density in microalgae | kJ $g^{-1}$ |
| Labour | Number of employees | Technicians + engineers |
| SI | Solar irradiance | kWh $m^{-2}$ $y^{-1}$ |
| El | Electricity demand | GWh $y^{-1}$ |
| Land | Land rent cost | MNOK $y^{-1}$ |

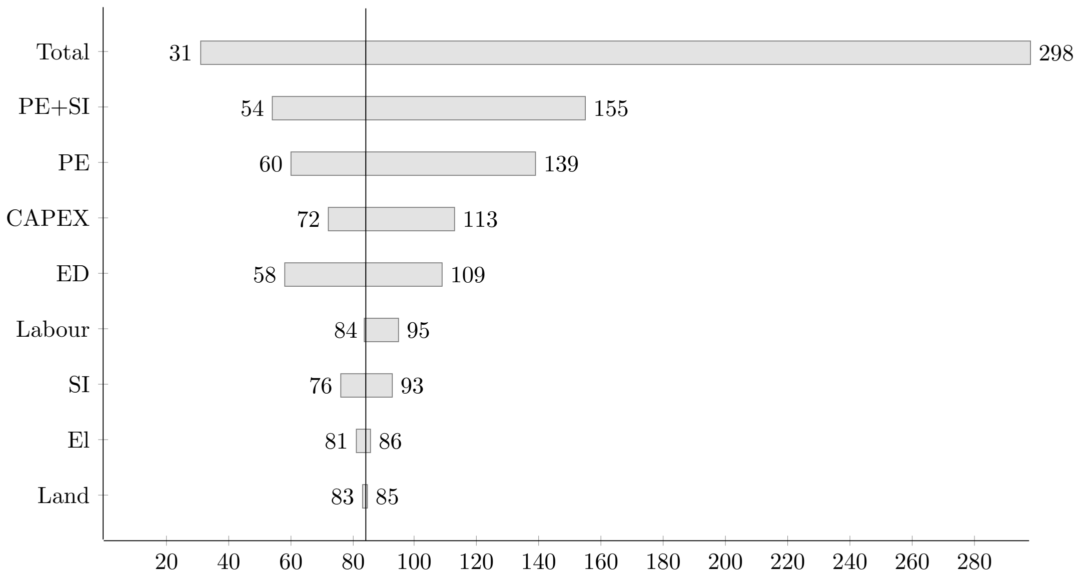


***Figure 6:*** *Sensitivity analysis for scenario 1 showing change in production cost with respect to baseline cost of 84 NOK kg$^{-1}$.*

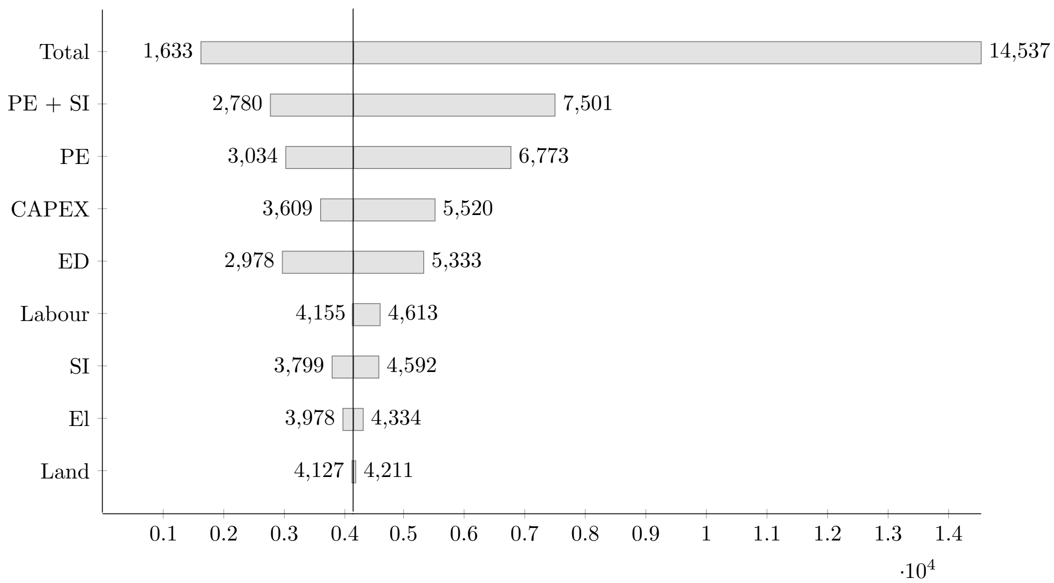


***Figure 7:*** *Sensitivity analysis for scenario 2 showing change in production cost with respect to baseline cost of 4,155 NOK kg$^{-1}$.*

# 5 Discussion

The discussion centers around how the two scenarios are compared in terms of profitability and sustainability. It also covers how the cost of the produced algae products could compete with the current market prices, and uncertainties are described and evaluated.

## 5.1 Scenario 1

### 5.1.1 Economic profitability

For scenario 1, the focus was to choose a microalgae suitable for replacing bulk parts of the fish feed, especially the fish oil. From the results of the analysis it became clear that the price of the paste became too high for this. It would have to be sold for at least 180 NOK $kg^{-1}$ DW. This price will not make the paste able to compete as an EPA source compared to the prices of the bulk products. The fish oil price is currently about 13 NOK $kg^{-1}$, while fishmeal is about 12 NOK $kg^{-1}$. At 15 times the market price, it is highly unlikely that the paste will have any success as a bulk product in today's market.

Although the paste did not seem to be an economical viable bulk source of EPA for fish feed, some of the other content of the algae turned out to be interesting. The algae paste contains minerals, vitamins, pigments and antioxidants which are often added in small portions as fish feed additives. In addition, algae in fish feed have shown some benefits on immunity, stress resistance and improved survival of larvae. These contents and benefits could justify the higher price, and the paste could probably be exploited as an additive in the feed or as larvae feed. If the algae can be used as an additive it might contribute with some parts of the bulk products as well, depending on the needed amount of supplements.

In the study done by Steinrücken et al. in Bergen, the algae reached a higher EPA content than earlier reported. This bodes well for cultivating at Skogn, as the conditions in terms of solar irradiance and temperature are similar to Bergen. Other research of microalgae cultivation are mainly located at southern latitudes.

The profit and loss analysis for scenario 1 shows that the lowest price that will give a payback time below 10 years is 180 NOK $kg^{-1}$ DW. This is a price lower than the market price of algal biomass for aquaculture, which were found to be 400–1,200 NOK $kg^{-1}$ DW. Assuming these values are correct and given for supplement ingredients, the price of 180 NOK $kg^{-1}$ DW will make the investment break even, making neither a profit nor a loss. By choosing 250 NOK $kg^{-1}$ DW, a payback time of 5.2 years and a ROI of 32.6 % are achievable. This price is still far below the market price for algal biomass for aquaculture, and could provide a competitive advantage.

### 5.1.2 Sustainability

Using *P. tricornutum* as a bulk ingredient might be profitable in the future. This depends on rising prices in the fish feed industry, improvement of microalgae strains and lowering production costs as technology is developing. If this happens it would be a great advantage as algae naturally is a fish feed source, and compared to fish oil and fishmeal it would skip steps in the food chain. This provides sustainability in the fish feed production, due to the growing demand and limited supply of fish oil and fishmeal.

The total content of fishmeal and fish oil in fish feed has decreased from about 90 % in 1990 to about 30 % in 2018. The replaced vegetal materials do not contribute with EFAs to the fish feed as the marine raw materials do. The consequences of less EFAs in the fish feed adversely affect the fish health and performance. This results in less EFAs in the fish products for human consumption. This development is a current issue in the aquaculture. The algae paste, however, will contribute to higher levels of EFAs in the fish feed.

The long transport of fish feed ingredients is another sustainability issue. Microalgae can be grown close to the fish feed factories, in contrast to the soy from Brazil and anchoveta from Peru. The algae triumph over soy both because of their area-effective quality, shorter shipping distances and the EFAs contribution.

### 5.1.3 Uncertainties and challenges

Even though there are ongoing experiments on algae as fish feed, it is clear from the documented content in fish feed that the paste is not a developed ingredient. Consequently, the paste does not currently have a large market as a fish feed ingredient. This causes uncertainties when predicting market price and market demand. The prices of 400–1,200 NOK $kg^{-1}$ DW have been used as base values. These values are from 2014, and might have changed since then because of market demand and technological improvements. Some of the prices and exact amounts of the ingredients, are confidential within the fish feed industry. This makes it problematic to compare the paste with the traditional feed and determine the viability of the paste.

The combination of a new market and new technology increases the risk of the investment. The paste is a new and undeveloped product, and the biofilm reactor is a novel technology. A sustainable fish feed production is dependent on new ingredients, and this can affect the development of the market. The market may have become more mature when the technology is fully developed and ready for installation. If so, the combination of new technology and new product will be eliminated, and the risk of the investment will be reduced.

## 5.2 Scenario 2

### 5.2.1 Economic profitability

The results from the economic profitability analysis illustrate values of importance. The high value product astaxanthin provides a fundamental economic profitability. The investigated prices per kg DW astaxanthin were within the market prices at 20,000–57,000 NOK $kg^{-1}$, as well as three prices below; 4,800, 8,000 and 10,000 NOK $kg^{-1}$ DW. The lowest price will give a payback time of about 10 years, and theoretically make the investment break even. All the other prices will lead to a profitable investment and give a payback time below 10 years. A price of 8,000 NOK $kg^{-1}$ will probably be an appropriate price level to settle for. This gives a payback time of 5.2 years, and a ROI of 32.5 %. The fact that this is below half the current market price is of interest as it will cause a competitive advantage.

The price of 20,000 NOK $kg^{-1}$, which is in the low end of the market range, gives a ROI of 66.8 % and a payback time of 1.9 years. Approaching the high end of the market price range, 57,000 NOK $kg^{-1}$ gives a payback time under a year, and a ROI of 173 %. However, this is probably not a realistic price for the fish feed market, but rather a reasonable price for direct human consumption products, since this market is dependent on natural astaxanthin.

The production cost of synthetic astaxanthin is about 8,100 NOK kg$^{-1}$. The results from the profitability analysis give a production cost of 4,155 NOK kg$^{-1}$. This is lower than for the aforementioned study in China by Li et al. of 5,841 NOK kg$^{-1}$ as well. This is probably because of the low operating costs of Inalve's biofilm reactor compared to other methods. It has both a low electricity and water demand, and the absence of raw material costs might be a contributing factor as well.

Despite the high value of astaxanthin, the amount added in the fish feed is small. In average 54 mg gets added per kg fish feed, which equals 54 ppm. With the astaxanthin price of 8,000 NOK kg$^{-1}$ the astaxanthin price per kg feed will be NOK 0.43. With 20,000 NOK kg$^{-1}$ the astaxanthin price per kg feed is NOK 1.08. The price of the total fish feed is around 12 NOK kg$^{-1}$. The astaxanthin price of 8,000 NOK kg$^{-1}$ will contribute with less than 4 % of the total feed price per kg.

With the scale of 1 ha, the astaxanthin production is 1,438 kg each year, which can contribute to 26,630 t fish feed. Assuming that a fish feed producer buys synthetic astaxanthin for 20,000 NOK kg$^{-1}$, the amount needed for 26,630 t will be priced at NOK 28,760,000. By changing the price to 8,000 NOK kg$^{-1}$ the costs will be reduced to NOK 11,504,000. This means that the fish feed producer can save MNOK 17.3 each year.

The full scale area of 0.6 km$^2$ was based on the accessible $CO_2$ from Biokraft. This would lead to a production of astaxanthin which would correspond to about 12.5 % of the international market. With an inclusion rate of 54 ppm, this amount covers the astaxanthin need for 1.6 Mt fish feed, about the same amount as the total fish feed consumption in Norway. There are different compositions for the various fish stages, and not all of these contain astaxanthin. It is not allowed to add astaxanthin to fish younger than six months. Exactly when it gets added, seems to be confidential information from the fish feed producers. This makes it difficult to find the total amount of astaxanthin needed for fish feed in Norway. Assuming the fish gets 54 ppm astaxanthin in the feed continuously from six months to slaughtering, 84 % of the total fish's feed consumption, will contain astaxanthin. This is based on Table 1 from Chapter 2.5. Based on this, the full scale plant will cover the whole demand in Norway, and even more. The accessible $CO_2$ will probably become higher in few years, as Biokraft increase their biogas production. Hence, the full scale algae production has the potential to increase even more.

The full scale plant will increase the global astaxanthin market. By suddenly increasing the supply this much, it is likely that the market price would decrease. However, the profitability analysis from this research shows that the price level could settle much lower than the market price. Likely, the viability for this installation would not be adversely affected. It will probably still have a competitive advantage.

Despite the fact that the main product of this scenario was the high value product astaxanthin, the remaining defatted biomass could give a valuable product as well. Based on the market prices of 95–195 NOK kg$^{-1}$, the defatted biomass was estimated to have a price level of 145 NOK kg$^{-1}$ DW. The price of the biomass did not affect the ROI and payback time remarkably, as shown in Appendix C. The price of 0 NOK kg$^{-1}$ DW gave a payback time of 2.3 years, compared to 1.9 with the value of 145 NOK kg$^{-1}$ DW. This shows the possibility of settling for a price lower than 95 NOK kg$^{-1}$, to get a competitive advantage in the market. Even though this is not the product that makes the scenario profitable, it contributes to important valuable nutrients for the fish. The fact that the remaining astaxanthin portion provides the need for astaxanthin when the algae meal has an inclusion rate of 12 % in the feed, makes the defatted biomass even more valuable. An inclusion of defatted biomass as 3 % of the feed has given shrimp a higher growth rate. This has not been tested on salmon yet, but it has a potential to be used as an additive.

### 5.2.2 Sustainability

The broad interest in natural astaxanthin is supported by both the health benefits and by the environmental benefits of not using fossil sources for production. The astaxanthin market consists of 95 % synthetic astaxanthin, but natural astaxanthin have been proven to have positive health properties, and the interest for it is growing.

The defatted biomass could support a part of the need for new sustainable ingredients in fish feed. Also, it is advantageous to utilize the residual part of the algae, even though its not affecting the profitability remarkably.

### 5.2.3 Uncertainties and challenges

The market prices found are for the whole astaxanthin market, as the astaxanthin prices for fish feed specific are confidential. It is therefore difficult to know which market prices belongs to the fish feed market. Even so, it is probably in the lower end of the market price range, as it is assumed that the high end belongs to the natural astaxanthin for human consumption.

Furthermore it is difficult to find the total amount astaxanthin needed for fish feed in Norway, due to the confidential information from the fish feed producers. This makes it challenging to compare the amount of produced astaxanthin with the Norwegian demand.

## 5.3 Comparing the two scenarios

### 5.3.1 Economic profitability

Assuming the products are sold at the low end of the given market price, scenario 2 has the highest ROI. It might also have a safer market because it exists at greater extent already. The use of algae paste in fish feed is a novel market, and is therefore a less sturdy investment. Even so, the algae paste might be a good solution for the growing need of new ingredients in fish feed.

A benefit of the paste is the fact that it can be used fresh and unprocessed, and therefore results in lower OPEX and CAPEX. A disadvantage is that it has short durability; about a week when stored in a refrigerator at a temperature of about 5 ℃. This can be a challenge due to the dependence of a weekly delivery of the paste. Scenario 1 is therefore dependent on good collaboration with local fish feed manufacturers because of the short durability. An advantage with scenario 2 is the possibility to freeze the astaxanthin to make it possible to produce enough through the summer to sell for the whole year. The paste with its short durability can only be sold from April to September and this might make it difficult to find potential buyers.

### 5.3.2 Uncertainties and challenges

No previous studies have identical conditions compared to this study. Extensive literature studies of similar economic analyzes have been done, but neither the geographical conditions, the size of the cultivation plant, nor the cultivation method are identical as for this study. The investment costs are based on approximate values for conditions as equal as possible. The Inalve reactors are currently a technology under development. The price forecast of 100 EUR $m^{-2}$ is included as a necessary prerequisite for being able to invest. Today's price is closer to 800 EUR $m^{-2}$. The investment can therefore not necessarily be done *tomorrow*, as the technology probably will need some years to develop.

Generally, there is a large variation between species regarding content and cultivation conditions. Nutrient limitation and temperature changing can be used to affect the content of the algae. By research on the specific species requirement, it is possible to develop the microalgae cultivation technology. Research and development of strains with the right nutrient content for fish feed should be a priority. To lower the price of algae for fish feed, research on species and production methods is important. The photosynthetic efficiency appears as the most significant single parameter of the sensitivity analysis. Thus, research to modify and improve the biological productivity by increasing the photosynthetic efficiency is necessary.

### 5.3.3 Sustainability

Investing in a microalgae production plant at Skogn will lead to better utilization of local resources, and result in product circulation between the factories. First the by-products from nearby industries are used for biogas production. Furthermore, by-products from the biogas production make it favourable for algae production. The algae could be used by the local fish feed manufacturer. It is beneficial for manufacturers to reduce the consumption of ingredients that are limited, unsustainable or have to be shipped long distances. If there is excess in the production and not all the algae products are sold, it will be possible to use the algae for biogas, even though this will not be profitable yet. The microalgae production plant will also exploit warm water from Norske Skog Skogn which will lead to a reduced electricity demand. Inalve's machines cause the water and electricity demand to be lower compared to other cultivation methods.

Both scenarios will produce sustainable and valuable products. There is a growing desire, among both consumers and manufacturers, to use ingredients in fish feed which are both sustainable and give positive health effect for the fish. This desire will be satisfied if the microalgae production plant will be built.

# 6 Conclusion

This thesis has confirmed the profitability of cultivating microalgae in a by-product from a biogas plant at Skogn in Trøndelag, Norway. There are multiple market potentials for algae products and the interest for the area-efficient, high-productive and sustainable product is growing. Currently it is necessary to sell the algae as high value products to be profitable.

The thesis has examined two scenarios, each with its own algae species and final algae product. Scenario 1 included cultivation of *Phaeodactylum tricornutum* to produce an algae paste with high EPA content. The paste can act as a substitute for EPA-containing ingredients in fish feed, which have been reported to decrease in recent years. This would not be profitable yet, but it could be profitable to use it as a feed supplement. Scenario 2 included cultivation of *Haematococcus pluvialis.* This species is considered the best natural source of the red colour pigment astaxanthin, which is a product with high value and market demand. The astaxanthin is a product for fish feed industry as well; it is added in the feed to make salmon flesh red and to provide beneficial health effects. In addition to the astaxanthin, scenario 2 would also produce a defatted biomass, which could serve as a valuable nutritional ingredient in fish feed.

The opportunities for growing microalgae at Skogn are given by the free access to nitrogen and phosphorus from the by-product, and the extended sun hours in the summer due to the northern location. The by-product provides a cost-effective source of nutrients. Another advantage is the proximity to the fish feed manufacturers. The rotating biofilm reactor ensures less operational costs and energy demand compared to traditional methods. This has been crucial for the positive outcome of the analysis.

The investment of a microalgae production plant is confirmed profitable, supported by the market prices that have been found in combination with the calculated production costs. Assuming that the market prices are correct, it is concluded that scenario 2 will be the most economically safe choice. Synthetic astaxanthin is widely used in aquaculture today, and has therefore a fully developed market. The astaxanthin from microalgae produced at Skogn is in this thesis calculated to be priced below half the current market price, and still make the investment profitable. Even though scenario 2 is considered the optimum choice, scenario 1 would provide an important contribution to solve the sustainable issue in the fish feed ingredient development. But as this scenario has both novel technology and novel market, the risk of the investment will be higher. Scenario 2 also provides a high value-product, which is a clear necessity if competing on the market with an algae product.

# 7 Further work

In this chapter, the authors' suggestions for further work and thoughts on development are presented. The suggestions are beyond the scope of this thesis, but arose from discussions and hypotheses and can be used as an inspiration for the client Biokraft or other interested.

In the end of the project, weighted nutrient density score (**WNDS**) was discovered. It is a tool to compare different food types in terms of nutrient content for daily human requirement. It was examined to use WNDS for algae compared to other fish feed, to support the benefits of algae. Of course it will not be the same nutritional requirement for fish as for human. A WNDS developed for fish is therefore considered as an interesting possible next step.

The cultivation period of six months, from April to September, was based on the extended sun hours due to the northern location. As the microalgae require light, the production will be able to operate all year round if it is installed LED-lights in the greenhouse. This investment and possibility is assumed to be an interesting step further.

Biokraft is also recommended to examine the possibility of growing several microalgae species to provide different fractions of the required fish food. This research should be done in cooperation with specialists in fish feed composition and in microalgae cultivation. Cultivation of several species requires caution in terms of risk of infection.

Finally, it is necessary to mention the importance of developing species and strains. Microalgae are a large and diverse group and the development of the genetic modification has not come far. It will be interesting to see how research and testing can improve the biological potential to improve the productivity, photosynthetic efficiency and durability, to reduce costs. Biologist researchers will have to screen the biodiversity to identify robust and productive strains with high EPA or astaxanthin levels. The optimum inclusion level for algae in fish feed has to be found, and species and strains with the right nutritional profile and high nutrient digestibility have to be identified.

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# A Results of a pilot size of 100 $m^2$

Calculations for microalgae pilot plants of 100 $m^2$ were done, for both scenarios, using the same procedure as for the plant of 1 ha. The tables and figure in this appendix show the results.

***Table A.1:*** *The major equipment costs for pilot size of 100 $m^2$.*

| Item | Scenario 1 [NOK] | Scenario 2 [NOK] |
|---|---|---|
| Biofilm reactors | 96,033 | 96,033 |
| Bead miller | – | 24,468 |
| Spray dryer | – | 11,327 |
| Supercritical $CO_2$ facility | – | 37,888 |
| Conveyer belts | – | 12,083 |
| Storage tanks | – | 3,679 |
| Refrigerator | 1,435 | – |
| Greenhouse | 80,000 | 80,000 |
| District heating system | 69,624 | 69,624 |
| Major equipment costs | 596,804 | 684,816 |

***Table A.2:*** *CAPEX and depreciation found using the major equipment costs and Lang factors, for pilot size of 100 $m^2$.*

| Item | Lang factors | Scenario 1 [NOK] | Scenario 2 [NOK] |
|---|---|---|---|
| Major equipment costs | 1 | 596,804 | 684,816 |
| Installation costs | 0.20 | 119,361 | 136,963 |
| Instrumentation and control | 0.15 | 89,521 | 102,722 |
| Piping | 0.20 | 119,361 | 136,963 |
| Electrical | 0.10 | 59,680 | 68,482 |
| Buildings | 0.23 | 137,265 | 157,508 |
| Yard improvement | 0.12 | 71,617 | 82,178 |
| Service facilities | 0.20 | 119,362 | 136,963 |
| Engineering and supervision | 0.30 | 179,041 | 205,445 |
| Construction expenses | 0.05 | 29,840 | 34,241 |
| Contractor's fee | 0.03 | 17,904 | 20,544 |
| Contingency | 0.08 | 47,744 | 54,785 |
| CAPEX | | 1,587,500 | 1,821,610 |
| Depreciation | | 158,750 | 182,161 |

*Table A.3: The annual production costs for pilot size of 100 m$^2$.*

| Item | Scenario 1 [NOK] | Scenario 2 [NOK] |
|---|---|---|
| Land | 2,000 | 2,000 |
| Electricity | 5,275 | 8,549 |
| Labour | 208,500 | 208,500 |
| Depreciation | 158,153 | 182,161 |
| Ethanol | - | 368 |
| Total production costs | 373,929 | 401,577 |

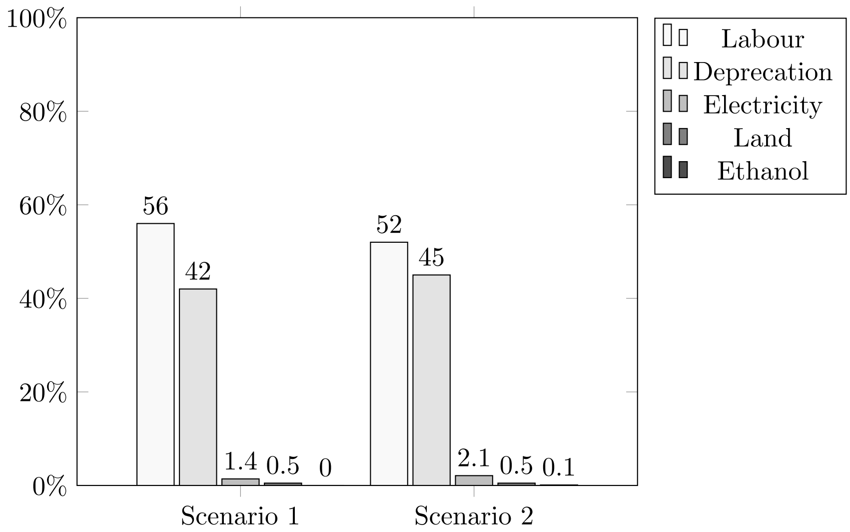


***Figure A.1:*** *Percentage distribution of the production costs for pilot size of 100 m$^2$.*

***Table A.4:*** *P&L analysis for scenario 1 for pilot size of 100 m$^2$.*

| | Scenario 1 [NOK] | Scenario 2 [NOK] |
|---|---|---|
| Price pr kg DW biomass | 1,100 | 43,000 + 145 |
| DW biomass [kg] | 575 | 14.4 + 561 |
| Revenue | 632,668 | 699,602 |
| OPEX | 215,775 | 219,426 |
| EBITDA | 416,893 | 480,185 |
| Depreciation | 158,153 | 182,161 |
| EBIT | 258,740 | 298,024 |
| Interest expense dept | 51,559 | 59,376 |
| Interest income on cash | – | – |
| EBT | 207,181 | 238,648 |
| Tax (22 %) | 45,580 | 52,503 |
| EAT | 161,601 | 186,146 |
| CAD | 371,313 | 427,683 |
| CAPEX | 1,581,532 | 1,821,610 |
| ROI [%] | 23.5 | 23.5 |
| Payback time [years] | 9.8 | 9.8 |

# B Digestate information

Biokraft produces on average 31.3 L digestate per $m^3$ $CH_4$. The annual biogas production is 125 GWh $y^{-1}$. From April to September, this corresponds to 6.25 $MSm^3$. The content of nitrogen and phosphorus in the digestate were given by Anna Synnøve Røstad Norgård at Biokraft, and are listed in Table B.1.

***Table B.1:*** *Nitrogen and phosphorus content of digestate from biogas production at Biokraft.*

| Date | Total N [mg $L^{-1}$] | Total P [mg $L^{-1}$] |
|---|---:|---:|
| 26.10.18 | 9,425 | 178 |
| 31.10.18 | – | 181 |
| 22.11.18 | 3,984 | 200 |
| 06.12.18 | 2,004 | 103 |
| 18.12.18 | 4,558 | 262 |
| 04.01.19 | 5,436 | 303 |
| 16.01.19 | 7,448 | 326 |
| 23.01.19 | 4,856 | 496 |
| 25.01.19 | 4,601 | 316 |
| Average | 5,289 | 263 |

# C Profit and loss analysis with varying defatted biomass price

In the main analysis for scenario 2 the defatted biomass price is set to 145 NOK $kg^{-1}$ with a varying astaxanthin price. It is also of interest to show how the overall results are affected by change in the defatted biomass price. The results of a set astaxanthin price and a varying defatted biomass price is shown in Table C.1. Even a reduction to 0 NOK $kg^{-1}$ will give the preferable payback time of 2.3 years.

***Table C.1:*** *P&L analysis for scenario 2 with varying defatted biomass price.*

| | [NOK] | [NOK] | [NOK] | [NOK] | [NOK] |
|---|---|---|---|---|---|
| Astaxanthin: | | | | | |
| Price per kg DW | 20,000 | 20,000 | 20,000 | 20,000 | 20,000 |
| DW production [kg] | 1,438 | 1,438 | 1,438 | 1,438 | 1,438 |
| Defatted biomass: | | | | | |
| Price per kg DW | 0 | 45 | 95 | 145 | 195 |
| DW production [kg] | 37,385 | 37,385 | 37,385 | 37,385 | 37,385 |
| Revenue | 28,757,647 | 30,439,969 | 32,309,216 | 34,178,464 | 36,047,711 |
| OPEX | 2,050,148 | 2,050,148 | 2,050,148 | 2,050,148 | 2,050,148 |
| EBITDA | 26,707,499 | 28,389,822 | 30,259,069 | 32,128,316 | 33,997,563 |
| Depreciation | 3,924,540 | 3,924,540 | 3,924,540 | 3,924,540 | 3,924,540 |
| EBIT | 22,782,959 | 24,465,281 | 26,334,528 | 28,203,775 | 30,073,022 |
| Interest expense dept | 1,277,837 | 1,277,837 | 1,277,837 | 1,277,837 | 1,277,837 |
| Interest income on cash | – | – | – | – | – |
| EBT | 21,505,122 | 23,187,444 | 25,056,691 | 26,925,938 | 28,795,185 |
| Tax (22 %) | 4,731,127 | 5,101,238 | 5,512,472 | 5,923,706 | 6,334,941 |
| EAT | 16,773,995 | 18,086,207 | 19,544,219 | 21,002,232 | 22,460,245 |
| CAD | 21,976,372 | 23,288,584 | 24,746,597 | 26,204,609 | 27,662,622 |
| CAPEX | 39,245,403 | 39,245,403 | 39,245,403 | 39,245,403 | 39,245,403 |
| ROI [%] | 56.0 | 59.3 | 63.1 | 66.8 | 70.5 |
| Payback time [years] | 2.3 | 2.2 | 2.0 | 1.9 | 1.7 |

# D District heating investment calculation

Jan Helge Ekeren from Norske Varmeleveranser AS contributed with a price estimate on investment of the district heating system. The mail from Ekeren, in Norwegian, is shown in this appendix.

Hei,
Det er fortsatt mye som er uklart for å gjøre et regnestykke på dette så du for se på følgene som en skisse til videre detaljering/utredning:
Dimensjonering: 1 ha = 10.000 m2
Drivhus - antatt max oppvarmingsbehov (i april): 50w/m2 – > 500kW effekt som er det dere må dimensjonere for
Oppvarming til luft betyr viftekonvektorer som eneste mulig løsning (så vidt jeg vet)
Med 35-40 grader på spillvann blir det liten temperaturdifferanse å fyre drivhuset med (10-15 grader) avhengig av mengde konvektorer (radiatorer) dere investerer i. Jeg regner 40/30 (40 grader på turvann – 30 grader på returvann og 20 grader temperatur
Total behov vannmengde (l/s): 500 / (10 x 4,2) = 12 liter/s = 43 m3/h
Viftekonvektorer jeg finner på nettet trenger 0,5l/s og gir da 0,5l/s x 10 grader (40-30) x 4,2 = 21kW avgift effekt. Dere trenger ca. 500kW (antatt). Det betyr anslagsvis 25 (23,8) konvektorer spredt rundt i drivhuset (eller færre som er større)
Dersom dere får bare 35 grader på turvannet så må dere ha dobbelt så mange konvektorer.
Med de temperaturer du har oppgitt anta kr 500/kW til konvektorer = i størrelsesorden kr. 250.000,-
Regn kr. 5000 for montering per konvektor = 5000 x 25 = 125.000
Røropplegg i drivhuset (uisolert) - gjetter ca. 100.000,-

Sentral styring i drivhuset (eller annet sted): ca. 50.000,-
Strøm - 50–100A = 50.000,-
Fjernvarmerør 100m mellom drivhus og varmekilde = 250.000,- (avhenger svært av grunnforhold og om det er opparbeidet areal eller ikke)
Prosjektering: 100.000,-
Sum: 925.000,-
Merk at det er gjort mange forutsetninger ovenfor og summen kan fort bli det dobbelt (men neppe halvparten). Legger du til grunn investering på 1.500.000 så har du noe som kan være troverdig (dersom du får 40 grader frem til drivhuset). Du får kort driftstid (april og muligens noe i mai – utover dette vil drivhuset klare seg med solen?
Jeg vet ikke om dette er til noe hjelp. Du får spørre om noe er uklart. Lykke til med oppgaven!
Med vennlig hilsen
Jan Helge

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