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Potential environmental impacts from fish sludge biogas production in Norwegian salmon farming

Miljøpotensial af biogas produksjon på fiskeslam fra norsk lakseoppdrett

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Abstract

Salmon is generally considered an environmentally friendly food to consume, however salmon escape, sea lice and nutrient leaching into the ocean are serious environmental problems of the present day open net pen farming systems. Adopting closed containment systems would alleviate those problems as well as produce substrate for biogas production. In this master thesis, the potential environmental benefit of fish sludge biogas production was estimated using the methodology of life cycle assessment (LCA). The environmental potential was estimated for salmon producers in the surroundings of a newly stablished biogas plant Biokraft in Skogn, Sør-Trondelag, and well as on the national level for the Norway of Norway. The BioValueChain model programmed in the software SimaPro was used to estimate the environmental impacts of each life cycle stage focusing on global warming and eutrophication potential. For the modelling, I considered that biofuel would replace diesel and the digestate would replace mineral fertilizers.

The results showed a negative global warming potential of -206.7 kg CO_2 eq, primarily due to the avoided emissions from the substitution of diesel which were - 258 kg CO_2 eq. The negative global warming values are interpreted as a positive environmental impact. The largest positive emissions came from the transportation phase and fish sludge transport distance was more important than the transport of the digestate to the fields as fertilizer. If obtaining a positive environmental impact, fish sludge transportation distance should be kept short and less than 283 km and digestate fertilizer should be transported no more than 541 km. Sensitivity analyses were also done on the parameters that were most uncertain and could influence the model results. The substrate dry matter content can change the outcome of the biogas production because of the transportation stage as well as the potential biogas production is an important parameter. The environmental impact of eutrophication was 1.1.98 kg PO_4^{-3} for the reference scenario, however, it was difficult to determent if this is an environmental benefit because there is not real control assessing the LCA whithout biogas production. The environmental potential of biogas production from fish sludge from the major salmon producers in the surrounding of Biokraft (Marine Harvest, Lerøy Midnor and Nova Sea) was estimated to be 3 600 ton CO_2 eq per year, while the estimate for all of Norway assuming sludge is transported 250 km was 9 323 ton CO_2 eq per year.

In conclusion there is a significant potential of biogas production from fish sludge to reduce the environmental impact associated with salmon fish farming in Norway.

Acknowledgements

I want to thank the NMBU for opening the door for continue my personal and professional development. Thanks to all those who have directly and indirectly made possible the end of this cycle in my life. I want to thank my two supervisors Ola Westengen and especially Ole Jørgen Hanssen for guiding me with the good research topic and putting me in contact with the right people. I also want to thank Kari-Anne Lyng for teaching me her model and Simon Alexander Saxegård for helping me to understand the SimaPro software. I also want to thank my lovely partner Signe for incredible support, family, friends, and of course God.

Table of Contents

List of Figures

List of tables

1 Introduction

The population around the world continues to increase as the world continues to warm up. Multiple factors are the cause of greenhouse emissions contributing to an increase of temperature. Around the globe temperatures are increasing, seasons are shifting and sea levels are rising as a consequence of climate change. Greenhouse gas emissions are mostly caused by the use of fossil fuel as an energy source. Norway is a country with vast oil and gas resources and high energy consumption rates per capita. The Norwegian government has implemented the EU Renewables Directive with the goal for Norway that the share of renewable energy in 2020 should be 67.5% compared to 30.1% in 2005 (IFE 2015). Renewable energy in form of hydropower is already well utilized in Norway, but biogas production is still at an early stage.

Salmon is healthy to eat and it is also not as bad for the environment as other types of meat such as beef and pork. In fact salmon has been termed “the super chicken of the sea” because it is one of the most sustainable meats available in the world (Torrissen, Olsen et al. 2011). According to Marine Harvest (2015), the carbon footprint of salmon is 2.9 kg CO_2 / kg edible meat compared to 3.4 kg CO_2 / kg for chicken, 5.9 kg CO_2 / kg for pork, and 30 kg CO_2 / kg of beef. Furthermore, in an LCA study salmon was also found to have comparable environmental impacts as chicken (Ellingsen and Aanondsen 2006). However, due to the enormous size of the Norwegian salmon production, it may still have negative impacts on the environment. Therefore there is a need to look for new opportunities and evaluate the environemtnal impact from biogas production from salmon sludge using a life cycle approach.

Norwegian salmon production is among the most environmentally friendly in a global perspective (Pelletier, Tyedmers et al. 2009). But there are several problems associated with the current production method, such as sea lice and salmon escapes, that advocates developing more closed systems (Braaten, Lange et al. 2010). Also, the production is continuously increasing and consumers are demandingsustainable fish.The substantial size of the salmon production in Norway and produced large amounts of organic waste, which could be used for biogas production. There is a great unused potential if fish manure could be collected and treated as substrate in the anaerobic digestion process where biogas is produced.

Utilizing fish manure or sludge as a substrate for biogas digestion has only been done on experimental level and has not been applied to main stream salmon production at large scale. This is primarily because the current production systems of open net-pens do not allow for the collection of the sludge and new closed systems must be developed and tested first. As this is costly, it is necessary to determine the potential of the environmental impacts or benefits that can be derived from invested in closed systems, collecting the sludge and processing it through anaerobic digestion. Another important aspect is that salmon farms are located along the fjords and transportation distance to a biogas plant can be long and heavy as fish sludge is very watery with a low dry matter content. To find out exactly how long fish sludge can be transported to a biogas reactor while achieving positive environmental benefits, it is necessary to perform a life cycle assessment that accounts for all environmental impacts from collection of the sludge to the replacement effects for the outputs from the biogas digestor (gas and liquid digestate).

1.1 Thesis objective

This master thesis project focuses on the currently unused biogas potential of sludge from salmon farms producing salmon to full size (grow-out production) in the surroundings of the biogas plant Biokraft in Sør-Trøndelag, Central Norway and for all of Norway. The main objective of the thesis is to determine:

What is the potential for biogas produced from fish sludge to reduce the environmental impacts of salmon production estimated for central Norway and on a national level?

In additional the following research questions were defined and answered in the thesis:

- What are the potential environmental impacts in terms of global warming and eutrophication of incorporating a biogas value chain in Norwegian salmon and using fish sludge as biogas substrate?
- What would be the environmental benefit for the major Norwegian salmon producer Marine Harvest, Lerøy and Nova Sea if they utilized the Biokraft AS biogas plant in Skogn for biogas production of the fish sludge from the farms in the vicinity?
- How much fish sludge could be collected from salmon farming in all of Norway if closed systems were used and what would be the environmental benefit of producing biogas from it?
- How does transport influence the environmental benefits of biogas production and what is the maximum transport distances of the fish sludge and the digestate fertilizer possible for the process to be environmentally positive?

- What other model parameters can greatly influence the environmental outcome of the model results?

In order to fulfill the objeve two main tasks are performed:

- Adaptation of the BioValueChain model to run with fish sludge as a biogas substrate and calculation of the environmental benefits in terms of global warming potential and eutrophication potential of the biogas value chain for a reference scenario and alternative scenarios. Two alternative scenarios were made varying the transportation distances (one of the fish sludge to the biogas plant and the other of the biogas digestate used as fertilizer to determine the tipping point where biogas production does not produce an environmental benefit and four alternative scenarios in order to test the impact and sensitivity of key parameters.
- The result of the BioValueChain model were upscaled to estimate the environmental potential for biogas production from fish sludge produced on salmon farms in the surroundings of Biokraft AS in Skogn and for all Norwegian salmon production.

2 Background

2.1 Norwegian salmon production

Norway is the world's largest producer of farmed salmon and in 2014 produced more than half of the global salmon production, which was around 2 million tons (MarineHarvest 2015). Since 1997, salmon production in Norway has increased drastically and just over the last 10 years the quantity of fish has doubled from approximately 600 000 ton to over 1.2 million ton (Figure 1). The vast majority of fish produced in Norway is salmon, which constitutes 94.5% of the total aquaculture production (SSB 2016).

2.1.1 Market value and export

Salmon industry is the second largest revenue generator in Norway (reference?). In 2014, the first-hand value from the salmon production was 41 823 mill NOK, which was an increase of 10 % compared to the previous year (SSB 2016).

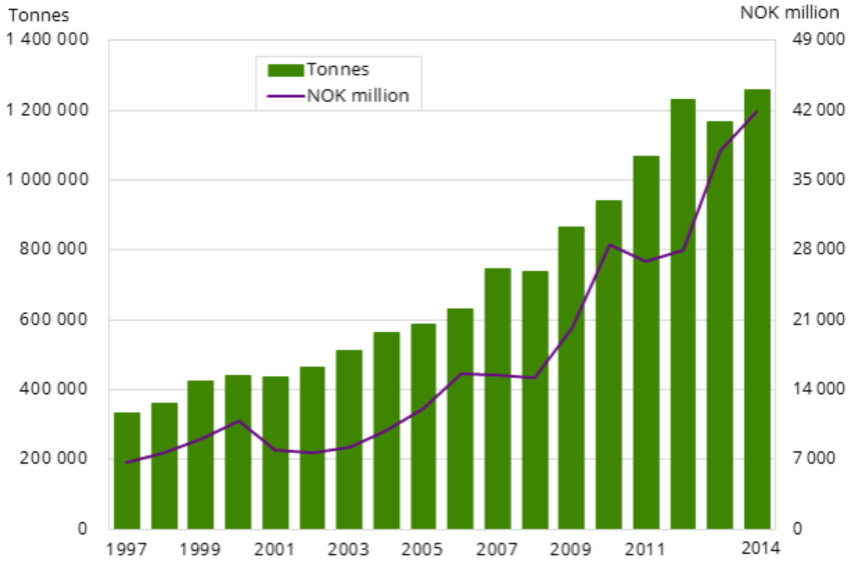


Figure 1 Salmon production in Norway since 1997; first-hand value and quantity of fish production (SSB 2016).

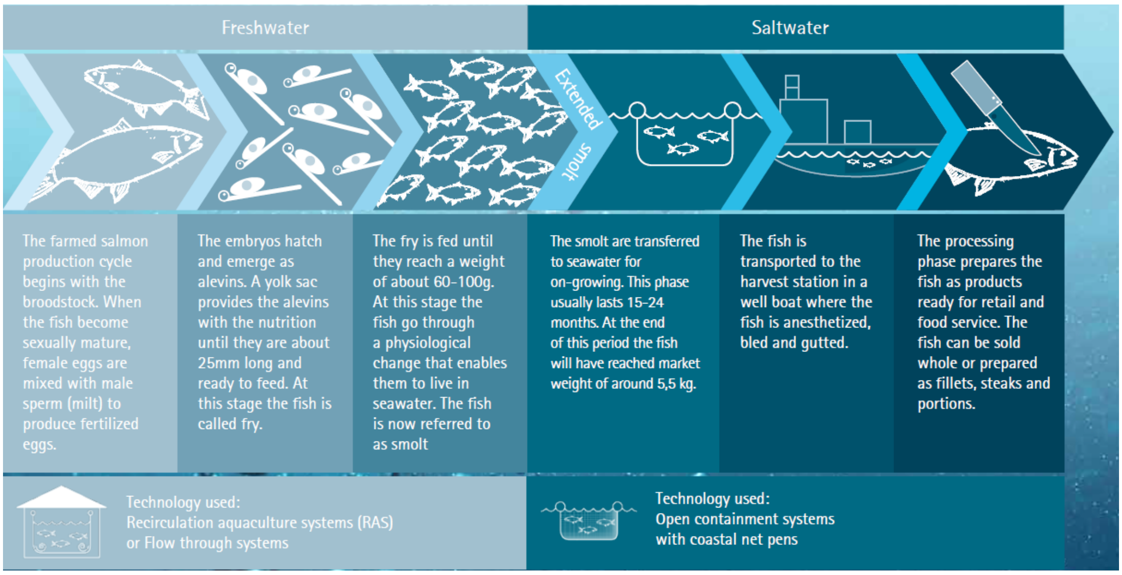
By far the most of the salmon produced is headed for the international market. The export of salmon has seen a drastic rise over the last ten years as well reaching 1 033 818 tons in 2015 (SSB 2016). In 2005 the main countries importing Norwegian salmon were Japan, Denmark and France. This has changed when looking at the statistic for 2015. Here Poland is the number one importer followed by France and Denmark. Japan is not importing nearly as much salmon in 2015, only 34 531 tons compared to 139 454 tons (Poland), 121 073 tons (France), and 78 084 tons (Denmark) according to statistic Norway (SSB 2016).

2.1.2 Legal framework

Norwegian salmon farming companies have to comply with several legal acts. There are 60 laws or acs regulating the salmon production in Norway (Teknologirådet 2012). The most important laws are the Aquaculture Act of 17 June 2005 and the Food Safety Act of 19 December 2003 (MarineHarvest 2015). Other regulations relevant for salmon farming are the Pollution Control Act, the Harbor Act, the Water Resources Act and the Nature Diversity Act (Accenture 2013). It is also required to have a salmon farming license and these are given in a limited number by the Norwegian Ministry of Trade, Industry and Fisheries and controlled by the Directorate of Fisheries. When the license is given permission is provided to produce 780 ton fish biomass per year, except for Troms and Finnmark, where the allowance is 945 tons (Stortinget 2013). No normal licenses have been given since 2009, instead “green biomass licenses" are available for development of sustainable and environmentally friendly production technologies (Accenture 2013).

2.1.3 *Salmon production cycle*

The salmon production cycle in the ocean takes around three years and can be divided into six steps as shown in Figure 2 (Accenture 2013). The three first steps take place in freshwater system usually on land in closed tanks (Figure 2). This part also takes about one year (MarineHarvest 2015). In the first step the broodstock produces the fertilized eggs. In the second step, as the embryos hatch they are provided with nutrients from a yolk sac where they live until they are 25 mm long. In the third step, they fry is growing into smolt, which is the size of approximately 100 g fish where they are transferred to seawater cages. There is a limit for smolt production in the onshore tanks, which is that they can reach a maximum of 250 g in this stage (Accenture 2013). The fourth step is the transfer of the smolt into the open ocean seawater cages, where the salmon grows and develops a weight of approximately 4 to 5 kg in a period of 15 to 24 months. In the fifth step, the salmon are transported by the well boat to the harvesting plant. In the final and sixth step, the salmon are slaughtered, gutted and processed further if necessary. The first three steps are called smolt production and the last steps until slaughter are referred to as the grow-out production. The majority of the salmon are sold whole and gutted on ice (MarineHarvest 2015).



The farmed salmon production cycle begins with the broodstock. When the fish become sexually mature, female eggs are mixed with male sperm (milt) to produce fertilized eggs.

The embryos hatch and emerge as alevins. A yolk sac provides the alevins with the nutrition until they are about 25mm long and ready to feed. At this stage the fish is called fry.

The fry is fed until they reach a weight of about 60-100g. At this stage the fish go through a physiological change that enables them to live in seawater. The fish is now referred to as smolt

The smolt are transferred to seawater for on-growing. This phase usually lasts 15-24 months. At the end of this period the fish will have reached market weight of around 5,5 kg.

The fish is transported to the harvest station in a well boat where the fish is anesthetized, bled and gutted.

The processing phase prepares the fish as products ready for retail and food service. The fish can be sold whole or prepared as fillets, steaks and portions.

Technology used:
Recirculation aquaculture systems (RAS)
or Flow through systems

Technology used:
Open containment systems
with coastal net pens

Figure 2 Salmon farming production cycle. Graphic from (Accenture 2013)

2.1.4 Salmon farming systems

Generally, there are six technologies utilized in the salmon farming in Norway two of them are land-base and the rest are sea based (Accenture 2013). These technologies can be applied in freshwater and seawater depending on the type. Most commonly, the salmon production consists of a land-based phase for the smolt production and and open ocean phase in net cage pens where the grow-out takes place. The two land-based technologies are called Recirculating Aquaculture Systems (RAS), in which the water is treated in tanks, filtered, oxygenated and reused, and flow-through systems where water is pumped through tanks on land but not reused. The sea-based thechnologies have the largest production of salmon and perform the grow-out operation. Open containment systems with coastal net pens are located along the coast or in fjords where the sea water flows through the net pens. Closed containment systems have coastal cages with large tank or sink, which separate the fish environment from the sea but in turn uses seawater for oxygenation. Closed containment systems with offshore cages can be located on or below the water surface.

The land-based flow-through and recirculating aquaculture systems (RAS) are basically closed systems of tanks with water that either flows through, for example as part of a river, or is recirculated. In 2006 only 2 % of smolt productions were RAS (Bergheim, Drengstig et al. 2009), however but by 2013 this number was 13%. In a recent report by the Norwegian food authority (Mattilsynet), they found a total of 193 smolt productions of salmon and trout in Norway and the vast majority of these were flow-though systems. Only 25 of the 193 systems were RAS or partially recirculation systems (Mattilsynet 2014). The trend of changing from flow-through to RAS systems might be because of the many benefits of RAS systems, such as not being depending on seasonal water flow and (in Norway) the lower temperatures limiting production from fall to spring (Bergheim, Drengstig et al. 2009).

2.1.4.1 Land-based flow-through systems (smolt production)

The flow-through systems are also called single-pass flow-through systems with oxygenation where the water flows through the systems at a rate of 0.3 L / kg min (Bergheim, Drengstig et al. 2009). In a flow through system the main water supply comes from a lake or river and the water is treated by aeration, seawater or lime addition and heating (Figure 3). After treatment, the water is used for the indoor hatchery and the outdoor grow-out tanks. When the water has served its purporse, the effluents are disposed back to the river. Before entering the river or lake again, it is filtered through a microscreen.

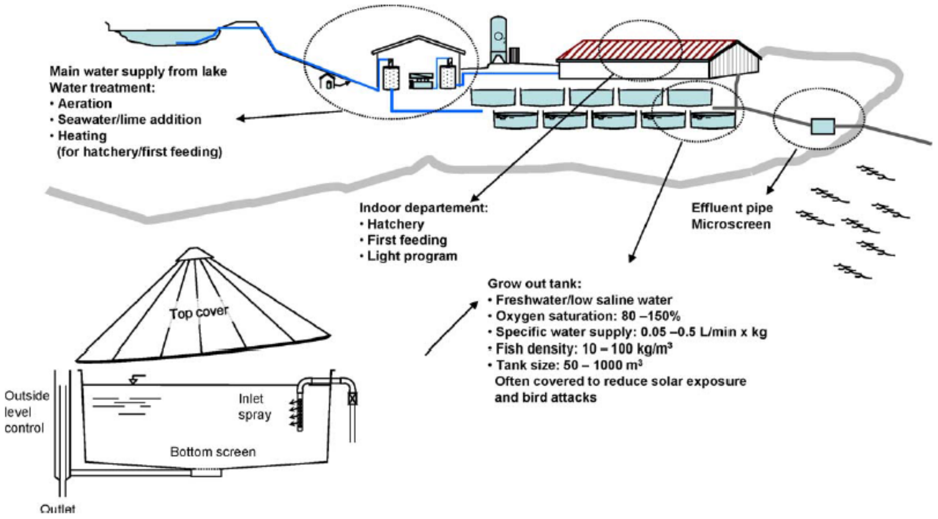


Figure 3 Schematic drawing of a single-phase flow through systems. Source: (Bergheim, Drengstig et al. 2009)

2.1.4.2 Land-based recirculating aquaculture systems (smolt production)

In the RAS systems the water receives several treatments. In brief these treatments are first, a treatment for the removal of solids, then ammonia is removed and finally, the water is oxygenated so it can be reused (Figure 4). According to the graphic, it starts with the grow-out tank where the smolt is raised and the sludge it produced. Secondly, the solids are removal such as fecal material and uneaten foods are removed by filters. In the third step, biofiltration or ammonia removal takes place where beneficial bacteria are realized and convert ammonia into nitrogen. The forth step is the oxygenation of water and removal of carbon dioxide (CO_2), which allows for recirculation. The RAS technology is utilized for the production of fish and other aquatic organisms by reusing the water. The technology is based on the use of biotic and/or mechanical filters and closed system tanks with recirculating water.

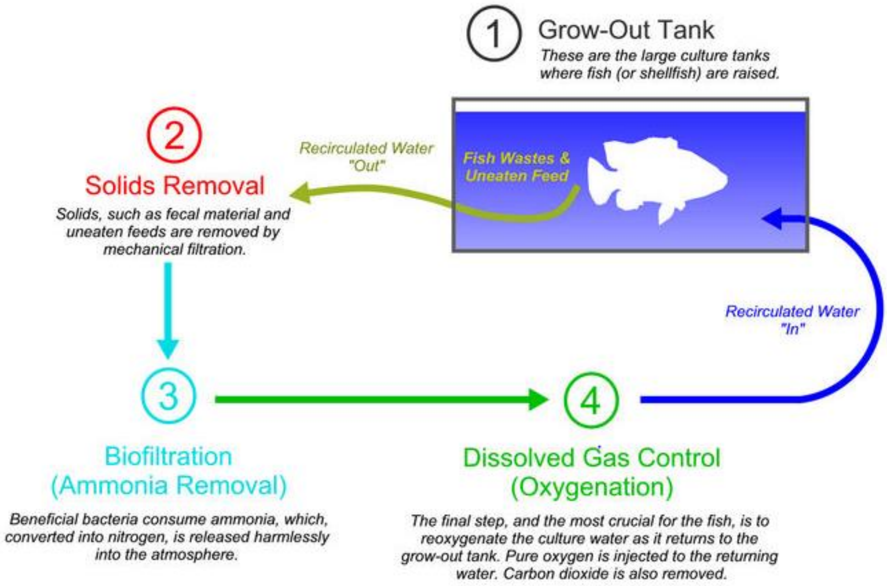


Figure 4 An example of a flow diagram for Recirculating Aquaculture System (RAS). Source: http://www.blueridgeaquaculture.com/recirculatingaquaculture.cfm

As mentioned, RAS is not the most commonly used type of system but Marine Harvest and Lerøy have been initiating productions using RAS for mostly smolt production. In 2013, Marine Harvest had five RAS projects with one of them being a full cycle salmon growing project (Accenture 2013). Lerøy Midnor AS also constructed one of the worlds largest smolt RAS production in 2013 (Accenture 2013).

2.1.4.3 Ocean-based open containment net pens (grow-out salmon)

The majority (95%) of Norwegian aquaculture is taking place in open cage systems (Svalheim and Solli 2012). This system is also referred to as net-pen aquaculture. Furthermore, there has been a trend in the increase of the large and very large sized production systems. The dimension of this open nets are approximately 160 m in circumference and 40 m in depth (Teknologirådet 2012), which allows to have a big salmon production. In the most commonly used systems only the smolt production is in closed tanks and the majority of the fish life time is in open water systems, where the feed excrement waste flows into the ocean.

Open containment systems with offshore net pens and platform are placed further out in the ocean and are resistant to waves (Accenture 2013). The large floating open net-cage pens are low maintenance designed to resist saltwater corrotion and made of strong materials to hold conditions offshore. These floating pens have a deck for better access and are usually located offshore or in sheltered bays along the coast where the ocean has calm water. They can hold a lot of fish without oxygenating the water because the natural currents of the ocean makes the water flow through (Accenture 2013).

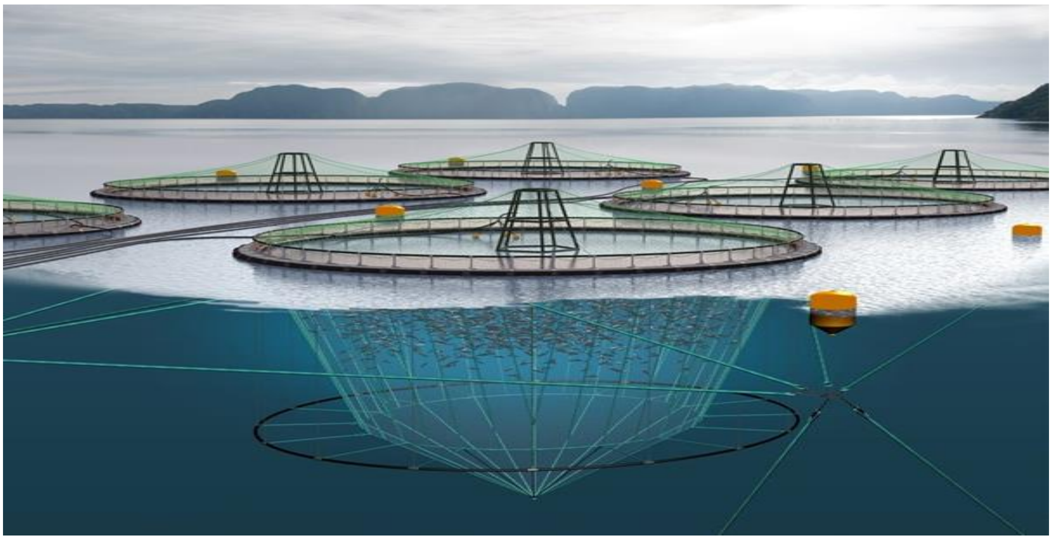


Figure 5 The large floating open net-cage pens. Source (Accenture 2013).

2.1.4.4 Ocean-based closed containment systems and new technologies

There are three types of relevant closed containment grow-out systems for Norwegian salmon production 1) floating closed systems with rigid walls of glassfiber or concrete, 2) floating closed systems with flexible walls of plastic, and 3) closed and sunken systems standing on the ocean bottom made of concrete (Teknologirådet 2012). The closed system technology is still in the testing phase in Norway and has been that for many years. However, in a Accenture-WWF report from 2013 there were 13 (ongoing or under development) projects listed for closed containment systystems with cages located along the coast. Most of these used some kind of flexible cage and they also have designed the production systems for extended smolt, which is smolt up to 1 kg (Accenture 2013). The key salmon producers such as Marine Harvest, and Lerøy are envovled in these projects. Lerøy announced in 2015 that they has placed the first closed container in the ocean, however only for production of extended smolt (Lerøy 2015). Several aquaculture companies are developing closed cages. The aquaculture equipment company AquaFarm have developed a closed cage called Netpun. It has a diameter of 40 m, depth of 22 and a diameter of 126 m and has been in the ocean on the Norwegian west coast since 2013 (AquaFarm 2016). MSC Aqua AS have developed a smaller closed cage called the AquaDome, which has a diameter of 27 m but is made for full scale production 2. The Ecomerden has been developed in collaboration with Innovation

Norway, Sulefisk, Sterner and Serge Ferrari. The Ecomerden is also operating with extenden or post smolt up to one kilo (Ecomerden 2016).

2.1.5 Environmental problems from salmon farming

The current ways to produce salmon in Norway is associated with several environmental impacts. The Norwegian Institute of Marine Research releases every year a report about the risks of marine farming. In the last report, they concluded that disease pressure from salmon lice is by far the largest environmental threat (Svåsand, Karlsen et al. 2016) and the open net systems increase the escape of lice to the native fish populations and endanger wild salmon. Several scienctic articles also present the problem of sea lice. Recently, it was found that the sea lice have a moderate regulatory effect on the wild salmon populations and even more worrying is that the salmon lice are developing resistance to the drugs used agains them (Torrissen, Jones et al. 2013).

Although, nitrogen concentrations are increasing due to the release of fish waste into the ocean, it is not considered a major environmental problem with the current production levels in most locations (Svåsand, Karlsen et al. 2016). However, in areas with high fish productivity and pour water flow, such as the deep fjords, it can be a problem. The same conclusion is made in regards to the increased loads of organic material (Svåsand, Karlsen et al. 2016).

Other environmental impacts include greenhouse emissions, acidification, reduced biological diversity, eutrophication, ecotoxicity, visual disturbance (Ellingsen, Olaussen et al. 2009).

The net-pen aquaculture systems are considered a potential threat to the environment (Mirzoyan, Tal et al. 2010). The escapes of farm salmon infected with sea lice are considered really dangerous because the sea lice can exterminate wild salmon. Wild salmon smolt in Norway is also threatened from hydropower plants because the damming of the water reduces the water flow and elevates water temperature, which gives a lethal kidney disease to the salmon (Sterud, Forseth et al. 2007).

The potential of farm salmon is considered to be growing but at the same time sectors in the Norwegian society are concerned due to practices implemented in salmon farming. These groups of society are the professional fishers, sport fishers, conservationist and recreational group which have demand to stop and no more increase production do the harm to the ecosystem (Hersoug 2015).

2.2 Biogas production

Biogas production is an excellent way to transform waste into a useful product such as an energy source or fertilizer. There are also other output from the biogas process, for example if the biogas is converted by a generator to electricity or compost (Figure 6). The illustration below gives a good overview of the whole biogas production chain starting with the substrate input and ending the biogas output of diesel and fertilizer.

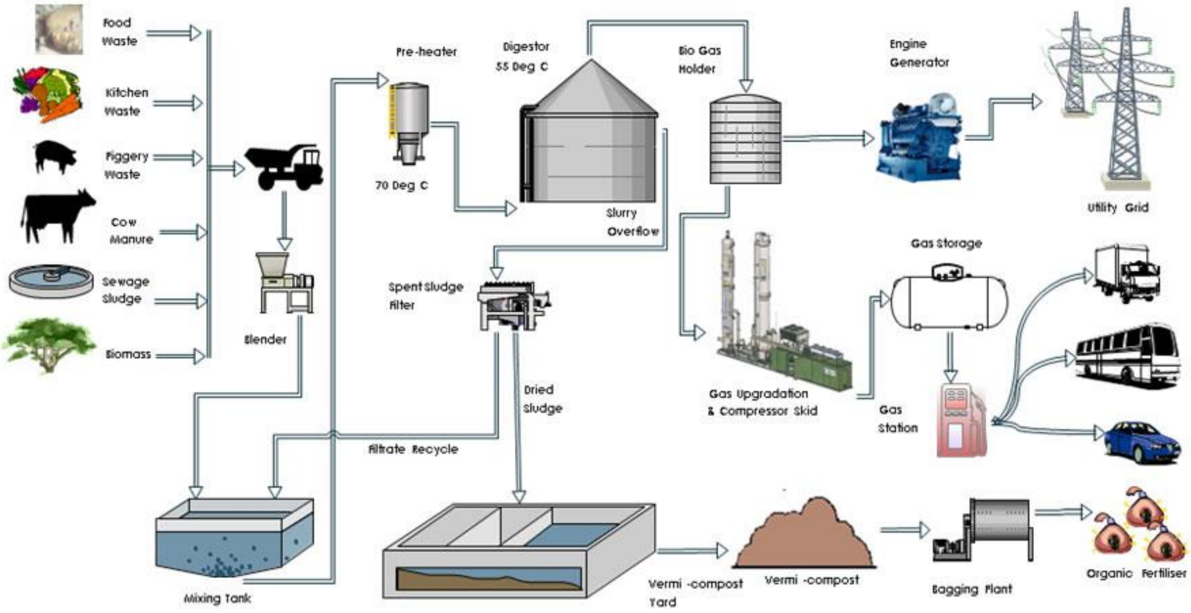


Figure 6 Illustration of the biogas value process chain. Source (ClosedLoopSystems 2016).

The biogas production is a fragile process, which can be inhibited by imbalance between the microorganisms performing the different steps. This is influenced by the temperature, composition of the substrate and the timing of feeding the reactor with substrate (Vangdal, Kvamm-Lichtenfeld et al. 2014).

2.2.1 Anaerobic digestion process

Biogas digestion is the conversion by different microorganisms in a complex system where as result of decomposition of organic compounds in the substrates launch the fermentative digestion. The biogas process has four main stages (Mirzoyan, Tal et al. 2010):

1) Hydrolysis where microorganisms and enzymes, hydrolyse and decompose the organic polymers and transform carbohydrates, fats and proteins into sugars, fatty acids and amino acids,

2) Fermentation where acidogenic bacteria break down sugars, fatty and amino acids and make Volatile Fatty Acids, NH_3 (ammonia), CO_2 (Carbon-di-oxide) and H_2S_2 (hydrogen sulphide).
3) Acetogenesis where acetogenic bacteria make the compounds above into acetic acid, CO_2 and H (hydrogen).
4) Methanogensis where the methanogenic bacteria transfor acidic acis, CO_2 and H into a mixture of CH_4 (methane) and CO_2.

Biogas digestion normally takes place under anaerobic conditions. During the anaerobic process organic pollutants such as COD and BOD are converted into biogases (CO_2 and CH_4) and a biodigestate.

2.2.2 Fish sludge as substrate

Fish sludge is the term used for the waste products left in the water by aquaculture. It consists of fish feaces, uneaten food and partially digested food (Figure 7). The nutrients in the sludge can either be dissolved in the water or particulate as as sediments. The nutrient flow model (Figure 7) was published by Bergheim and Asgard (1996) and later applied by several others (Braaten, Lange et al. 2010; Svalheim and Solli 2012) is based on the experimental study by Berheim et al (1998). The model gives a good overview of the quantities of nutrients released based on the mass balance principle considering N, P and organic material in the feed, the feed conversion ratio and the feed taken into the fish.

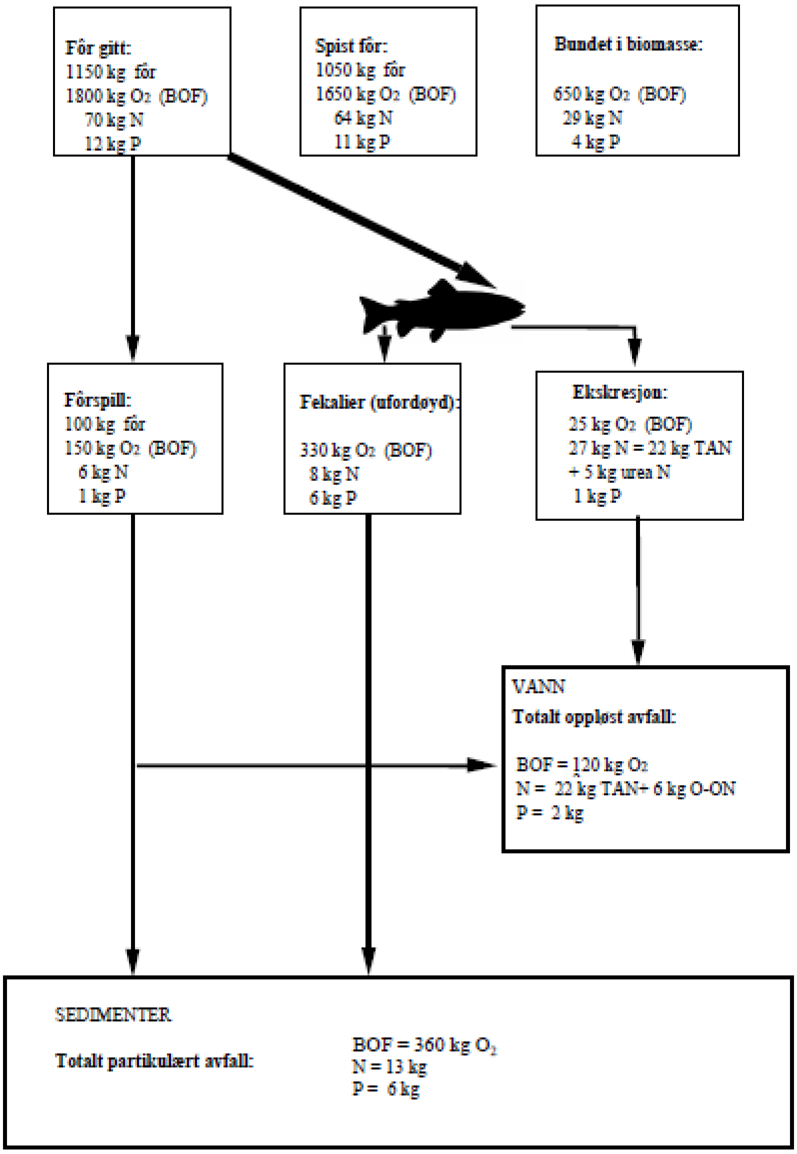


Figure 7 Nutrient flow balance model for salmon or trout with high energy feed. Source (Braaten, Lange et al. 2010)

There are several challenges associate with using fish sludge as a substrate for anaerobic digestion. First, the sludge has to be collected and treated to a suitable consistency good for digestion by dewatering. Secondly, the sludge may need to be treated to avoid problem that can inhibit the biogas process.

2.2.2.1 *Sludge collection and dewatering*

Fish sludge collection from the closed containment systems is a reality. Testing of the Neptune cages has show that 60-80% of the waste during production (AquaFarm 2016). Older studies of commercial systems found that sludge dewatering can be performed with drum sieves or filters as illustrated in Figure 8 and result in collection of 70-75% of the solid particles (Bergheim, Cripps et al. 1998).

It is not feasible to collect dissolved organic waste material and it is therefore only possible to remove the particulate waste materials (Braaten, Lange et al. 2010). There are several types of strainers or sieves that can be used to collect the particulate fish. Using a particle trap is better to obtain a more concentrated sludge that does not require drying and a particle traps collects the particles faster than the strainers before nutrients are dissolved(Braaten, Lange et al. 2010).

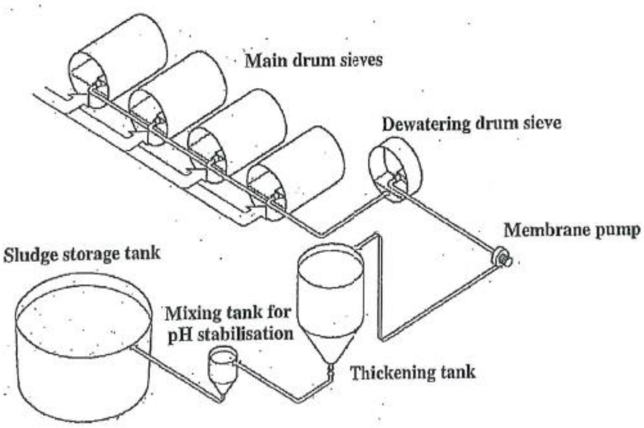


Figure 8 Illustration of fish sludge dewatering. Source (Bergheim, Cripps et al. 1998)

2.2.2.2 Potential problems with fish sludge as substrate

Some of the problems associated with use of fish sludge as substrate for anaerobic digestion are related the salinity of the sludgg but also the low dry matter content and protein content can be problematic (Svalheim and Solli 2012). After biogas production, it is also necessary that the digestate can be used and is not toxic for spreading on land. Preferable it should have a fertilizing effect. It is therefore imporatant to be aware of the salinity, chemical toxicity, heavy metals and micro nutrients contents of the digestate (Vangdal, Kvamm-Lichtenfeld et al. 2014).

To avoid spreading fish pathogens and to reduce the strong smell of the sludge, it can be necessary to perform a stabilizing treatment also where chalk is added. In Norway it is normal to used burnt chalk (CaO). According to (Braaten, Lange et al. 2010) it is necessary to add 120-150 g CaO per kg DM sludge, thus 12-15 kg chalk to 500 L of sludge with 12% DM content.

Pretreatment of the fish sludge substrate can be done in many ways such as thermal, ultrasonic, alkali, ozonation, bioglogical and mechanical pretreatment (Kondusamy and Kalamdhad 2014). In the model, only mechanical pretreatment was assumed to take place and cause environmental impacts due to the burning of the byproduct filterered out and the water usage in the process.

2.3 Life cycle assessment methodology

Life cycle assessmet (LCA) also known as Life cycle analysis or cradle to the grave analysis was rapidly developing during the 1990s. It is noteworthy that since the 1990s until 2016 LCA reached an important development and international standardization. The LCA is a technique used to evaluate environmental impacts of all stages of a product's life and service from cradle to grave. From raw materials extraction following by each stage of the manufacturing process, i.e., logistics, use, reparation ,maintenance, waste and treatment. The main objective of LCA is to provide a good comparison of the environmental effects providing by the products and services considering all the resources utilized in the process of transformation looking forward how this transformation affect the environment. The information generated by the assessment can help provide a better base in regards to policy development and improvement in decision making helping to build a better future. The LCA method has been standardized by the International Organization of Standardization (ISO) in several steps. The principals and framework of LCA was written in 1997 as ISO 14040 (ISO 1997). In 1998, LCA was further developed in the publication of the goal and scope definition and inventory analysis ISO 14041 (ISO 1998). In 2000, the life cycle impact assessment (ISO14042) and the life cycle interpretation ISO 14043 (ISO 1998) were published. The data documentation format (ISO/TS14048) was released in 2002. The most recent LCA standardization of requirements and guidelines is made by the ISO 14044 (International Organization for Standardization (ISO 2006).

2.3.1 LCA Framework

There are five main steps to complete life cycle assessment: goal definition, scope definition, inventory analysis, impact assessment and interpretation (Figure 9). The first step is goal definition, which defines the purpose of the study. This inlcudesthe purpose of the project, identification of who will be the audience and how the results will be utilized. According to the JRC (2010), The goal definition should include the following 6 aspects: 1) intentede application of the results, 2) limitations due to the method, assumptions and impact coverage, 3) reasons for carrying out the study and decision context, 4) target audience of the results, 5) comparative studies to be disclosed to the public, 6) commissioner of the study and other influential actors.

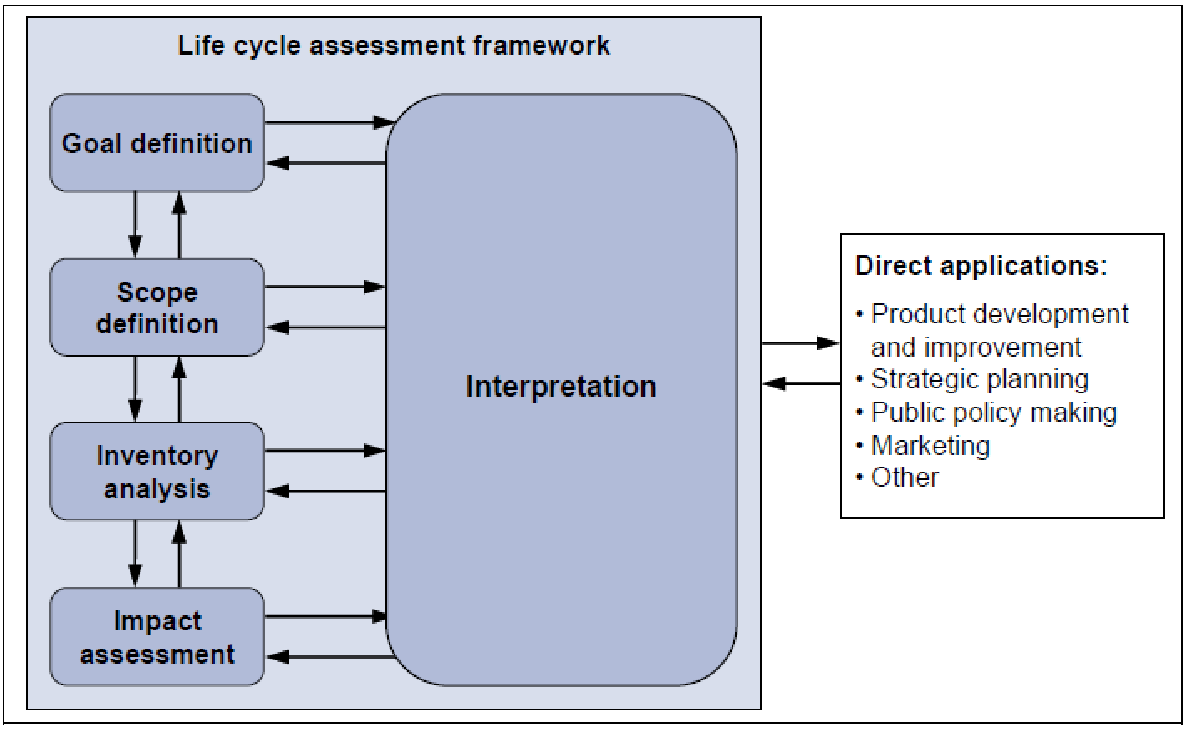


Figure 9 Life cycle assessmet framework. Source JRC (2010).

2.3.1.1 Scope definition

The second step it is the scope definition, whichhelps to scope out the project in terms of what to analyze and how. There are 10 points that should be addressed in the scope definition:

1. The type(s) of the deliverable(s) of the LCI/LCA study, in line with the intend application(s).
2. The system or process that is studied and its function(s), functional unit, and reference flow(s).
3. LCI modelling framework and handling of multifunctional processes and products.
4. System boundaries, completeness requirements, and related cut-off rules.
5. LCIA impact categories to be covered and selection of specific LCIA methods to be applied as well as - if included - normalisation data and weighting set.

6. Other LCI data quality requirements regarding technological, geographical and time-related representativeness and appropriateness.
7. Types, quality and sources of required data and information, and here especially the required precision and maximum permitted uncertainties.
8. Special requirements for comparisons between systems.
9. Identifying critical review needs.
10. Planning reporting of the results.

2.3.1.2 Inventory analysis

The third step is the inventory analysis, in which data is collected, the system is modelled, and results are calculated. Here the flows of emissions, energy and waste are calculated. Data can sSbe collected as primary data either from facilities or literature data. There are two main types of LCI modelling: attributional, where the systems has a static technosphere or consequential modelling where the system is in a dynamic technosphere (JRC, 2010). Another issue that should be addressed in the description of the inventory analysis is where allocation or system expansion or substitution is applied.

2.3.1.3 Impact assessment

The fourth step is the impact assessmentwhere the inventory results are described into the final results that are understandable to the audience. In this step, the calculated environmental impacts are converted into the impact categories, such as global warming potential (GWP), eutrophication potential (EP), ozone depletion,or human health risk . There are two requirements in the LCA: characterization and classification. Classification groups the emissions into categories and during characterization; normalize within category, e.g., CO2 equivalence to global warming potential.

The last and fiths step is the interpretation, whereanalyzes and conclusions are drawn from the results and utilized as tools for instance contribution and sensitivity analysis to reach deeper in to the findings. LCA is an interactive process and therefore we can see arrows going both directions between each step. If one step is completed it is possible to go back and clarify a previous step. For exemple the background data assumptions of the model or other considerations with the model. LCA can be applied for different purposes for example product development, strategic planning and other.

2.3.1.4 Interpretation

Interpretation in LCA can be defined as: *"a systematic technique to identify, quantify, check, and evaluate information from the results of the life cycle inventory and/or the life cycle impact assessment"* (ISO 1998). It is rarely a simple things but rather complex to interpret life cycle results. In order to make a good interpretation, the interpretation should be based on an understanding of the accuracy of the results (Skone 2000). Correct interpretation should therefore start with evaluation of the data elements and how they contribute to the impact categories, the sensitivity of the data, the completeness and consistency of the study (Skone 2000). Finally, conclusions and recommendation should be based on detailed knowledge of how the study was conducted (Skone 2000).

3 Methods and materials

3.1 Thesis methodology

In this thesis I have utilized the methodology of LCA to find out and quantify the environmental impacts of adding a biogas value chain to salmon production. More specifically, I estimated the environmental impacts and focus on global warming and eutrophication potentials using the BioValueChain model.

I evaluate the effect of the transporte distance of the fish sludge and of the biogas digestate fertilizer on the environmental benefit to producing the biogas. The BioValueChain model (Lyng, Modahl et al. 2015) used to calculate the environmental impacts and perform the life cycle inventory is programmed in the software SimaPro.

The results of the thesis were produced by making the following steps:

1. Define the goal and the scope of the study including the functional unit, reference flows, system boundaries and substitution alternatives.
2. Adaptation of the BioValueChain model to run with fish sludge as a biogas substrate in the following way:
    a. Substrate-related parameters of dry matter, carbon, nitrogen, and phosphorous content, biogas production, theoretical biogas potential and methane content of the

    biogas were transformed to conditions related to sludge from aquaculture according to literature.
    b. Adapt the life cycle stages for fish sludge as substrate by developing parameters for collection and dewatering of the aquaculture sludge or evaluating existing ones based on available literature.
    c. Model parameters were set to reflect that all biogas produced is upgraded to fuel and replaces diesel, and that all digestate is used wet as a mineral fertilizer replacement.
3. Model run and calculation of the environmental impacts in terms of global warming and eutrophication potential of the biogas value chain by:
    a. Running a reference scenario using the fish sludge parameters .
    b. Exploring scenarios assuming different transportation distances of the fish sludge and biogas digestate fertilizer to determine the environmental tipping point where the global warming potential is equal to zero.
    c. Running alternative scenarios exploring the sensitivity of the substrate dry matter content, methane potential, theoretical biogas potential and potential biogas production.
4. Upscale the model results and estimate potentential environmental benefit of biogas production from fish sludge first for salmon producers in the vicinity of Biokraft AS and second for all of Norway.

3.2 LCA on fish sludge waste systems

In general, an LCA tracks the inflows and out flows of a product, service or sector from the cradle to the grave but for waste systems it is normally not done in this way (Finnveden 1999). Instead the environmental impacts upstream are ignored and the LCA begins where the waste is generated. The first stage of the life cycle starts with transportation of the fish sludge. In the same way the environmental impact related to downstream processes can also be ignore and the last life cycle stage that is considered is the substitution effects from the use of the biogas and biogas digestate. The type of LCA done in this thesis can be called a gate to gate study.

3.2.1 Scope and goal definition

The reason for performing this LCA study is to determine the potential environmental benefit from biogas production using fish sludge from salmon farms. More specifically the goal of the study is to determine the feasible transport distance of the fish sludge from the salmon farms to the biogas plant using the hypothetical case studies of Lerøy Midnor, Marine Harvest, and Nova Sea fish farms and the Biokraf AS biogas plant. Scenarios were modelled using the BioValueChain model to determine the environmental impacts from the life cycle of fish sludge biogas production using different transport distances between the fish farms where the sludge is produced and the biogas production plants. Alternative scenaios were also modelled changing the parameters: substrate dry matter, theoretical biogas potential, potential biogas production and methane potential.

The life cycle stages modelled in the thesis resemble those presented in Lyng et al (2013) and are show in Figure 10 below.

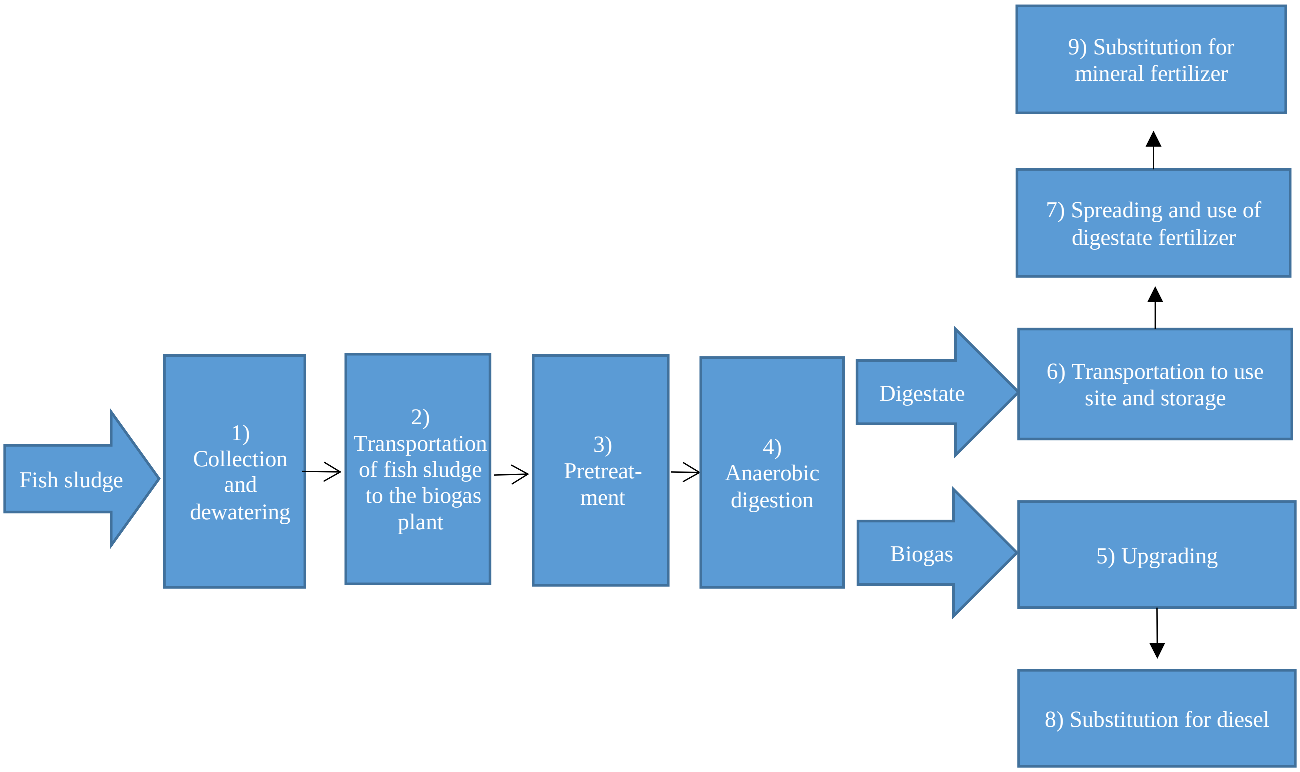


Figure 10 Flow chart for fish sludge biogas life cycle.

The life cycle stages included the following processes and steps: 1) Collection and dewatering of fish sludge, 2) Transportation of the sludge from the fish farm to the biogas plant, 3) pretreatment at the plant by filtering, 4) biogas (anaerobic) digestion which separates the sludge into gas and digestate, 5) upgrading of biogas to diesel, 6) transport of the digestate fertilizer to agricultural fields and storage, 7) spreading and use of the digestate fertilizer, and 8) substitution of diesel by biogas, 9) substitution of mineral fertilizer by the liquid digestate fertilizer. Only the two substitution steps 8 and 9 are counting negative environmental impacts in the LCA. In this study I assume that the biogas produced is exclusively upgraded to diesel, which is used by buses as this is very realistic for Norway. It is also possible that the digestate could replace compost or peat, which could be associated with avoided CO2 emissions, however for simplicity, I assume all digestate remains liquid (no dewatering phase of the digestate) and replaces mineral fertilizer.

No emissions or leaching is assumed to occur from storing of the fish sludge on fish farms before transport to the biogas plant. It is highly likely the sludge will be stored in closed tanks and gaseos emissions are therefore unlikely to be significant. All parameters related to storing of substrate in the original model are therefore set to zero. Impacts related to the infrastructure, such as transportation of the fish sludge are accounted for.

3.2.2 Functional unit and system boundaries

The functional unit in this LCA study is given in accordance with that provided in the original article describing the BioValueChain model: The functional unit for the model is hence defined as: *"Treatment of a specific amount of Dry Matter (tonnes DM per year) of organic substrates of a given mix (organic waste and/or manure) in a specific region, including avoided emissions caused by the generated products when substituting materials and energy carriers"* (Lyng et al 2015). In this study the organic waste considered is fish sludge produced from salmon farming.

3.2.3 Life cycle inventory (LCI)

To perform the life cycle inventory making the actual calculations of the environmental impacts, I have used the BioValueChain model, which is programmed in SimaPro. The background data used by SimaPro in the BioValueChain model comes from the EcoInvent 3 allocation default database. Such background data includes transport processes, incineration and energy generation (Swiss Centre for Life Cycle Inventories 2014).

The digestate resulting from the anaerobic digestion can be split into a dry and a wet phase. The dry phase can be used a compost and applied to parks and gardens and replace peat application. However, in these scenarios I assume that all the digestate is applied as liquid fertilizer and replace mineral fertilizer. The nitrogen content of the digestate and the plant accessible nitrogen determines the quanity of mineral fertilizer that is substitute.

3.2.4 Life cycle impact assessment (LCIA)

An impact category groups various substance emissions into a single quantifiable measure of the impact on the environment, either global or local. For this work I focus on the global warming potential (GWP), and eutrophication potential (EP) although there are other impact categories in the BioValueChain model are ozone layer depletion potential (ODP), acidification potential (AP), photochemical oxidation (POCP), and abiotic depletion potential (ADP). In addition to those, commonly used categoires are hman toxicity and ecotoxicity (DanishEPA 2005), land use, ionizing radiation, and particulate matter (GreenDelta 2015).

The global warming potential (GWP), also termed climate change, is defined as the alteration of the global temperature caused by the emissions of greenhouse gasses and the impact indicators is the disturbance in global temperature and climatic phenomena (GreenDelta 2015). Normally, and in the BioValueChain model, the GWP is measured by the unit of CO_2 eq.

Eutrophication can be defined as the accumulation of nutrients in aquatic systems (GreenDelta 2015) and it is the collective measure of nutrients leaching into water. It is the an increase or higher concentration of phosphorus and/or nitrogen, that has leached into the water, which procreates an explotion of phytoplantom. The increased nutrient concentrations consume all the oxygen in the water and harm all organisms living there and is also toxic for humans. Most of the pollution is derived from the use of fertilizer for agriculture. Also the use of fertilizers and human sewage is considered the major cause of the eutrophication. The impact indicators of EP is an increase in phosphorous or nitrogen concentration in the water and/or the formation of algae biomass and the unit used in LCA can be either kg PO_4^{-3} eq or kg N eq (GreenDelta 2015). In the BioValueChain model kg PO_4^{-3} eq is used.

3.3 BioValueChain model

To run the BioValueChain model with fish sludge as substrate, I used the original set-up made for food waste and changed the parameter values to fit to fish sludge. The structure and most parameters for food waste fit well to fish sludge because the food waste model also included a pretreatment phase which is likely to be needed for fish sludge. Therefore, only the values had to be changed. The original model did not account for dewatering of the sludge at the location where the waste is produced. Because fish sludge is likely to be collected as a runny liquid, it is reasonable to assume that fish sludge is dewatered before it is transported to the biogas plant. Therefore, an additional life cycle stage of dewatering (stage 1 in Figure 10) was added to the model.

3.3.1 Adding initial dewatering to the model

The dewatering phase (life cycle stage 1) of the fish sludge was modelled in the same way as the pretreatment phase in order to maintain the original structure of the model. A dry matter modification parameter (parameter name M_substrate_TS_modifisert) was added. This addition helped to model the change of the dry matter content from the initial of 4 % to 12 % making it drier. During transportation and digestion, the fish sludge is assumed to have 12 %, which is partly based on experimental studies using fish sludge in anaerobic digestion (Gebauer 2004; Gebauer and Eikebrokk 2006; Svalheim and Solli 2012). Several parameters were specifically set in SimaPro, particularly those related to substrate quality, i.e dry matter, nitrogen and phosphorous content, and pretreatment, parameter names including “forbeh” in Table 1.

Table 1 Parameter names and values used in the added dewatering phase (life cycle stage 1).

Original parameter name	Description	Value
M_substrat_TS	Share of DM content of fish sludge (fraction)	0.04
M_substrat_TS_modifisert	Share of DM content of fish sludge after dewatering process (percent given as fraction)	0.12
M_substrat_mengde_C	Carbon conent of fish sludge (kg C/ton DM)	400
M_substrat_mengde_N	Nitrogen content of fish sludge (kg N/ton DM)	25
M_substrat_mengde_P	Phosphorous content of fish sludge (kg P/ton DM)	0.1
M_forbeh_el	Electricity consumption in biogas per ton DM substrate (KWh / ton DM)	48
M_brennverdi_sikterest	Burn value of the rennverdi for sikterest (MJ/kg)	2.55
M_forbeh_COD	Emissions of COD (mg/ton DM)	2.47
M_forbeh_totP	Emissions of total phosphorous (mg/ton DM)	0.019
M_forbeh_totN	Emissions of total nitrogen (mg/ton DM)	0.48
M_forbeh_vann	Water consumption during pretreatment (ton water/ton DM)	1.6
Trp_forbeh_beh	Transport distance between pretreatment and biogas plant (km)	0
M_forbeh_CH4_bio	Emissions of biological methane during pretreatment	0
M_forbeh_N2O	Emissions of N2O during pretreatment	0
M_T2	Transportation of the fish sludge	0
M_forbeh_sikterest	Fraction of the substrate that is filtered out during pretreatment (ton DM fitrate/ton DM substrate)	0

The result of the dewatering life cycle stage was then “added to” the the rest of the scenarios with a manual calculations.

3.3.2 Model parameter values of the reference scenario

The values of fourteen parameters were specifically changed to run the model for fish sludge as a substrate (Table 2). New values relevant for fish sludge were found in literature, except for the transport distances of the fish sludge and digestate fertilizer. To detmine the transportation distance of the reference scenario, I allocated the Lerøy Midnor fishing locations and estimated the distances to Skogn where the biogas plant Biokraft AS is located and took the average of the distances. The six grow-out salom operations localized were Lensvik, Fevåg, Snillfjord, Valsøybotn, Dolmøy, and Hemnskjela and the average distance from these to Skogn is equal to approximately 170 km. This was the value used for the reference scenario. Transport distance of the digestate fertilizer was assumed to be 50 km, which was equal to the default value in the original model.

Table 2 Parameters changed to represent fish sludge and their values in the reference scenario.

Parameter name	Original parameter name	Description	Value	Source of reference scenaion
Substrate dry matter content	M_substrat_TS	Share of DM content of fish sludge (fraction)	0.12	(Gebauer and Eikebrokk 2006; Mirzoyan, Tal et al. 2010; Svalheim and Solli 2012)
Substrate nitrogen content	M_substrat_mengde_N	Nitrogen content of fish sludge (kg N/ton DM)	25	(Vangdal, Kvamm-Lichtenfeld et al. 2014)
Substrate phosphorous content	M_substrat_mengde_P	Phosphorous content of fish sludge (kg P/ton DM)	0.1	(Vangdal, Kvamm-Lichtenfeld et al. 2014)
Fish sludge transportation	M_T2	Transport of fish sludge from storage at the farm to biogas plants (km).	170	Average distance from Lerøy Midnor AS fish farms to Skogn
Digestate fertilizer transportation	Trp_biogassanl_lager	Distance from biogas plant to spreading of digestate fertilizer (km)	50	Assumption
Potential biogas production	M_Nm3_per_tonn_TS	Biogas potential per ton fish sludge (Nm3/ton DM).	270	(Gebauer and Eikebrokk 2006; Svalheim and Solli 2012)

Methane potential	M_metaninnh_biogass	Share of methane in the biogas produced from fish sludge.	0.6	(Mirzoyan, Tal et al. 2010)
Theoretical biogas potential	Biogassanlegg_reelt_ utbytte	Percentage of the theoretical amount of energy that the plant can produce	0.7	(Svalheim and Solli 2012)

3.3.3 Alternative scenario modelling

Alternative scenarios were modelled to find out the sensitivity of the model to certain parameters. In the sensitivity analsys, the same scenario was run several times changing one parameter value and the purpose is to determine the effect of a specific parameter on the results. Six types of alternative scenario were modelled changing the parameters that have the largest influence on the results. Choosing to run scenario analsyses for these parameters was also because the reference values (used in the reference scenaios) were probably the most uncertainty. The justifications for changing the parameters and the number of modelled scenarios are shown in Table 3.

Table 3 Parameters that are changed in scenario analyses and justification for change.

Scenario number	Scenario name	Parameter name	Justification for change	Scenario values
1	Transport fish sludge	M_T2	Value is case specific and should be calculated for the case. Reference scenario assume 270 km.	8 scenarios: 0, 200, 250, 300, 400, 500
2	Transport fertilizer digestate to field	Trp_biogassanl_lager	Value can differ a lot depending on location of biogass plant	7 scenarios: 0, 50, 100,200, 300 ,400, 500 km
3	Substrate dry matter	M_substrate_TS	Gebauer & Eikebrokk 2006 gives 6-12%.	Scenario with 6, 10 and 15%
4	Theoretical biogas potential	Biogassanlegg_reelt_utbytte	Svalheim & Solli gives 55-70%	3 scenarios: 0.3, 0.5 and 0.8
5	Potential biogas production	M_Nm3_per_tonn_TS	Values found are much lower for fish sludge than for food waste (default 600). Svalheim & Solli give a theoretical average of 217 m3/tonn TS Gebauer & Eikebrokk 2006 give 260-280 mL/g VS.	3 scenarios: 100, 400, 600
6	Methane content	M_metaninnh_biogas	Mirzoyan 2010, Gebauer 2004 and Gebauer 2006 provides lower values; estimate is 0.6	3 scenarios: 0.3, 0.5 and 0.8

3.4 Estimation of the environmental potential

In the second part of the thesis, the results from the BioValueChain model were upscaled in order to estimate the potential environmental benefits of biogas production for major salmon producers in Norway. The model provides the results in the functional unit of ton DM sludge but data in this unit is not known by the producers. That is why it is needed to estimate the potential sludge produced during fish production.

3.4.1 Sludge quantification

To estimate the amount of fish sludge potentially available for biogas production the original author of the fish nutrient flow model (Figure 7) was consulted and through personal communication it was confirmed that 1 ton of fish produced gives approximately 1 ton of sludge with a dry matter (DM) content of 10% (Bergheim 2016). The estimate is based on an experiment with sludge collection from a commercial smolt farm performed in 1998 (Bergheim, Cripps et al. 1998). In this study, modelling was done with a dry matter content of 12 % as the reference scenario, hence this value was used to estimate the sludge quantity. Hence, from 1 tonn of fish, 120 kg sludge DM could be produced.

3.4.2 Upscaling environmental benefits of biogas production

To upscale the results and make the calucation of the potential environmental benefits that could be achieved by major salmon companies in Norway, a simple multiplication was done of the global warming potential estimated in the reference scenario with the estimated sludge produced by each of the major companies (total potential = kg CO_2 eq / ton DM sludge × ton DM sludge produced). The same calculation was done for all of Norwegian salmon production.

The following three companies were chosen: Lerøy Midnor AS, Marine Harvest, and Nova Sea. The companies were chosen because they are among the top producers of salmon in Norway (MarineHarvest 2015) and have production locations in central Norway in the vicinity of Biokraft AS in Skogn.

4 Results

In this section the results are presented first for the reference scenario, second transportation scenarios, third biogas production efficiency scenarios.

4.1 Reference scenario

The reference scenario resulted in an overall negative global warming potential of -206.7 kg CO_2 eq (Figure 11), meaning that there is a net avoidance of emissions for the total biogas value chain from fish sludge and a positive environmental effect (negative results equals a positive environmental impact). The majority of the emissions arrived during life cycle stage 2, the transportation of fish sludge, which was 312 kg CO_2 eq. The largest net CO_2 removal (negative emissions) occurring during stage 9, which is the substitution of mineral fertilizer. In this step avoided emissions equaled -394 kg CO_2 eq (Figure 11). Avoided emissions from the substitution of diesel in life cycle stage 8 were - 258 kg CO_2 eq. It also visible in tree network of the GWP that the transport of the sludge is the main contributor of CO_2 emissions (Figure 12) .

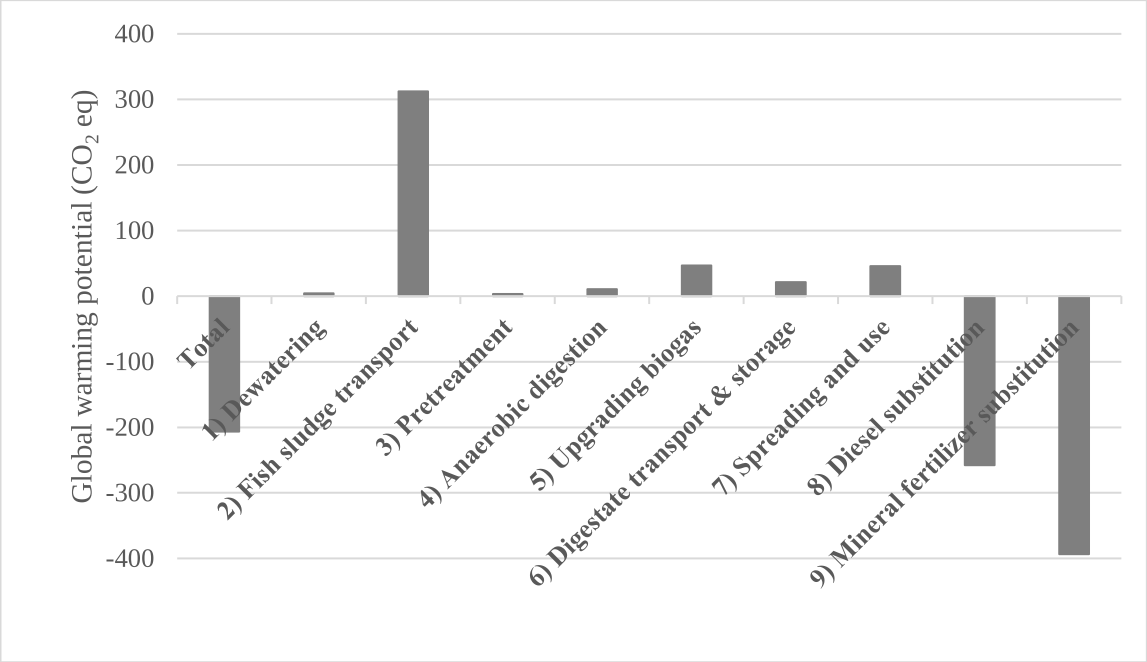


Figure 11 Global warming potential for each life cycle stage of the reference scenario.. Total shows the value for the whole life cycle.

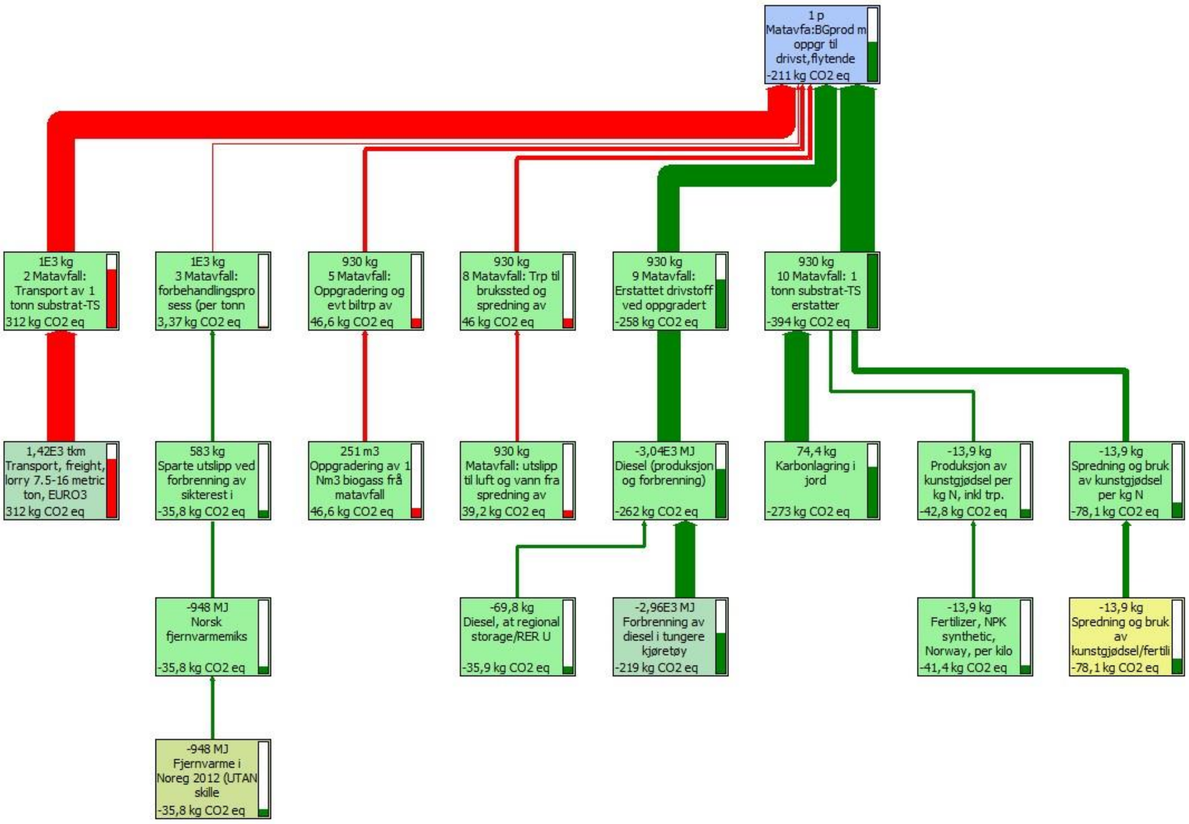


Figure 12 Tree network of global warming potential of the biogas fish sludge value chain.

Overall, there was a positive but rather small eutrophication of 1.189 kg PO_4^{-3} for the reference scenario. That does not necessarily mean that implementing a biogas value chain with fish sludge as substrate has a negative environmental impact (a positive result value equals a negative environmental impact).

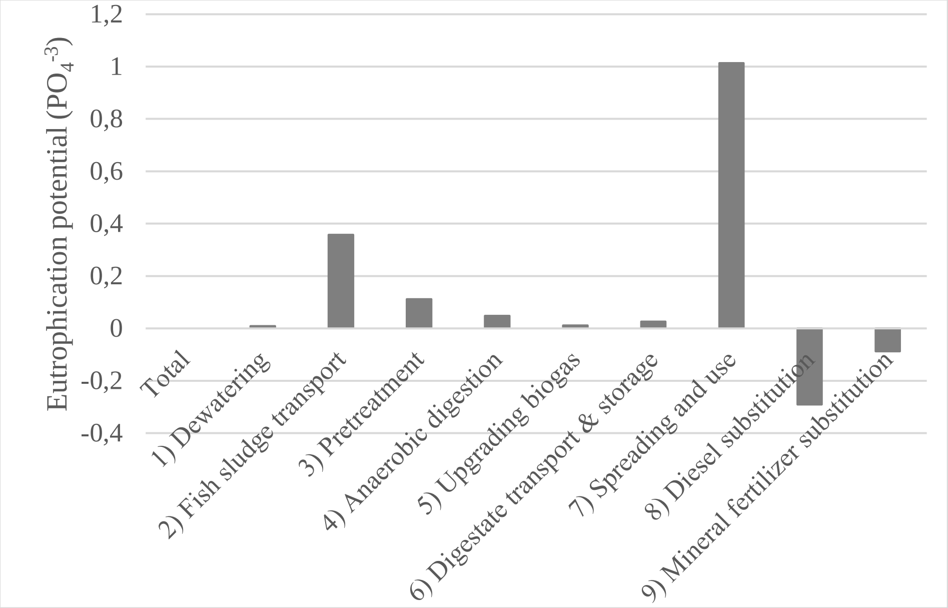


Figure 13 Eutrophication potential from reference scenario per life cycle stage. Total shows the value for the whole life cycle.

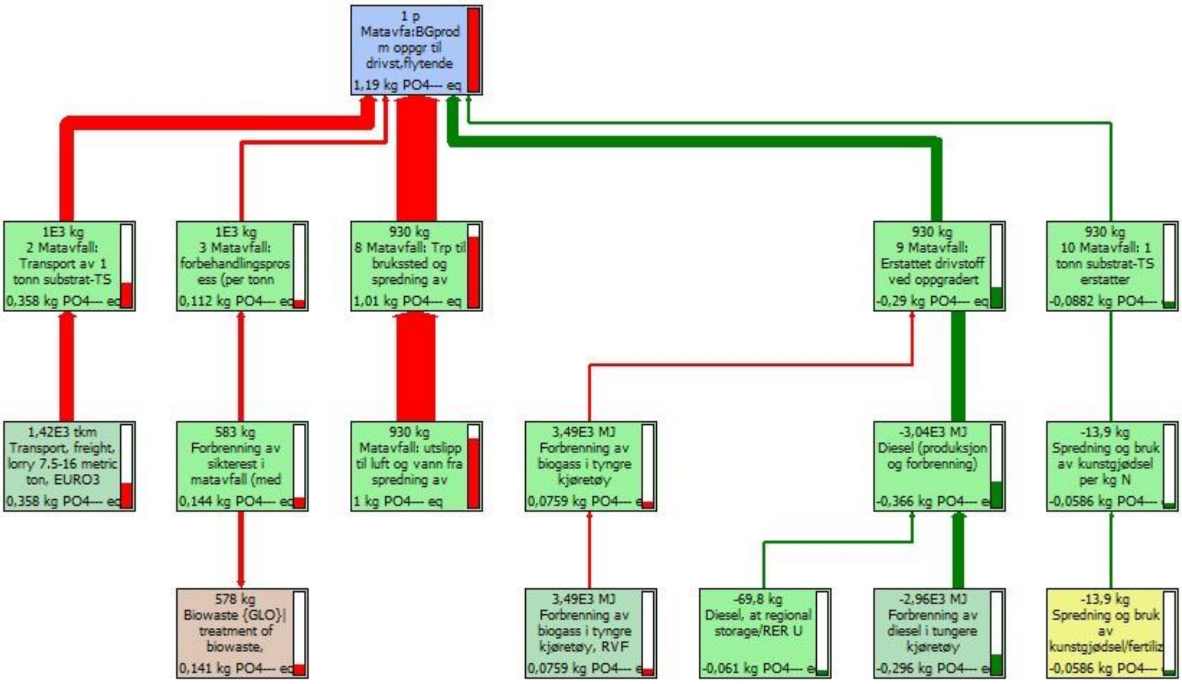


Figure 14 Tree network of eutrophication of the biogas fish sludge value chain.

Environmental impacts from eutrophication were largest from the spreading and use of the liquid digestate (life cycle stage 7) of 1.0 kg PO_4^{-3}. The tree illustration of the value chain show that these emissions are air and water related and come primarily from spreading (Figure 14).

The BioValueChain model provides results several other impact categories, and four of these are generally considered imporatant. These are ozone depletion potential (ODP), photochemical oxidation (POCP), abiotic depletion, and acidification potential (AP). The general trend for these categories is that AP follows eutrophication, but the three others show a somewhat different pattern. The total environmental impact were all postivie values with ozone depletion of $3.08E^{-5}$ kg CFC^{-11} eq, photochemical oxidation of 0.03 kg C2H4 eq, abiotic depletion of 0.0015 kg Sb eq, and acidification 4.61 kg SO_2 eq (Figure 15). The largest positive values (negative environemtnal impacts) came from stage 2 fish sludge transportation for both ozone depletion of $5.57E\text{-}05^5$ kg CFC^{-11}, abiotic depletion of 0.0013 kg Sb eq and for photochemical oxidation of 0.059 kg C2H4 eq (Figure 15). However, for acidification, the largest postifive value came from stage 7 spreading and use of digestate fertilizer (as is the case for eutrophication). Life cycle stage 9 mineral fertilizer substitution represents the largest negative contribution for ODP and POCP with ozone depletion of $-3.31E^{-5}$ kg CFC^{-11} eq and photochemical oxidicaiton of -0.00058 ($5.8E^{-4}$) kg C_2H_4 eq (Figure 15). For acidification, the negative values come from the process 8 diesel substitution with -1.407 kg SO_2 eq; and then for stage 9 mineral fertilizer substitution of 0.332 kg SO_2 eq (Figure 15). Abiotic depletion did not have any negative values.

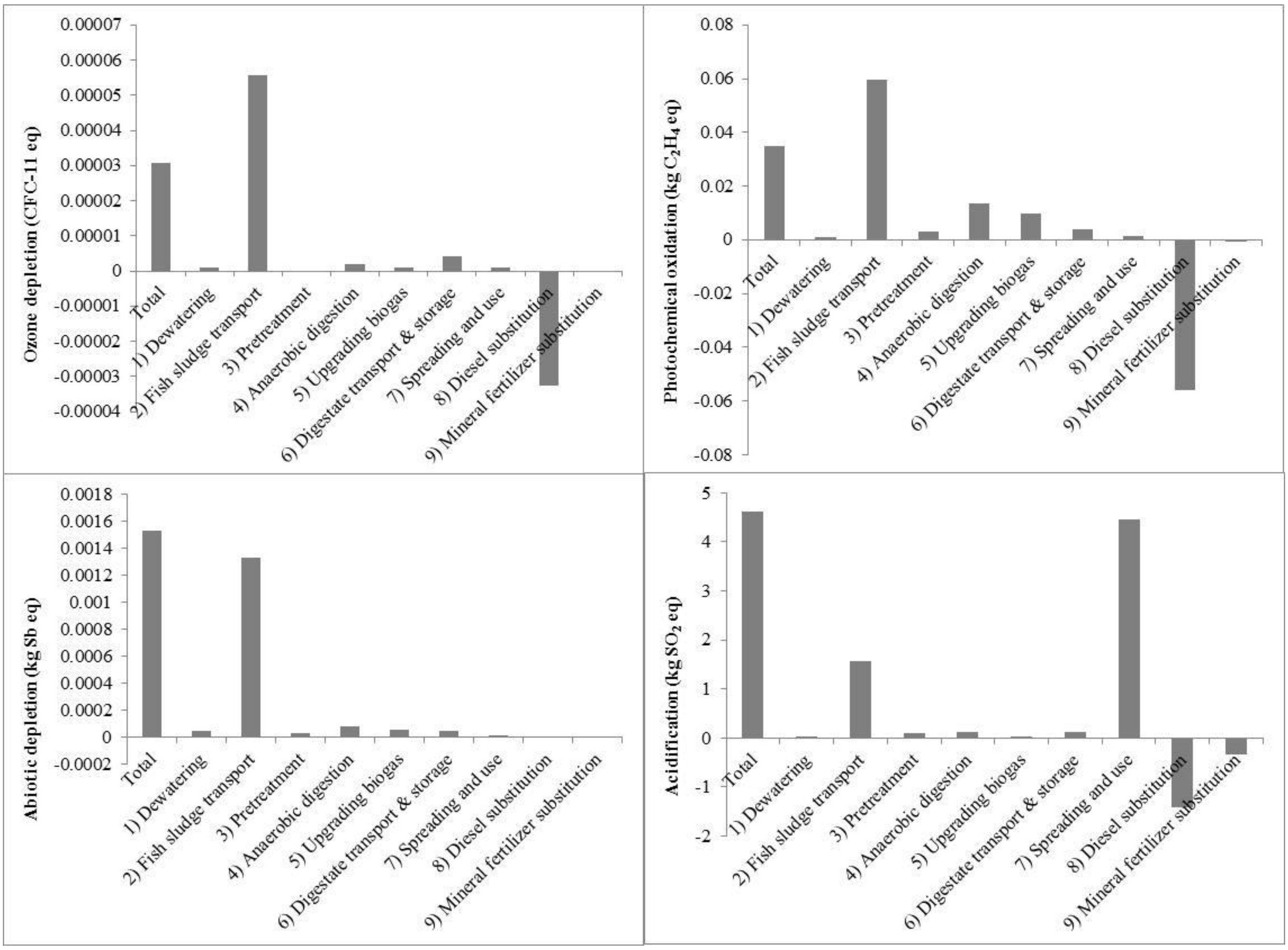


Figure 15 Impact categories ozone depletion (top left), photochemical oxidation (top right), abiotic depletion (bottom left) and acidification (bottom right) for each life cycle stage including the total for all the stage, i.e. the whole life cycle.

4.2 Transportation scenarios

Three types of transportation scenarios were modelled in the thesis. In the first two, actual transportation distance in model was changed; first, the transportation distance of the fish sludge from the fish farm to the biogas plant (parameter name M_T2), and second the transportation distance of the digestate fertilizer from the biogas plant to the use site or field where it is applied (parameter nameTrp_biogassanl_lager). In the third scenario the dry matter content of the substrate (parameter name M_substrate_TS) was altered, which affected the environmental costs associated with the transportation life cycle stage.

4.2.1 Transport distance of fish sludge

Transportation of the fish sludge to the biogas plant from the fish farm has a great influence on the overall environmental benefit in terms of global warming potential from the biogas production. When sludge is transported longer than 283 km there is no longer an environmental benefit of the biogas production (Figure 16; where the line croses the x axis). There is a linear relationship between the transport distance and the global warming potential. With a transport distance of zero, the global warming benefit would be more than double that of the reference scenario and equal to -519 kg CO_2 eq (Figure 16; where the lines croses the y axis).

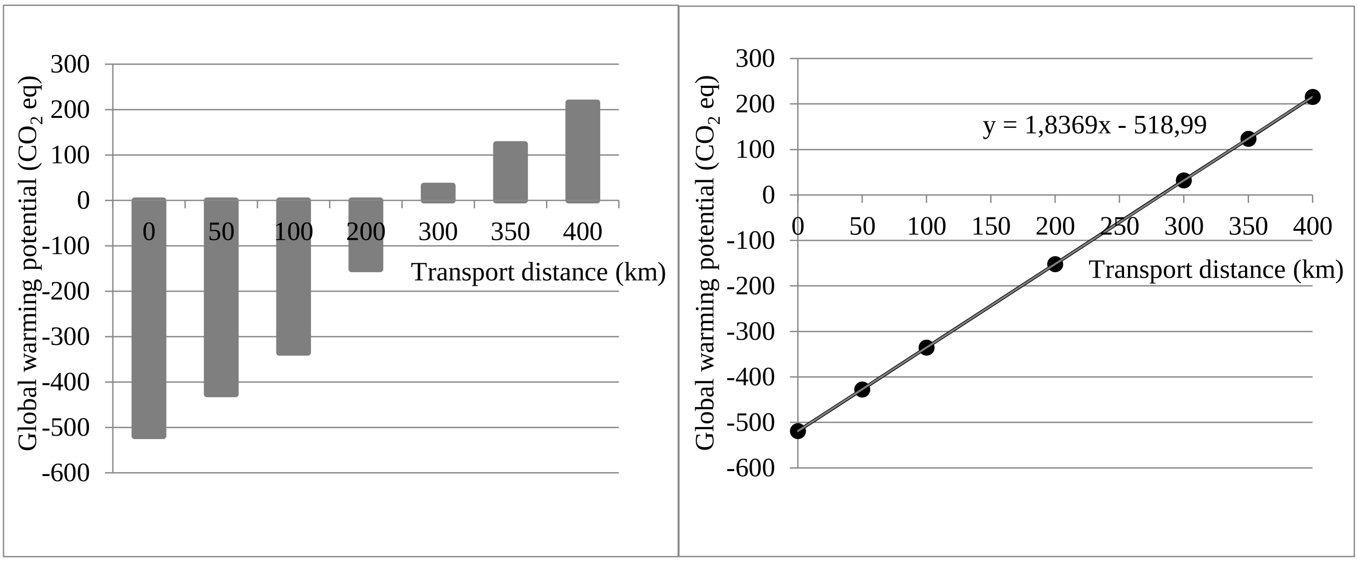


Figure 16 Global warming potential from scenarios with different transportation distance of the fish sludge.

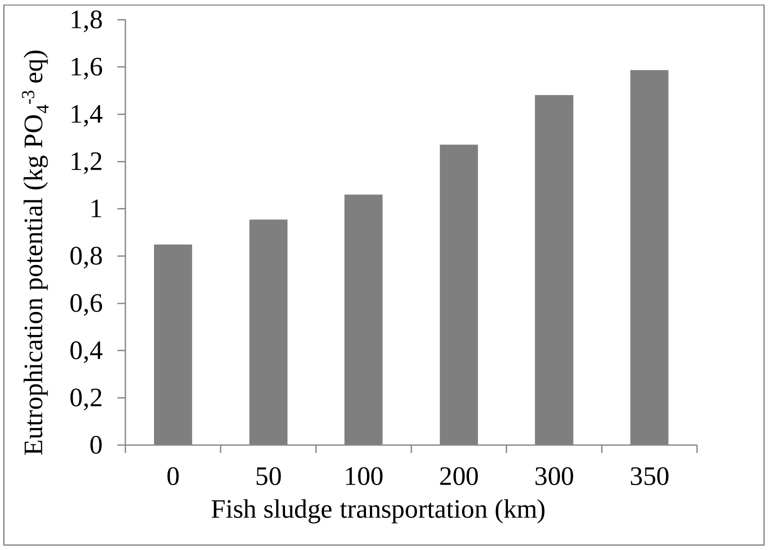


Figure 17 Eutrophication potential from scenarios with different transportation distance of the fish sludge

The eutrophication potential for the same scenarios also showed a positive correlations, where incrasing fish sludge transportation distance causes a substantial increase in the eutrophication potential (Figure 17).

4.2.2 Transport distance of digestate liquid fertilizer

Doubling the distance from 50 km to 100 km reduced the environmental benefit to 185 kg CO_2 eq compared to the 206 kg CO_2 eq for the reference scenario (50 km). Reducing the transportation distance to 0 km only had a small effect on the global warming to -232 kg CO_2 eq. The linear relation between the transport distance and the GWP could be describe by the equation $y = 0.4293x - 232.7$. This means that the maximum transportation distance of the fertilizer would be $x = 232.7/0.4293 = 541$ km. As could be expected, the effect on the results were visible only in life cycle stage 6, where the transportation and storage of the liquid digestate takes place (data not shown).

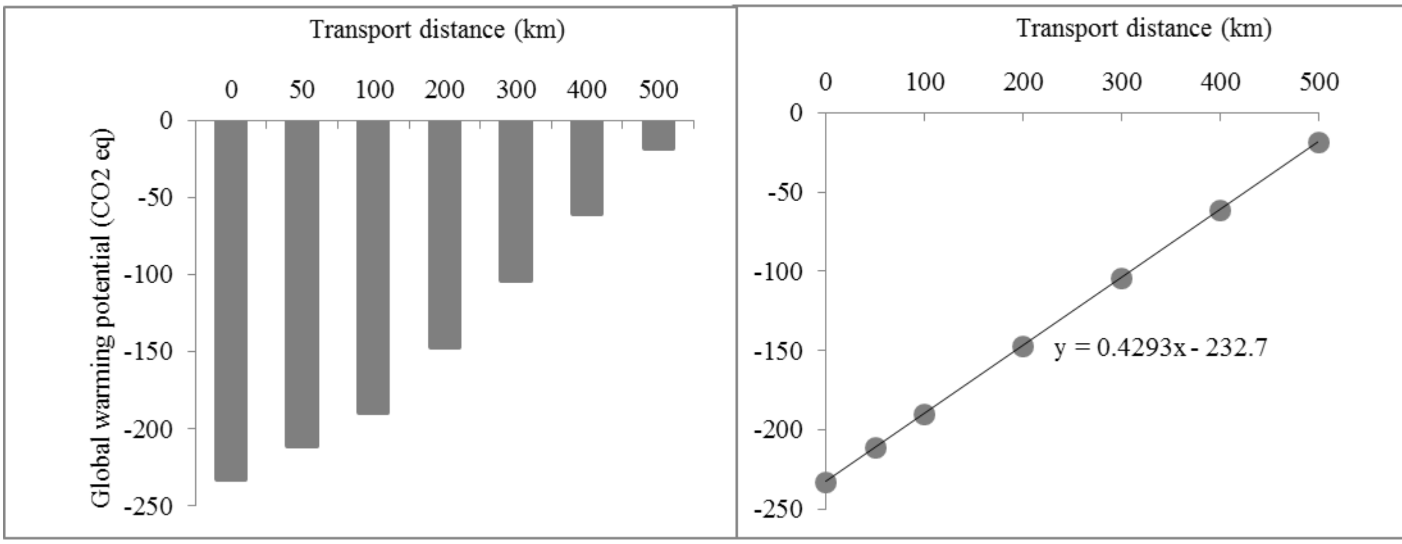


Figure 18 Global warming potential for scenarios with alternative transport scenarios of the digestate fertilizer displayed with columns (left side) and as points with a correlation line (right side).

The eutrophiciation potential increased with increasing transportation distance of the fish sludge. It was also in life cycle stage 6 where the the effect was found.

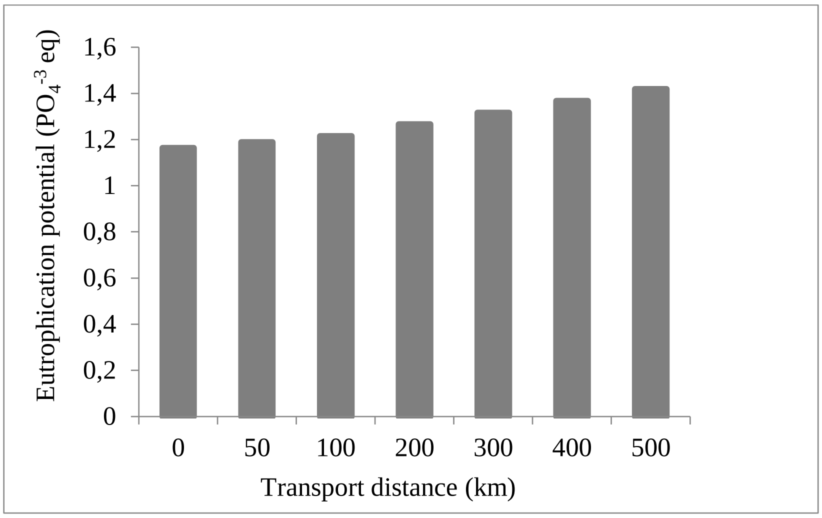


Figure 19 Eutrophication potential from scenarios with different transportation distance of the digestate fertilizer.

4.2.3 Substrate dry matter content

The dry matter contet of the substrate influences the environmental impacts resulting from the transportation phases of the biogas life cycle. The wetter the sludge is, the heavier it is and more emissions will occur during its transportation. The effect was largest in life cycle stage 2 fish sludge transportation and also life cycle stage 3 of pretreatment (Figure 20). Reducing the dry matter content to 6 % resulted in such large emissions from transportation that the net effect from the biogas production value chain was positive global warming potential of 104 kg CO_2 eq (Figure 20). Increasing the dry matter content to 15 % gave a global warming potential of -269 kg CO_2 eq.

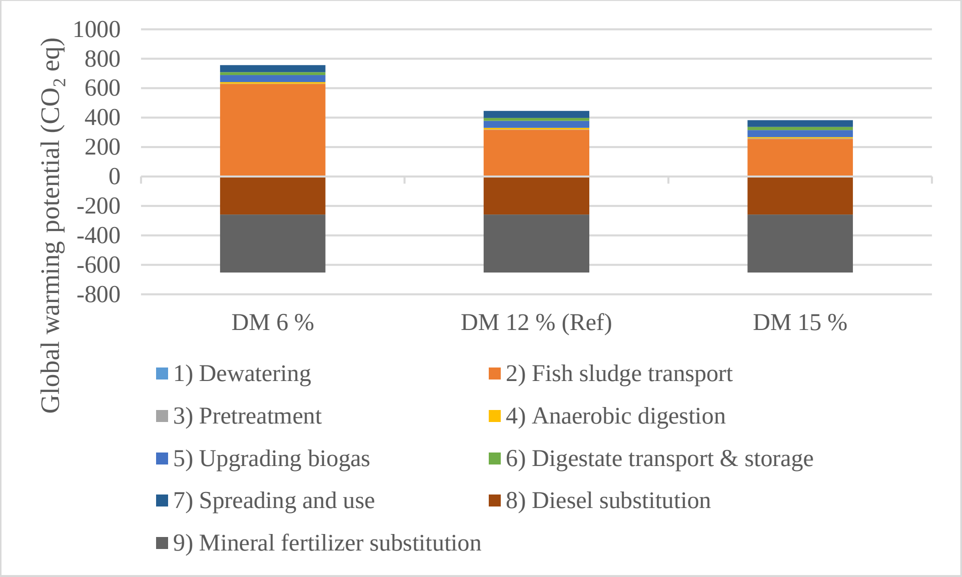


Figure 20 Global warming potential with a low (6%) and high (15%) dry matter content of the substrate.

Eutrophication was also largest with the smallest dry matter content 1.78 kg PO_4^{-3}eq, but didn't change so much when the content was increased to 15 % (1.194 kg PO_4^{-3}eq) compared to the reference scenario with 12 % giving 1.198 kg PO_4^{-3}eq. Overall changing the dry matter content did not affect the eutrophication potential that much.

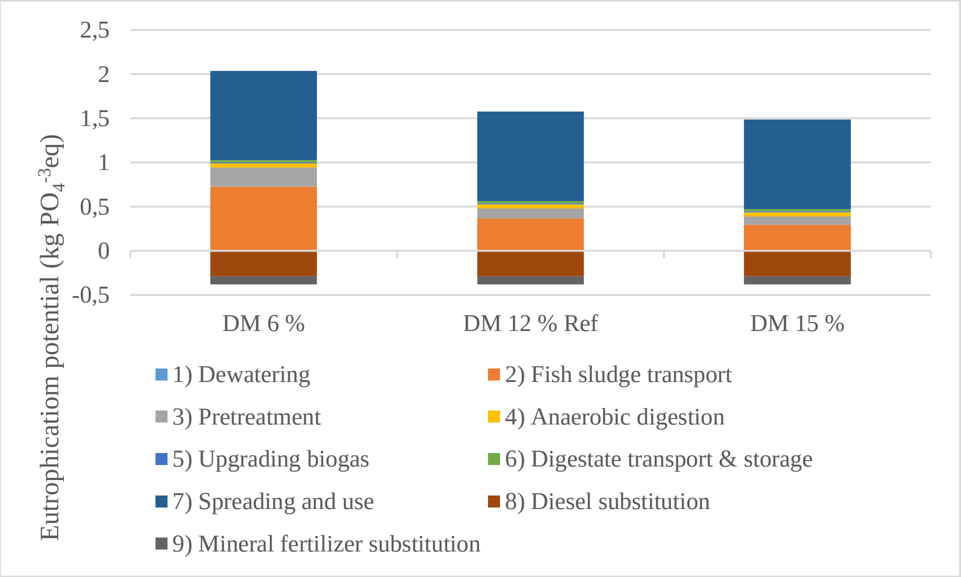


Figure 21 Eutrohpication with a low (6%) and high (15%) dry matter content of the substrate in addition to the reference scenario with 12 % DM in the substrate.

4.3 Biogas production efficiency scenarios

Three types of scenarios concerning the biogas production efficiency were modelled where the following three parameters were altered: 1) the theoretical biogas potential (Biogassanlegg_reelt_utbytte; unit is a fraction), 2) the potential biogas production (M_Nm3_per_tonn_TS), and 3) the methane potential (M_metaninnh_biogas). In the first scenarios with the theoretical biogas potential, I made to scenarios with a low (0.55) and high (0.8) value in addition to the reference value from 0.7. In the second scenarios, the potential biogas production was lowered to 100 Nm^3/ton DM and increased to 400 Nm^3/ton DM and 600 Nm^3/ton DM in addition to the reference value of 270 Nm^3/ton DM. The final scenario on the methane potential was also modelled with two lower values of 0.3 and 0.5 and a high value (0.8) in addition to the reference value of 0.6.

4.3.1 Theoretical biogas potential

The theoretical biogas potential (Biogassanlegg_reelt_utbytte) is given as a percentage of the theoretical amount of energy that a plant can produce and depends on pretreatment and residence time in the plant. When increasing the parameter from 0.55 to 0.8 according to literature, the global warming potential gets smaller (from -151 kg CO_2 eq to -243 kg CO_2 eq). Even with a lower theoretical biogas potential, the net environmental benefit from biogas production was positive (negative values). Changing the theoretical biogas potential only influenced the global warming potential in life cycle stage 9 substitution of mineral fertilizer (Figure 22).

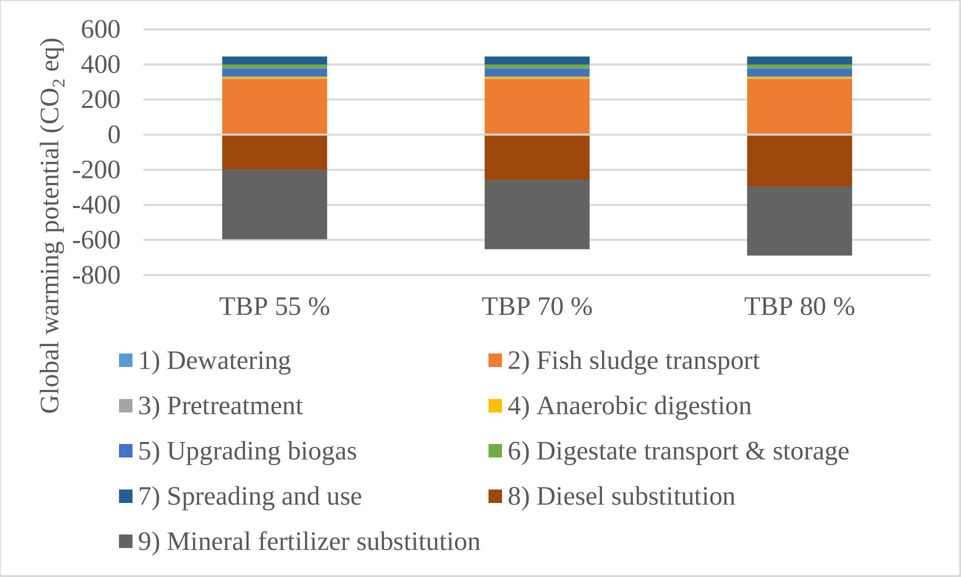


Figure 22 Global warming potential with a low (0.55) and high (0.8) scenario for the theoretical biogas potential parameter. Reference scenarios with 0.7 is also shown.

The eutrophication potential was not greatly affected by changing the theoretical biogas potential. When increasing the parameter value from 0.55 to 0.8 resulted in a slightly smaller eutrophication value from 1.261 kg PO_4^{-3} eq (TBP 55 %) to 1.16 kg PO_4^{-3} (TBP of 80 %) (Figure 23). As for global warming, the eutrophication only changed in life cycle stage 9, which is the substitution of mineral fertilizer (Figure 23.)

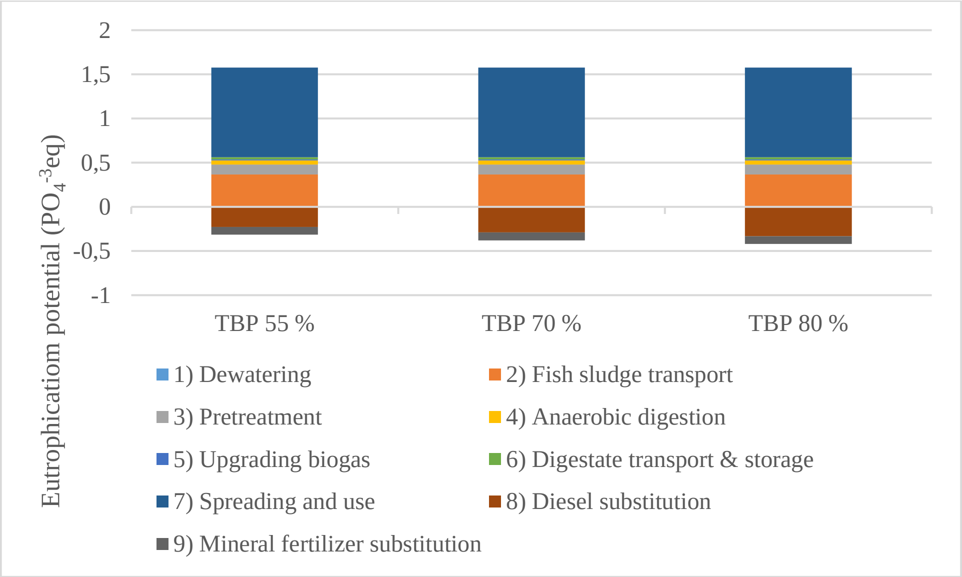


Figure 23 Eutrophication potential with a theoretical biogas potential (TBP) of 55%, 70 % (reference scenario and 80 %.

4.3.2 Potential biogas production

The potential biogas production (parameter M_Nm3_per_tonn_TS) is the amount of gas produced per ton of substrate given in units of normal (N) m^3/ton DM and for the reference scenario a value of 270 Nm^3/ton DM was used. In addition to the reference scenario three alternative scenarios were modelled with parameter values 100, 400, and 600 Nm^3/ton DM. In the alternative scenarios, when the value was doubled to 600 Nm^3/ton DM it resulted in more than twice as large negative global warming potential of -465 kg CO_2 eq. With a potential biogas production of 400 m^3/ton DM, the global warming potential was -308 kg CO2 eq. For the third and last alternative scenario, reducing the potential biogas production to 100 Nm^3/ton DM also reduced the global warming potential to -73 kg CO_2 eq. In the model, the relationship between the global warming potential and the parameter potential biogas production is exactly linear and showed a strong decreasing global warming with increasing biogas production (Figure 24).

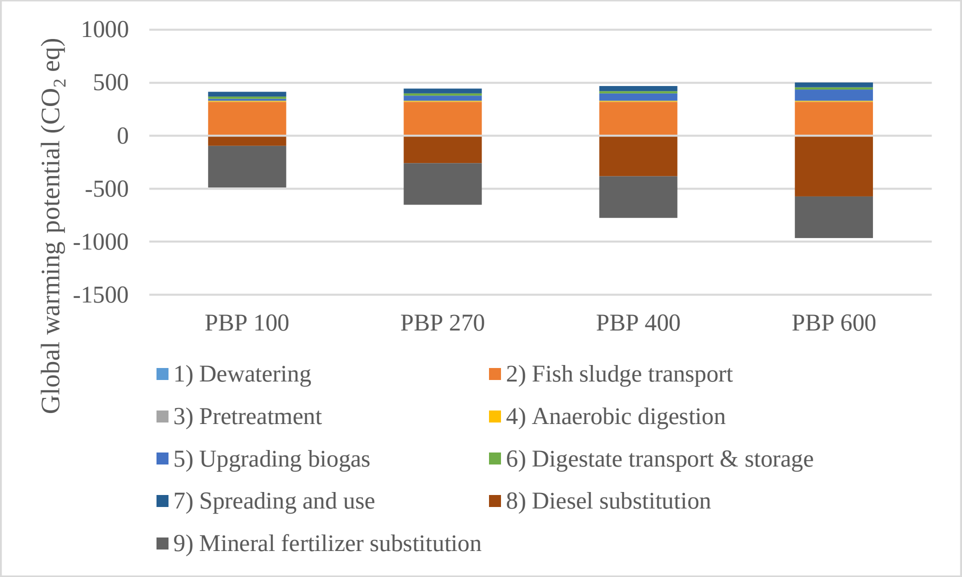


Figure 24 Global warming potential with three scenarios for the potential biogas production per tonn dry matter of (PBP) 100 ,400 and 600 Nm^3/ton DM, as well as reference scenario value of 270 Nm^3/ton DM.

The eutrophication potential of the same scenarios were positive contrary to the global warming. Eutrophication gets smaller when increasing the value for potential biogas production. The effect was quite substantial and increasing to 600 Nm^3/ton DM resulted in a smaller eutrophication of 0.86 kg PO_4^{-3} eq compared to the scenario with the smallest biogas production of 100 Nm^3/ton DM, which gave 1.37 kg PO_4^{-3} eq (Figure 25).

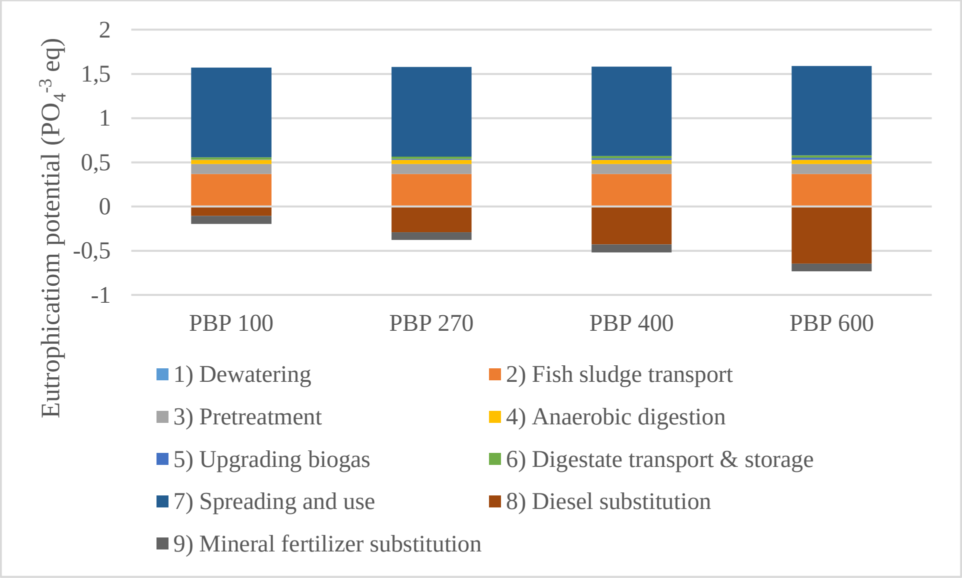


Figure 25 Eutrophication with three scenarios for the potential biogas production per tonn dry matter (PBP) of 100 ,400 and 600 Nm3 / ton DM, and the reference scenario value of 270 Nm3 / ton DM.

For both global warming (Figure 24) and eutrophication (Figure 25), the effect of the changing the potential biogas production parameter occurred in life cycle stage 5 (upgrading of biogas to fuel) and stage 9 (substitution of mineral fertilizer).

4.3.3 *Methane potential*

In these scenarios the methane potential (parameter M_metaninnh_biogas) was changed. The methane potential is given as the fraction of the biogas that is methane, and that can be upgraded to fuel. The three alternative scenarios gave global warming potentials of -98.5 kg CO_2 eq with a methane potential (MP) of 30%, -170.6 kg CO_2 eq for MP 50 %, and -278.9 kg CO_2 eq for MP of 80 % (Figure 26). The results showed that the higher the methane potential, gives a smaller global warming potential (Figure 26).

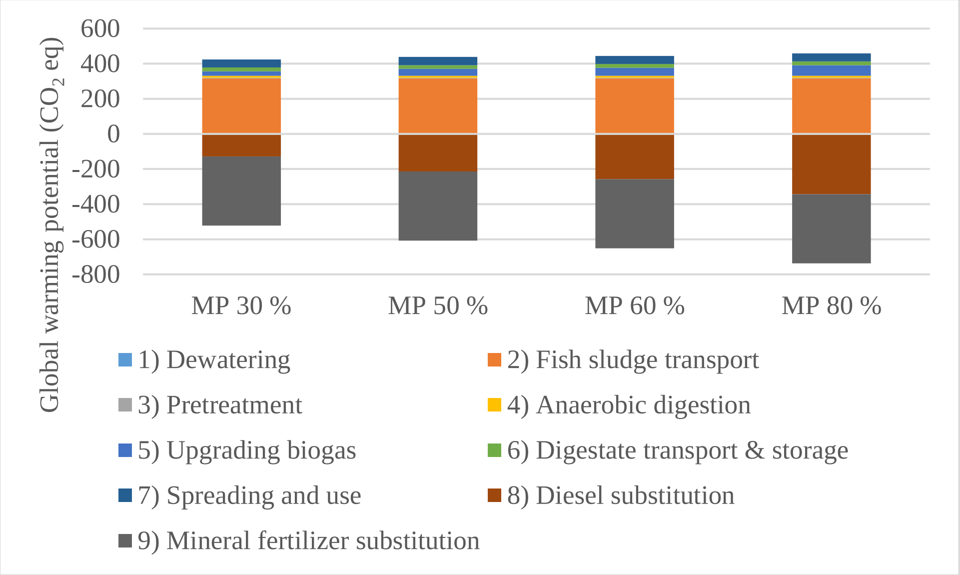


Figure 26 Global warming potential with four scenarios with different methane potential (MP) of 30 %, 50 %, 60 % (reference scenario) and 80 %.

The eutrophication potential was reduced when increasing the parameter value of the methane potential. The smallest methane potential of 30% showed the biggest eutrophication. There is a quite little difference between the eutrophication potentials of the different scenarios.

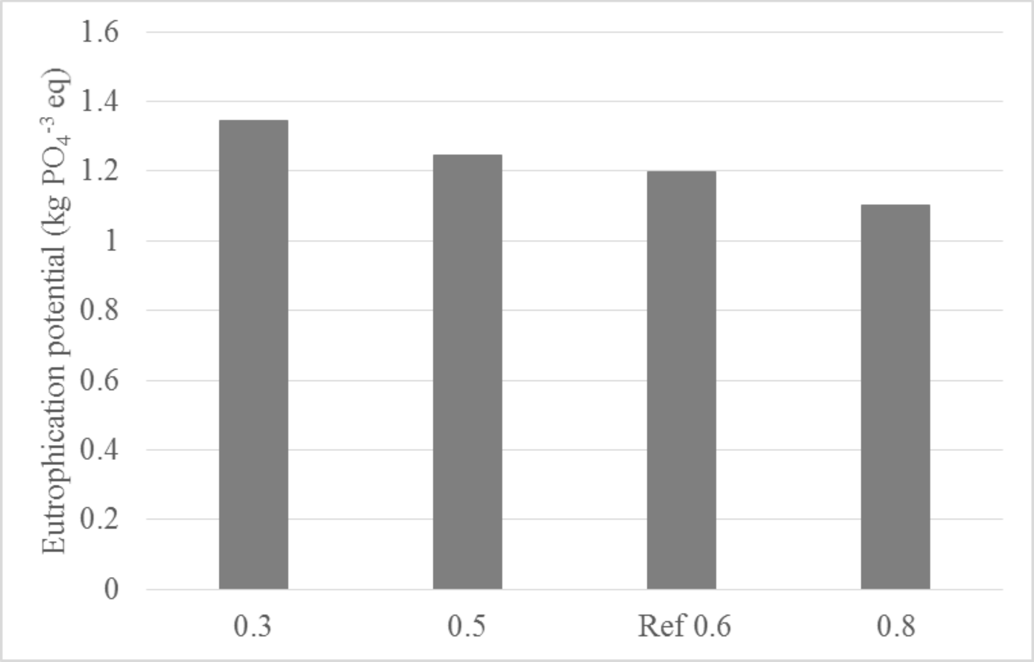


Figure 27 Eutrophication potential (kg PO4-2 eq) with four scenarios with different methane potential 30 %, 50 %, 60 % (reference scenario) and 80 %.

The effect of the changing the methane potential parameter occurs in the life cycle stages 5 upgrading biogas and in stage 9 substitution of mineral fertilizer, which was also the case for the scenarios chaing the potential biogas production parameter. This was the case for both the global warming potential (Figure 26) and the eutrophication.

4.4 Potential environmental benefits from biogas production

The potential environmental benefits were estimated from four hypothetical case studies assuming that new technology of closed containment cages is used and sludge is collected. Environmental benefits were estimated from the incorporaton of biogas production from salmon fish sludge for the three following companies: 1) Lerøy Midnor, 2) Marine Harvest and 3) Nova Sea. The fourth estimate was made for all Norwegian salmon production.

4.4.1 Lerøy Midnor AS case

According to the reference scenario there was an environmental benefit of 206 kg CO_2 eq per ton DM fish sludge. Assuming Lerøy Midnor AS sends all the fish sludge produced on their open ocean farms to Biokraft in Skogn, it could results in a substantial emission reduction. Lerøy Midnor AS produced approximately 68 300 ton fish in 2014 (65 000 ton expected in 2015) (Lerøy 2015). A fish production of 68 300 tons is equal to 8196 tons DM sludge (0.120

ton DM sludge × 68 300 tons fish = 8 196 tons DM sludge). This means that Lerøy Midnor could avoid emissions of 8169 ton DM sludge × 206 kg CO_2 eq/ ton DM sludge = 1 682 814 kg CO_2 = 1 683 ton CO_2 eq per year.

4.4.2 Marine Harvest case

Marine harvest is an international company farming the largest share of salmon production in Norway. In total Marine harvest has a production of 258 000 ton fish with 63 500 ton fish in the Mid-Norway region. The Mid-Norway production consists of 25 open ocean farms located from Averøy to Fosnes, which is a distance of approximately 460 km and Skogn located in the middle. Hence, if Marine Harvest sends all the sludge collected from the Mid-Norway farms, the avoided CO2 emissions can be calculated using the modelled results based on 200 km fish sludge transport distance. A global warming benefit of 1.8369 × 200 - 518,99 = -151.6 kg CO2 eq per ton fish sludge DM (see equation in Figure 16) can be estimated. Accordingly, 63 500 ton fish would yield (0.12 ton sludge/ton fish × 63 500 tons fish) 7 620 tons DM sludge. An avoided global warming potential of 7620 ton DM sludge × 151.6 kg CO_2 eq/ ton DM sludge = 1 155 192 kg CO_2 = 1 155 ton CO_2 eq per year could be achieved by Marine Harvest when using the existing Biokraft biogas plant.

4.4.3 Nova Sea AS case

Nova Sea AS was the 6th largest salmon producer in Norway in 2014 (MarineHarvest 2015). Nova Sea AS operate on the coastline of Helgeland county from the Island of Sømna to Gildeskål, which is a distance of approximately 400 km in a straight bird line. Assuming that Nova Sea AS install a biogas plant in the middle of their operations (fish sludge transportation distance of 200 km), a global warming benefit of 1.8369 × 200 - 518,99 = -151.6 kg CO2 eq (see equation in Figure 14) could be achieved per ton of fish. The total fish production of 41 923 ton (NovaSeas 2014) would yield approximately: 41 923 ton fish × 0.120 ton sludge/ ton fish = 5 031 ton sludge per year. With an environmental benefit of 151.6 kg CO2 eq /ton sludge, Nova Sea AS could avoid emissions of 5 031 ton sludge × 151.6 kg CO2 eq /ton sludge = 762 700 kg CO2 eq (762.7 ton CO2) per year.

4.4.4 All Norwegian salmon farms

This case explores the situation if all Norwegian salmon production adopted closed cage systems, collected the sludge and send it to a biogas plant within an average distance 250 km. The environmental impacts from the biogas value chain, assuming a transport distance of 250 km for the fish sludge would yield 1.8369 × 250 - 518,99 = -60 kg CO_2 eq (see equation in Figure 16) per ton of fish sludge DM. With the total Norewgian salmon production of approximately 1.3 mio ton (SSB 2016), an estimate of 1.3 mio ton * 0.12 ton DM sludge = 0.156 mio ton DM sludge = 156 000 ton DM sludge can be made. The avoided CO2 emissions could then be 156 000 tons DM sludge × 60 kg CO_2 eq / ton DM sludge = 9 323 ton CO_2 eq.

5 Discussion

5.1 Environmental benefit of fish sludge biogas production

Overall, making biogas from fish sludge gave a positive effect on the environment in terms of greenhouse gas emissions as the global warming potential was -206 kg CO_2 eq. For greenhouse gas emissions it is fairly straight forward to interpret the results as negative values indicate and avoidance or removal of CO_2. On the contrary, the environemtnal impact of eutrophication, it is more difficult to determine the actual effect of biogas from fish sludge because it was not possible to make an LCA of the salmon production system without the biogas production. The BioValueChain model has the functional unit of ton DM sludge and not ton of fish produced so it does not make sense to run it without the sludge. However, it is possible to make a rough estimation of the potential eutrophication for the fish sludge going into the ocean if it was not collected for biogas treatment. According to Bergheim, 1 ton of fish produced would result in 6 kg of P in the sediments and 2 kg dissolved, which is a total of 8 kg of P per ton fish (Bergheim and Braaten 2007). Converting that to the functional unit used in the modelling we would get 8 kg P per 120 kg DM sludge (assuming a dry matter content of 12 %), which is equal to 8 kg P / 120 kg DM sludge = 0.067 kg P / kg DM sludge (67 ton P / ton). This value is much smaller than the eutrophication potential of the reference scenario, which was 1.2 kg PO_4^{-3}/ ton DM sludge. But my value includes the whole life cycle and not only the production phase with the nutrient release from the fish sludge.

From all Norwegian salmon production of 1.3 mio ton fish equal to 156 000 ton DM sludge we can estimate that the P emissions to the ocean are approximately equal to 0.008 ton P × 1 mio ton = 8000 kg P per year (Bergheim and Braaten 2007). Although the EPA has not found nutrient release as a major concern, it is likely that a continuous release of 8000 kg P year after year will cause an environmental problem. Another facts is that the nutrient flow balance model for salmon is based on old experiments and it may be time to collect new data on the amount and nutrient content of sludge that can be collected from the newly developed closed systems.

Another challenging factor of interpretation is the issue of comparing the results for the different impact categories. What is worst for the environment? Global warming or eutrophication? That cannot be answered without some kind of weighing of the different categories, which was not possible in this study.

According to the 2014 environmental report for Nova Sea, greenhouse gas emissions from Nova Sea in 2014 were equal to 7006 ton CO_2 (NovaSeas 2014). When utilizing the fish sludge from the biogas production, Nova Sea could earn 762.7 ton CO_2 eq per year which is just a little less than 10 % of the total greenhouse gas emissions.

Biogas production from fish sludge seems to be especially beneficial if sludge transportation is minimized. Therefore RAS farms, especially full grow out operations could really make an environemtnal benefit. If a farm produces 1000 tonns every year, and has biogas plant on the location, the environmental a benefit of the plant would be highly significant. With no transport distance of the fish sludge an environmental benefit of 519 kg CO_2 eq / ton DM sludge could yield a total benefit of 62 280 kg CO_2-eq per year (assuming 12 % DM).

5.2 Uncertainty of the model results

Not all aspects were included in this LCA because the value chain being studied was hypothetical and not yet implemented. That means that the results produced may be critical in terms of the aspect such as transport distance, the efficiency of the biogas production, and the energy consumption related to the sludge collection and also running closed cage systems. In other words, to really determine the environmental impact of a biogas value chain connected with salmon production in Norway, it would be necessary to evaluate each specific case and measure transport distance, biogas efficiency and the electricity consumptions of the closed system and the sludge collection. This is needed in order to truly determine if the hypothetical case study is a good alternative in terms globale warming potential and eutrophication compared to the current open-net pens system. However, to try and compensate for this limitation in the study, several alternative scenarios were modelled varying the parameter values for the above-mentioned aspects.

Changing the transportation distance of the liquid fertilizer from the digestate did not affect the global warming potential as much as for the fish sludge transportation. The transport distance of especially the fish sludge from the farm to the biogas plant is a decisive factor in determining whether or not anaerobic digestion has an overall positive effect on the environment. Transportation was also found to be crucial in an LCA study of Norwegian salmon, where it was shown that the transport of fish to the slaughterhouse and the consumer is the main contributor of greenhouse gases (Ellingsen, Olaussen et al. 2009). Also, it was found that train and boat transport should be used instead of airplanes and trucks for transportation to the market (Ellingsen, Emanuelsson et al. 2009). It is possible that using boat transport instead of trucks to transport the fish sludge would lower the emissions and thereby enable a longer transportation distance. Unfortunately, this could not be tested in the model with the current set of parameters and input data.

Another aspect which could influence the environmental cost of the fish sludge transportation distance is the dry matter content of the fish sludge that is transported. In the current study scenarios were modelled with a DM content of 6 %, 12 %, and 15 %. New technology tested within a RAS context resulted in sludge thickening up to 92% DM by the use of belt-filter, drum fileter and composting (Olsen 2013). As the correlation between substrate dry matter content and global warming potential was not linear and there were only three points, it is not possible to extrapolate and make an estimate of global warming for fish sludge dry matter content of 92 %. In order to run BioValueChain model with a dry matter content for the substrate of 92 %, it would be needed to included the environmental impacts related of a new pretreatment steps, which include watering of the substrate to a more appropriate DM content for anaerobic digestion.

The energy consumption of the pumping and filtering or exchanging the water in closed systems have not been taking into account in the LCA of this study. It is possible that the electricity use associated with that could change the greenhouse gas accounting of this system. It was found that 25 000 kWh per year was used according to a report from 2012 (Teknologirådet 2012). The energy consumption was used for a smot production of 50 000 fish growing from 55 g to 750 g. In the LCI modelling in this study, the default value of 48 kWh was assumed in the dewatering phase and during the pretreatment (parameter name M_forbeh_el). Because it was not possible to find any information about the sludge production per kg smolt produced, it is difficult to convert the energy consumptions from the above mentioned smolt production to the grow-out systems.

5.3 Recommendations

Salmon producers should start adopting the closed system technologies for open ocean farming. With more more closed cages and the economic benefit from the produced bioenergy, it will probably be financially viable in the near future. More importantly, closed systems also eradicate the salmom escapes and reduce problems with sea lice, which benefits the salmon production. Furthermore, closed systems avoid the leaching of substantial amounts of nutrient such as P that may caused eutrophication in the future. Together with the closed systems, producers and industy partners should aim for efficient sludge collection technologies and low-energy consumption dewatering methods. Finally the most important is to minimize the sludge transport distance from the fish farm to the biogas plant.

Future studies could include the weighing of the impact categories as this is needed to better interpret the results. That would be a very difficult task to attach.

On a more specific level, model simulations using boat transport of the fish sludge would provide good input in finding a way to make the transportation costs smaller. Increasing the dry matter content substantially before sludge transportation would be very interesting. Clearly the large emissions from sludge transport can be reduced by increasing the dry matter content. There are technical solutions to dewatering the sludge up to 90 %. It would also be interesting to make some simulations with a very high dry matter content of the fish sludge and a much lower transportation distance resembling the sludge collection from a RAS production. There are an increasing number of RAS smolt systems in Norway that could surely have large environmental benefits from from sludge biogas production.

6 Conclusion

In this study I found a positive environmental impact of using fish sludge as substrate for biogas digestion and replacing diesel for biofuel and mineral fertilizer for organic digestate fertilizer. The LCA methodlogy gave results of global warming potential of -206 kg CO2, and eutrophication of 1.189 kg $PO4^{-3}$. Upscaling the model results showed that the major companies in the surrounding of the biogas plant Biokraft AS could also gain substantial environmental benefits converting to closed containment systems, collecting the fish sludge and sending it to Biokraft. However, it is crucial that the transport distance of the fish sludge does not exceed 283 km or that the digestate fertilizer is not transported further than 541 km. Relevant stakeholders should prioritize minimizing the distance for fish sludge travel over the digestate fertilizer travel.

It can be concluded that the environmental benefit for major salmon producers in the surrounding of Biokraft (Marine Harvest, Lerøy, and Nova Sea) could contribute with avoided emissions of 3600 ton CO_2 eq per year if they send all the sludge to Biokraft. The potential for all of Norwegian salmon production was estimated at 9 323 ton CO_2 eq per year. These estimates are substantial and show the great potential of the fish sludge, which is currently emitted into the ocean.

Finally, it should be noted that these results are associated with great uncertainty and especially the model parameter potential biogas production has a crucial influence on the size of the global warming potential.

7 References

Accenture (2013). Opportunities and challenges for sustainable farming of salmon closed systems and offshore in Norway. Pre-Study, Accenture & WWF.

AquaFarm. (2016). "Closed cages. Concept." from http://aquafarm.no/closed-cage/.

AquaFarm. (2016). "Environment. The challenges." from http://aquafarm.no/environment/.

Bergheim, A. (2016). Fish sludge production. C. Acosta.

Bergheim, A. and T. Asgard (1996). Waste production from aquaculture.

Bergheim, A. and B. Braaten (2007). Modell for utslipp fra norske matfiskeanlegg til sjø. Stavanger, International Research Institute of Stavanger AS (IRIS).

Bergheim, A., S. J. Cripps, et al. (1998). "A system for the treatment of sludge from land-based fish-farms." Aquatic Living Resources **11**(4): 279-287.

Bergheim, A., A. Drengstig, et al. (2009). "Production of Atlantic salmon smolts in Europe-Current characteristics and future trends." Aquacultural Engineering **41**(2): 46-52.

Braaten, B., G. Lange, et al. (2010). Vurdering av nye tekniske løsnigner for å redusere utslippene fra fiskeoppdrett til sjø. Rapport IRIS - 2010/134. Klima- og Forurensningsdirektoratet, KLIF, KLIF, NIVA, IRIS.

ClosedLoopSystems. (2016). "Biomethanation." from http://www.closedloopsystem.com/biomenthation.html.

DanishEPA (2005). Impact categories, normalisation and weighting in LCA. Environmental News No.78.

Ecomerden. (2016). "Merden." from http://www.ecomerden.no/merden.html.

Ellingsen, H. and A. Aanondsen (2006). "Environmental impacts of wild caught cod and farmed salmon - A comparison with chicken." International Journal of Life Cycle Assessment **11**(1): 60-65.

Ellingsen, H., A. Emanuelsson, et al. (2009). Energibruk og klimutslipp i eksport av norsk Sjømat. F.-o. kystdepartementet. Trondheim, Sintef Fiskeri og havbruk AS.

Ellingsen, H., J. O. Olaussen, et al. (2009). "Environmental analysis of the Norwegian fishery and aquaculture industry-A preliminary study focusing on farmed salmon." Marine Policy **33**(3): 479-488.

Gebauer, R. (2004). "Mesophilic anaerobic treatment of sludge from saline fish farm effluents with biogas production." Bioresource Technology **93**(2): 155-167.

Gebauer, R. and B. Eikebrokk (2006). "Mesophilic anaerobic treatment of sludge from salmon smolt hatching." Bioresource Technology **97**(18): 2389-2401.

GreenDelta (2015). LCIA methods. Impact assessment methods in Life Cycle Assessment and their impact categories. Version 1.5.4. Berlin, GreenDelta.

Hersoug, B. (2015). "The greening of Norwegian salmon production." Maritime Studies **14**: 19.

IFE (2015). Energy Efficiency Trends and Policies in Norway. Kjeller, Norway, Institute for Energy Technology.

ISO (1997). Environmental management - Life cycle assessment - Principles and framework. ISO 14040. I. S. organization.

ISO (1998). Environmental Management - Life Cycle Assessment - Life Cycle Interpretation. ISO/DIS 14043’ IS0 TC 207.

ISO (1998). Environmental management — Life cycle assessment — Goal and scope definition and inventory analysis. ISO 14041. I. S. organization.

ISO (2006). Environmental management. Life cycle assessment. Requirements and guidelines. ISO 14044. I. S. Organization. Geneva, ISO.

Kondusamy, D. and A. S. Kalamdhad (2014). "Pre-treatment and anaerobic digestion of food waste for high rate methane production – A review." Journal of Environmental Chemical Engineering **2**(3): 1821-1830.

Lerøy (2015). "Breaking new ground in aquaculture. Lerøys first closed aquaculture farm."

Lerøy. (2015). "Lerøy Q4 2014 ", from http://hugin.info/131537/R/1896565/672869.pdf.

Lyng, K.-A., I. S. Modahl, et al. (2015). "The BioValueChain model: a Norwegian model for calculating environmental impacts of biogas value chains." International Journal of Life Cycle Assessment **20**(4): 490-502.

MarineHarvest (2015). Salmon Farming Industry Handbook 2015. **Marine Harvest**.

Mattilsynet (2014). Water quality and water treatment in smolt systems (In Norwegian: VANNKVALITET OG VANNBEHANDLING I SETTEFISKANLEGG). RAPPORT Nasjonalt tilsynsprosjekt 2012-2014. Bergen, Mattilsynet Statens tilsyn for planter, fisk, dyr, og næringsmidler.

Mirzoyan, N., Y. Tal, et al. (2010). "Anaerobic digestion of sludge from intensive recirculating aquaculture systems: Review." Aquaculture **306**(1-4): 1-6.

NovaSeas (2014). Miljørapport 2014.

Olsen, B. H. (2013). "Langsand Salmon & RAS Design Innovations and Opportunities for New Technologies." from http://www.tidescanada.org/wp-content/uploads/2015/03/NEW_D2_-_12_Bjarne_Hald_Olsen.pdf.

Pelletier, N., P. Tyedmers, et al. (2009). "Not All Salmon Are Created Equal: Life Cycle Assessment (LCA) of Global Salmon Farming Systems." Environmental Science & Technology **43**(23): 8730-8736.

Skone, T. J. (2000). "What is Life Cycle Interpretation?" Environmental Progress **19**(2): 92-100.

SSB. (2016). "External trade in goods. Salmon."   Retrieved April, 2016, from https://www.ssb.no/statistikkbanken/SelectVarVal/Define.asp?MainTable=UhArFiskLand&KortNavnWeb=muh&PLanguage=1&checked=true.

SSB. (2016). "Further growth in aquaculture industry."   Retrieved April, 2016, from http://ssb.no/en/jord-skog-jakt-og-fiskeri/statistikker/fiskeoppdrett.

Sterud, E., T. Forseth, et al. (2007). "Severe mortality in wild Atlantic salmon Salmo salar due to proliferative kidney disease (PKD) caused by Tetracapsuloides bryosalmonae (Myxozoa)." Diseases of Aquatic Organisms **77**(3): 191-198.

Stortinget (2013). Meld. St. 22 (2012-2013) Melding til Stortinget. Verdens fremste sjømatnasjon.

Svalheim, Ø. and L. Solli (2012). Slam fra fiskeoppdrett til biogassproduksjon. Bioforsk Rapport Vol. 7 Nr.110 2012.

Svåsand, T., Ø. Karlsen, et al. (2016). Risikovurdering av norsk fiskeoppdrett 2016. . Fisken og havet særnr. 2-2016.

Teknologirådet (2012). The future salmon farming (in Norwegian Fremtidens lakseoppdrett). Rapport 01 2012. Oslo.

Torrissen, O., S. Jones, et al. (2013). "Salmon lice - impact on wild salmonids and salmon aquaculture." Journal of Fish Diseases **36**(3): 171-194.

Torrissen, O., R. E. Olsen, et al. (2011). "Atlantic Salmon (Salmo salar): The "Super-Chicken" of the Sea?" Reviews in Fisheries Science **19**(3): 257-278.

Vangdal, E., K. Kvamm-Lichtenfeld, et al. (2014). Fiskeslam frå oppdrettsanlegg. Gjødsel til planter eller råstoff for biogass? Bioforsk Report Vol. 9 Nr. 27 2014.

8 Appendix

Table: Parameters that have been changed in the BioValueChain model and their reference value.

Parameter name	Value	Description	Reference
Substrate quality			
M_substrat_TS	0.04	Share of DM content of fish sludge (fraction value)	(Svalheim and Solli 2012; Vangdal, Kvamm-Lichtenfeld et al. 2014)
M_substrate_TS_modifisert	0.12	Share of DM content of fish sludge after dewatering process	(Svalheim and Solli 2012; Vangdal, Kvamm-Lichtenfeld et al. 2014)
SF_Nm3_per_tonn_TS	270	Biogas potential per ton fish sludge (Nm3/ton DM). Default value = 600	(Mirzoyan, Tal et al. 2010; Svalheim and Solli 2012)
SF_metaninnh_biogas	0.63	Share of methane in the biogas produced from fish sludge. Default = 0.63	Use default value but run a low scenario with 50% because Mirzoyan et al 2010 provides values down to 4%
SF_substrate_mengde_N	25	Nitrogen content of fish sludge (kg N/ton DM)	Table 3 in Vangdal et al (2014); mean value
SF_substrate_mengde_P	0.1	Phosphorous content of fish sludge (kg P/ton DM)	Table 3 in Vangdal et al (2014).
Transport of fish sludge from the farm to the biogas plant			
M_T2	170	[Km] Transport of fish sludge from storage at the farm to biogas plants. Trailer Type: greater than 32 tonnes	Average distance from Lerøy Midnor fisheries to Biokraf AS in Skogn.
Pretreatment of fish sludge to biogas substrate			
M_forbeh_el	48	[KWh / ton TS] Electricity consumption in biogas per ton DM substrate.	Default value.
Trp_forbeh_beh	0	(km)Transport distance between pretreatment and biogas plant.	Assume 0 because pretreatment will be done at Biokraft.

Table: Parameters that have been changed in the BioValueChain model and their reference value.

Biogas production (anaerobic digestion)			
Biogassanlegg_reelt_utbytte	0.7	Percentage of the theoretical amount of energy that the plant can produce. Depends on pretreatment and residence time in the plant.	Default value. Run a scenario with 0.6 based on Solli pers comm saying 55-70%, probably in Svalheim & Solli 2012
Transport of digestate as fertilizer from biogas plant to agriculture farms			
Trp_biogassanl_lager	50	Distance from biogas plant to spreading of digestate fertilizer (km) Truck type: > 32 tonn.	Assume digestate is used for fertilizing local farms and default value of 50 km used. Scenarios run with 0-400 km
Biogas that replaces other energy carriers			
Andel_erst_diesel	1	Share of upgraded biogas to replace diesel in vehicles. Default = 1	Assume all biogas is used to replace diesel in vehicles.
Utilization of liquid digestate and dewatered digestate			
M_substrat_mengde_N	25	[Kg N/ton DM fish sludge] Nitrogen content per ton DM substrate from fish sludge.	Litterature value from Vangdal et al 2014
M_substrat_mengde_P	0.10	[kg P/ton DM fish sludge] Phosphor content per tonn DM substrat from fish.	Litterature value from Vangdal et al 2014
Avvanning_vatfase_som_gjodsel	1	On/off parameter. 1= wet phase and substitutes mineral fertilizer. 0 = wet phase not used as fertilizer. Default = 0	No dewatering of the digestate. Assumed wet phase is used for mineral fertilizer