Master's thesis

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

Sofie Møller

Reduction of CO_2 Emissions in the Salmon Farming Industry: The Potential for Energy Efficiency Measures and Electrification

Master's thesis in Energy and Environmental Engineering
Supervisor: Johan Berg Pettersen
June 2019

NTNU
Norwegian University of
Science and Technology

Sofie Møller

Reduction of CO_2 Emissions in the Salmon Farming Industry: The Potential for Energy Efficiency Measures and Electrification

Master's thesis in Energy and Environmental Engineering
Supervisor: Johan Berg Pettersen
June 2019

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

NTNU
Norwegian University of Science and Technology

Abstract

Electric power supply in the Norwegian salmon farming industry is conventionally provided either from diesel generators or electricity through connection to the mainland grid. It is desirable to increase the fraction of salmon farming localities connected to the grid in alignment with national climate mitigation targets. Salmon farming localities are often situated in areas where the power grid is weak which can make electrification costly.

This study has mapped the electrification potential of the onsite operations of salmon-farming in Trøndelag considering the local technical barriers of the existing power grid. The energy and power demand of the localities have has mapped and it has been analysed how the identified potential can contribute to reducing the CO_2 emissions of the industry.

The mapping revealed large variations in the onsite energy demand between localities with an average demand of 0,35 kWh/kg produced salmon. 50 % of the localities in Trøndelag are electrified and the average energy related emissions are 0,086 kg CO_2eq/kg produced salmon. The fraction of electrified localities can be increased 50 % to 83 % considering technical barriers of the existing local grid. Energy efficiency measures are crucial if several localities connected to the same transmission line plan to electrify. Electrification and efficiency improvements can contribute to reducing the onsite energy related emissions with up to 86 % per kg produced salmon. To enable electrification of the work vessel is the most important measure for reaching the emission reduction.

The salmon farming industry has a goal of a fivefold increase in production by 2050. Even with this growth the results indicate that electrification and efficiency measures are necessary to decrease the onsite energy related emission in line with national mitigation target in 2030. Additional mitigation measures are needed to reach the 2050 mitigation target.

Sammendrag

Elektrisk kraftforsyning til oppdrettsanlegg for laks dekkes i dag av dieselaggregater eller ved tilkobling til landstrøm. Det er ønskelig å øke andelen av oppdrettslokaliteter koblet på landstrøm for å redusere klimagassutslipp i takt med nasjonale klimamål. Oppdrettslokaliteter ligger ofte i områder hvor kraftnettet har begrenset kapasitet noe som kan gjøre det kostbart å elektrifisere.

Denne studien har kartlagt energi- og effektbruken til de lokalitets-spesifikke aktivitetene i lakseoppdrett samt kartlagt lokale forutsetninger for tilkobling av oppdrettsanlegg til landstrøm i Trøndelag.

Kartlegging av energibruken til de ulike lokalitetene viste stor variasjon og et gjennomsnittlig forbruk på 0,35 kWh/kg produsert laks. 50% av lokalitetene i Trøndelag er i dag elektrifisert og de energirelaterte klimagassutslippene er 0,086 kg CO_2eq/kg produsert laks. Andelen av elektrifiserte lokaliteter kan økes fra 50% til 83% uten ekstra kostander i form av anleggsbidrag. Energieffektivisering av fôrflåten er avgjørende for å øke andelen av elektrifiserte lokaliteter, spesielt hvis flere lokaliteter kobles på samme kraftlinje når de elektrifiseres. Energieffektivisering og elektrifisering av oppdrettsnæringen i Trøndelag kan bidra til å redusere de energirelaterte klimagassutslippene med 86%. Arbeidsbåten er den mest utslippsintensive operasjonen og har dermed størst potensiale til å bidra med utslippsreduksjon. Havbruksnæringen har som mål å femdoble produksjonen av laks og ørret mot 2050. Selv med denne veksten, kan elektrifisering og energieffektiviseringstiltak være et viktig tiltak for å redusere energirelaterte klimagassutslipp med 40% innen 2030. Ytterligere tiltak er nødvendig for å nå målet om en 80-95% reduksjon innen 2050.

Preface

This master thesis concludes my M.Sc at the Department of Energy and Process Engineering at NTNU. The thesis is the continued work of the specialisation project written the autumn of 2018.

The thesis has been dependent on data collection from salmon farming localities, and several people have been of importance for this work. I would like to thank Monicha Seternes, Line Rønningen, Merete Sandberg and Arnt Erik Tronvold for providing data on the energy demand of salmon farming localities. I would also like to thank Leon Erik Heinesen for providing data on the power demand of existing feed barges.

The analysation of the electrification potential would not have been possible without the help of the power grid companies with area concession in Trøndelag. Large thanks to Rune Paulsen, Hilde Rollefsen Næss, and Oda Andrea Hjelme in NTE, and Per Osen in Trønder Energi for taking the time to conduct this analysis.

In addition, I would like to thank Ole Svendgård, Kari Tyholt, Brage Mo, Ragnar Sæternes, and Marit Sandbakk for including me in discussions around the topic and providing me with important insights.

Special thanks go to my supervisor, Johan Berg Pettersen, for the continuous guidance and inspiration.

List of Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

Atlantic salmon farming is the second largest exporting industry in Norway and stands for a considerable amount of energy use, of which a significant amount is based on fossil fuels (Fiskeridirektoratet, 2017a). Norway is committed to a reduction of greenhouse gas (GHG) emissions through the Paris Agreement and thus dedicated to a target of an at least 40 % reduction of GHGs within 2030, compared to 1990 levels. In 2050, Norway should be a low carbon society with an 80-95 % reduction of GHG emissions in comparison to 1990 levels (Klimaloven, 2017). This requires action from all industries, including the aquaculture industry. In addition, a parliament proposal is setting high standards to new salmon farming localities and proposes that all new localities and their respective vessels are to be operated with zero emission technology or renewable fuel within 2020 (Lysbassen, Haltbrekken, Kaski, Nævra, & Fylkesnes, 2017). Given the high priority this has on the political agenda there is a large need for energy efficiency improvements and implementation of renewable energy sources in the aquaculture industry.

The marine operations of salmon farming are dependent on fossil fuels and consist of onsite operations including the feed barge and locality specific vessels. In addition to the onsite operations the well boat and other bulk vessel also stand for a considerable amount of fossil fuel demand. The feed barge is the most central process, and a decarbonisation of it allows for a further decarbonisation of the locality specific vessels. Results from previous research indicates that energy efficiency improvements and electrification of the feed barge and locality specific vessels can with good margins fulfil the industry's contribution to the climate mitigation goals (ABB & Bellona, 2018; DNV-GL, 2018; Møller, 2018). Electrification of the feed barge is in this study defined as connection to the mainland grid and electrification of vessels is defined as electric motors and battery packs which are charged by electricity from the mainland grid. Energy efficiency improvements are defined as components or processes which reduces the power and energy demand of an operation.

Energy demand and energy carriers in the aquaculture industry are mostly unknown and is a field with little research (Møller, 2018). This may lead to non-optimal solutions and challenges for the salmon farming companies, technology suppliers, and energy suppliers. There is a large need for acquisition of knowledge on the energy use in the aquaculture industry and understanding the operations that drives it.

In 2018, two reports were published on electrification of the salmon farming industry (ABB & Bellona, 2018; DNV-GL, 2018). ABB and Bellona (2018) studied the emission reduction potential of the onsite energy demand of salmon farming localities in Norway, including the energy demand of the locality specific operations of the well boat. The study found electrification of the locality specific operations to have a potential emission reduction equivalent to 180 000 passenger vehicles. The study was based on energy demand data for one company and several assumptions were made to quantify the emission reduction potential. DNV-GL (2018) studied the economic aspects regarding electrification of the feed barge and work vessel and found that 80 % of feed barges in Norway can be electrified profitably. However, no specifications were given on which localities this was the case for.

These studies have assumed that the energy and power demand of the localities could be delivered by the power grid companies. There are however several conditions which must be in place for electrification to be feasible. This has been left out of the scope of the previous studies. The local distribution grid must be able to deliver the power demand of the new loads of the salmon farming localities without reducing the security of supply for the remaining energy customers. As the salmon farming localities are situated along the coastline, often in less populated areas, the grid is not dimensioned for high loads. In this case, the salmon farming companies must pay for the grid investments they trigger which reduces the potential economic savings from the electrification process (NVE, 2015a, 2015b). There is a need for a systematic review of differences in the local technical conditions with regards to connecting to the mainland grid and a mapping of the potential for electrification of operations connected to the salmon farming industry.

In order to study the electrification potential of the onsite operations in the salmon farming industry, a mapping of the energy and power demand is needed. Power demand is defined as the electricity use in a moment and is the dimensioning factor for the power grid (NVE, 2016a). When new energy customers are connected to the power grid, the power demand of the new load must be known (NVE, 2016a; OED, 2019). Localities with a lower power demand have fewer barriers of electrification as the impact of the load causes less disturbances on the grid. Lowering the power demand of localities can thereby open up for further electrification in areas where the grid is too weak to deliver the original load of the locality. Power reductions can be achieved through energy efficiency improvements for the components and processes on a salmon farming locality.

1.2 Objectives

This thesis aims at providing a better understanding of the energy demand of the onsite operations in the aquaculture industry. The onsite operations include the feed barge and locality specific vessels. To minimize the uncertainty of the results it is important that real data from the salmon farming industry is used. The lack of data availability on the energy demand of salmon farming resulted in the geographical scope of the study being set to Trøndelag. Trøndelag stands for 25 % of the salmon production in Norway (Fiskeridirektoratet, 2019). Furthermore, the goal is to assess the electrification potential of salmon farming localities in Trøndelag and assess how reducing the power demand through energy efficiency improvements can increase the electrification potential. The electrification potential will be assessed for the salmon farming localities which are not connected to the mainland grid and will include electrification of the feed barge and locality specific vessel. The electrification potential will be studied based on the local technical barriers of the existing grid which implies that the new connection should not trigger grid investment. This will identify the low hanging fruits when it comes to decarbonising the salmon farming industry and the results can be directly integrated into strategies for decarbonizing the industry.

1.3 Problem formulation and research questions

This thesis aims at answering the following research questions:

- What is the energy demand of the onsite operations of salmon farming in Trøndelag and which operational requirements drives it?
- What is the electrification potential of salmon farming localities in Trøndelag when considering local technical barriers of the existing power grid?
- Which energy efficiency measures for the feed barge exist on the market today and to what extent can they contribute to reducing the power demand of the salmon farming localities with the purpose to enable electrification?
- To which degree can electrification and energy efficiency improvements contribute to emission reduction in line with the national mitigation targets?

1.4 Methodology

The steps taken to answer the research questions and achieve the objective of the study are:

1. Collect data on the energy demand and carriers of the onsite operations of salmon farming in Trøndelag and map the results using geographical information systems (GIS).
2. Disaggregate the energy demand data to understand the operations that drives the energy demand.
3. Calculate the related carbon footprint for the onsite energy demand of salmon farming localities.
4. Collect data for the power demand of existing feed barges.
5. Research and collect data on energy efficiency improvements for feed barges.
6. Scale the power demand to the production capacity of all non-electrified localities for a base case and efficiency scenario.
7. Map the power demand and connection point to the grid in GIS for all non-electrified localities.
8. Analyse the electrification potential of the non-electrified localities considering local technical barriers of the grid. This analysis will be conducted through collaboration with power grid companies with area concession of Trøndelag.
9. Use the results on the electrification potential and energy demand to analyse the emission reduction potential and compare to the national mitigation goals.

Numerous people have been contacted for this report both for data collection (step 1,4,8) and general discussion (step 1, 2, 5, 6, 8, 9). These are listed in Table B 1 in appendix B.

1.5 Outline

The report consists of five chapter including the introduction. Chapter 2 introduces the salmon farming industry and describes the operations that drive the energy demand of a salmon farm. In addition, the technical aspects of electrification and the barriers for the power grid are explained. Chapter 3 describes the methodology used when analysing the energy and power demand of the salmon farming localities as well as the carbon footprint and electrification potential. Chapter 4 presents and interprets the results. Chapter 5 concludes the findings and summarises the results. The report has two appendixes where Appendix A gives more detailed data and visualisations of the electrification potential in Trøndelag and appendix B contains additional material for the results and discussion.

2 Theory and Literature

Chapter 2 will present relevant theory about the energy demand and electrification of the processes in the aquaculture industry. It starts with an introduction to the salmon farming industry and its environmental concerns. Thereafter, earlier research on energy demand and carbon footprint is presented and an in-depth description of the energy demand of a salmon farming locality is given. The chapter continues with a description of the electricity grid and the technical aspects of electrification. Chapter 2.1, 2.2, 2.3.1, and 2.6 is based on the project thesis leading up to this research (Møller, 2018).

2.1 The salmon farming industry

In Norway, the Atlantic salmon farming industry had its start in the 1970s and has since then grown into one of Norway's largest industries (FAO, 2018). Norway supplies almost half the global production volume of salmon and has had an annual growth of 8 % since 1990 (Marine Harvest, 2018; Syse, 2016). This growth has been made possible due to the ideal conditions for salmon farming in Norway, with its long coastline and cold water. The ideal temperature range for Atlantic salmon is 8-14 °C (Marine Harvest, 2018).

Salmon farms are scattered along the Norwegian coastline, divided into 13 different production areas. The production areas are a consequence of the production area regulation which came into force in 2017, referred to as the traffic light system (Produksjonsområdeforskriften, 2017). Within each of the production areas, the industry's environmental impact is assessed in the form of how salmon lice affect the wild salmon. The production areas are labelled green, yellow or red based on the environmental situation. This sets the premises for future growth for the salmon farming localities (EY, 2017). If the environmental impact is acceptable (green) a growth of up to 6 % can be assigned. If the environmental impact is moderate (yellow) the capacity is frozen and if the environmental impact is unacceptable (red) the capacity must be lowered by 6 % (Regjeringen, 2019).

In 2018 there were 837 active salmon farming localities in Norway and the number of localities in operations varies every year (Fiskeridirektoratet, 2019). The aquaculture industry is a permit-based industry where the permits are restricted and must be applied for. Each permit is delimited a maximum allowed biomass (MTB) on two levels; company and locality. The MTB system means that the holder cannot at any time have a standing biomass (number of kg live fish in seawater) that exceeds the permitted MTB at company and locality level. The normal size of a permit is 780 tonnes and most localities have a production capacity between 780 tonnes – 7020 tonnes, however some larger localities exist (Fiskeridirektoratet, 2017b).

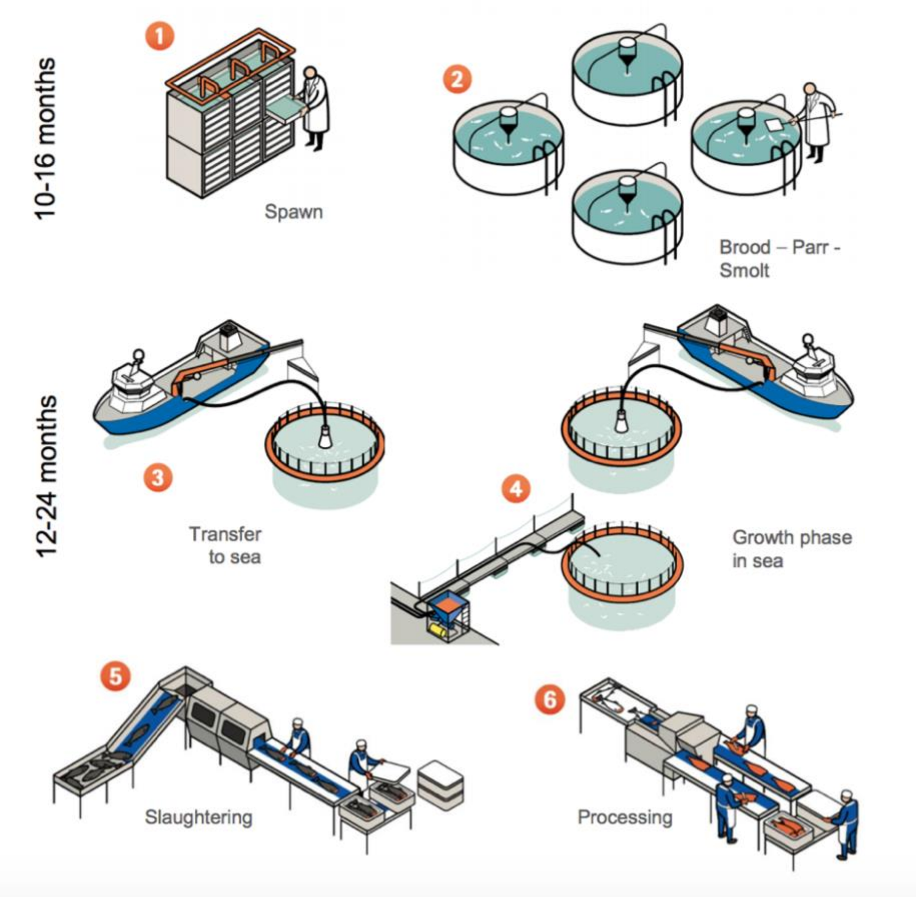


Figure 1: Production cycle of Atlantic salmon farming (Marine Harvest, 2018)

Atlantic salmon farming has a production cycle which can be seen in Figure 1. A production cycle lasts for approximately three years where the main part of the cycle is the seawater production. The production cycle starts by fertilizing the eggs. The fish are thereby transferred to a controlled freshwater system where they grow to be 100-150 grams (Marine Harvest, 2018). The controlled freshwater environment is based on land and is either a Flow Through or Recirculating Aquaculture System (RAS) (Bjørndal, Holte, Hilmarsen, & Tusvik, 2018). Once the fish have adapted to seawater they are transferred by a well boat to the seawater phase. This is conducted twice a year, in spring or autumn and is the main part of the cycle. The duration time of the seawater phase is between one and two years and depends on the seawater temperatures, feed ratios and individual differences. In the seawater phase, the salmon are kept in open net pens connected to a feed barge where they are fed through feeding hoses (Marine Harvest, 2018). The transportation of the feed to the feed barge is conducted with large bulk vessels (Berge, 2013).

The growth phase in sea requires services and routine operations which are conducted with three different vessels; work, transport and service vessels (DNV-GL, 2018). The salmon farming company owns two of the vessels, the transport and work vessel. The work vessel is under 15 meters and used for hosing of the pens, small delousing processes and other routine operations whereas the transport vessel is used for transporting people from the harbour to the pens. The service vessel, which is most commonly a well boat, is hired for larger operations including delousing, handling moorings and complicated lifts (DNV-GL, 2018).

A well boat is used for transporting the salmon for slaughtering and processing once they reach a weight of 4-5 kg. Once the salmon are removed from the pens, the localities are fallowed for a set time-period before starting a new production cycle. This reduces the risk of disease spreading (Werkman, Green, Murray, & Turnbull, 2010).

2.2 Environmental concerns in the aquaculture industry

Salmon farming causes environmental impacts both locally and globally. The main environmental concerns of the industry are summarised in Table 1 and are mostly focused on local impacts on the wild salmon population and direct impact on the surrounding environment.

Table 1: Environmental concerns in the Atlantic salmon farming industry (Miljødirektoratet, 2015)

Environmental concern	Consequence	Source
Escaped salmon	Interbreeding with wild salmon causing disease spreading and genetic diversity.	(Forseth et al., 2017; Taranger et al., 2015)
Salmon lice	Mortality of farmed salmon and risk of salmon lice infestation for wild salmon.	(Liu & Bjelland, 2014)
Discharges from pens	Pollution of faecal waste and uneaten feed impacts local ecosystem.	(Taranger et al., 2015)

In addition to the above mentioned environmental concerns the salmon farming industry contributes to global climate change through its emissions of greenhouse gases. These greenhouse gas emissions are primarily connected to the direct farm based energy use, feed ingredients and transport operations (Winther et al., 2009).

The salmon farming industry wishes to decrease its environmental impacts and has a goal of being Norway's most important industry in contribution to the sustainability development goals (SDGs) (SjømatNorge, 2018). Seafood Norway, which is the national association for over 600 salmon farming companies, have identified eight SDGs they aim at contributing to while doubling their production towards 2030 (SjømatNorge, 2018). The goals are focused on the triple bottom line of sustainability and are presented in Figure 2.

Environmental sustainability

Figure 2: Sustainable development goals which the aquaculture industry aims at contributing to towards 2030 (SjømatNorge, 2018)

A set of actions have been identified for the industry to contribute to the goals in Figure 2. The actions towards contributing to the environmental focused SDGs are focused on escaped salmon, discharges to water, and reducing the environmental and climate footprint of the industry. The negative impact on the wild salmon populations is to be reduced through monitoring salmon lice and tracing escaped salmon. The environmental footprint is to be decreased by increasing the fraction of animal and vegetable by-products in fish feed. The climate footprint will be reduced by a focus on energy efficiency, reduction in the use of fossil fuels, choice of refrigerants and choice of feed ingredients. Lastly, the aquaculture industry aims at promoting sustainable development through reducing discharges that threaten marine ecosystems, clean-up activities and environmental documentation through the value chain (SjømatNorge, 2018). The actions towards contributing to the social and economic focused SDGs are focused on increasing global food production, increasing Norwegian value creation and improving living standards.

Reducing the environmental impacts of the industry is somewhat a focus as it sets the premise for allowed growth in the different production areas (Produksjonsområdeforskriften, 2017). The challenges and ambitions of the industry have led to innovations in technology and production methods. Offshore fish farms, land-based fish farms and closed cage ocean farming are all technological innovations under development which will reduce the environmental challenges summarised in Table 1. Figure 3 shows the predictions of the future innovations in the salmon farming industry (Terjesen, 2017).

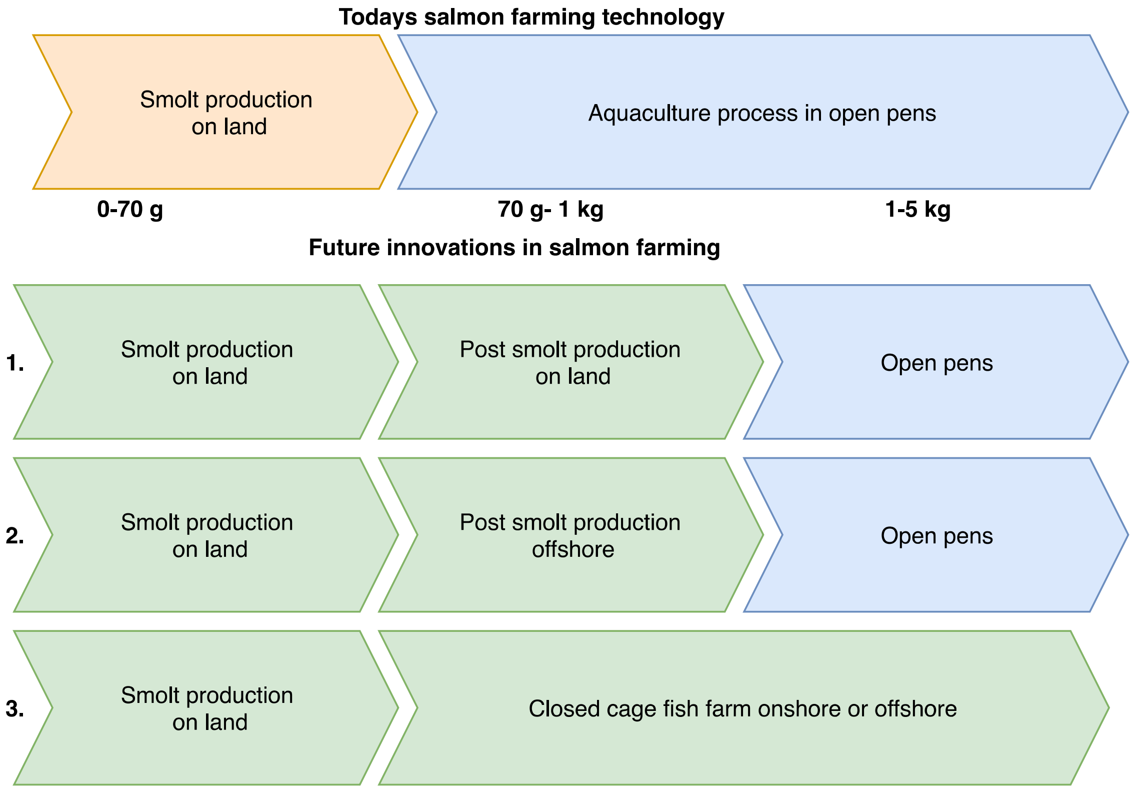


Figure 3: Current salmon farming technology and future predicted innovations in salmon farming. Formatted from Terjesen (Terjesen, 2017)

In addition to innovative production methods, there is a strong focus in the industry on reducing the climate change impacts by changing the energy carrier of the marine operations. Electrification is an established method for both increasing the energy efficiency and reducing the emissions of production in the salmon farming industry. This is due to the low carbon intensity of the Norwegian electricity mix which is primarily based on hydropower (Energi Norge, 2019a). Around 80 localities in Norway have applied for financial support through the state-owned Enova SF for electrification of the feed barge (Sandbakk, 2018).

Electrification of the feed barge is central in reducing the environmental impact of the industry as it allows for further electrification of vessels. For electrification to be possible an understanding of the energy use of the salmon farms is needed. This will be further elaborated in the next chapter.

2.3 Energy use

2.3.1 Current knowledge on energy use and greenhouse gas emissions in the salmon farming industry

Life Cycle Assessment (LCA) is a tool for assessing the full life cycle impacts of a product or service and can be used to better understand where in a production process the emissions are occurring (Curran, 2016). Several LCAs on the environmental impact of Atlantic salmon farming have been conducted (Ellingsen, Olaussen, & Utne, 2009; E. Hognes, Ziegler, & Sund, 2011; E. S. N. Hognes, Katarina; Sund,Veronica; Ziegler, Friederike, 2014; N. Pelletier & Tyedmers, 2007; Nathan Pelletier et al., 2009; Winther et al., 2009; Ziegler et al., 2013). The research has found the carbon footprint of Atlantic salmon farming to be 2.0 kg CO_2 per kg live weight salmon at farm gate (Nathan Pelletier et al., 2009; Winther et al., 2009).

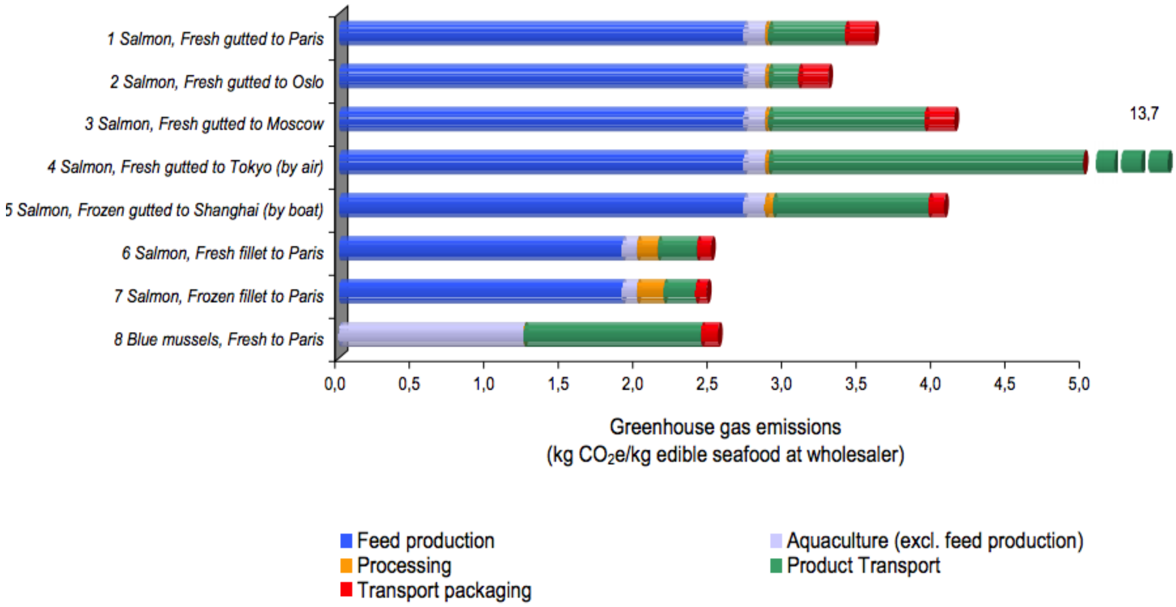


Figure 4: LCA results of the greenhouse gas emission caused by Atlantic salmon farming in Norway (Winther et al., 2009)

Figure 4 shows the LCA results of the greenhouse gas emissions from farmed Atlantic salmon transported to different locations (Winther et al., 2009). Feed production is the process dominating the impact when the salmon are not transported by air to wholesaler. The emissions from the product transport are influenced by the transport time, distance and mode (truck, ship, aircraft) as well as need for refrigeration (Ziegler et al., 2013).

The emissions from feed production are dependent on the composition of the salmon feed which is a combination of marine and vegetable ingredients. In 2010, the marine ingredients contributed with 39 % of the carbon footprint whereas the vegetable ingredients contributed with 47 % (E. Hognes et al., 2011). The carbon emissions from the marine ingredients stem from the fossil fuels used in the fisheries and the emissions of agricultural ingredients stem from emissions of methane and dinitrogen oxide in the agriculture processes (N. Pelletier & Tyedmers, 2007).

Energy use in the salmon farming industry is the focus of this study and a field with little research. The data that exists on the energy demand of the value chain of salmon farming has large variability, especially for the process smolt production and the feed barge (Møller, 2018). Two studies have analysed the cumulative energy demand (CED) per kg live weight salmon at farm gate (Ziegler & Hornborg, 2014). The CED was found to be 26 MJ/kg (Nathan Pelletier et al., 2009) and 28 MJ/ kg (Ziegler et al., 2013). The energy demand is similarly to the carbon footprint dominated by the feed production.

The project thesis leading up to this research studied the direct energy demand and respective emissions of the value chain of salmon farming. The study collected data from literature and found the transport operations of the well boat to have the highest energy demand and carbon footprint. The feed barge, in addition to the work vessel were important contributors to the energy demand and carbon footprint. Electrification measures for the feed barge, work vessel and well boat were found to have a potential of reducing the annual emissions from the salmon farming industry in Norway with 445 000 tonnes

CO_2eq. Of these processes, the feed barge was the most important process to electrify as it must be electrified in order for the locality specific vessels to electrify (Møller, 2018).

2.3.2 Energy use on a salmon farm locality

A salmon farming locality is centred around the feed barge and has a layout as can be seen in Figure 5. The pens, where the fish are grown, are typically made of plastic and the number of pens vary between localities based on the production capacity. The pens are connected to the feed barge through feeding hoses and contain technical equipment such as cage lights, underwater camera systems and environmental sensors (AkvaGroup, 2017). The feed barge is an installation containing a feeding system, control room, living section and equipment. In addition, salmon farming localities typically have two vessels, the transport and the work vessel, defined in Chapter 2.1.

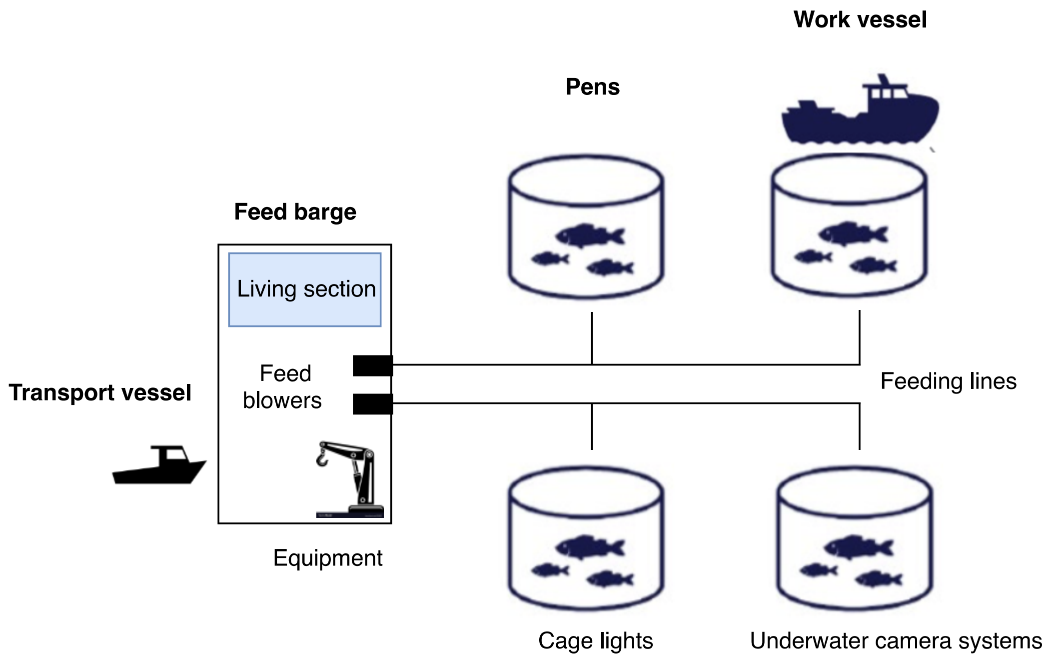


Figure 5: A typical salmon farming locality as seen from above

The onsite operations in salmon farming are energy intensive and both the feed barge and the locality specific vessels require energy. Diesel is the most common energy carrier for the work vessel, although one electric work vessel is on the market today (Soltveit, 2017). The transport vessel uses gasoline as its energy carrier and the feed barge has electricity or diesel as their main energy carrier. The electrified localities are connected to the mainland grid through subsea cables and the non-electrified localities use diesel generators to provide electricity. It has been estimated that 50 % of the localities in Norway are electrified (ABB & Bellona, 2018). The energy demanding components on the feed barge are described in Table 2.

Table 2: A description of the energy demanding components on the feed barge of a salmon farming locality

Components	Description	Sources
Feeding system	Silos containing pellets are connected to feed blowers generating transport air. The pellets are blown through plastic feeding hoses by compressed air generated by the blowers. The hoses stretch to each sea cage and have spreaders at the end which distributes the feed. One feed blowers per feeding line is required which each have a power demand of 22 or 30 kW.	(AkvaGroup, 2017; Heinesen, 2019; Holt, 2017; Syse, 2016; Wiken, 2018)
Cage lights	The farming cages use underwater lights to reduce maturation and increase growth. The lights are used in the winter months and are mostly metal halogen lights.	(AkvaGroup, 2017, 2019b; Steinsvik, 2019b)
Living section	The feed barges have a living section requiring heat and light. The heat is the most energy requiring element and is delivered through panel ovens.	(Heinesen, 2019; Syse, 2016)
Equipment	*Dead fish handling system*: The dead fish handling system is used to grind the dead fish from the pens and has a power demand of 14 kW. *Crane*: The crane is used for various lifts and other work and is usually 30 kW. *Camera system*: Underwater and surface cameras are used to monitor the feeding activity, fish behaviour, and sea lice. The power demand of the camera system can vary from 0,5 – 10 kW depending on the number of cages.	(AkvaGroup, 2017; Heinesen, 2019; Skov & Andreassen, 2018; Steinsvik, 2019a)

The energy use on the feed barge has daily and seasonal variations. The energy demand of the components on an existing feed barge has been made available by a salmon farming company. This data has been used to compile a consumption profile for a feed barge at a salmon farm locality with a production capacity of 3120 tonnes for a typical day in summer (July) and winter (February), shown in Figure 6a and Figure 6b respectively. The feed barge has four feeding hoses with a peak power demand of 22 kW which run at approximately 50 % of nominal power during feeding hours making the total power demand of the feeding system between 40-50 kW.

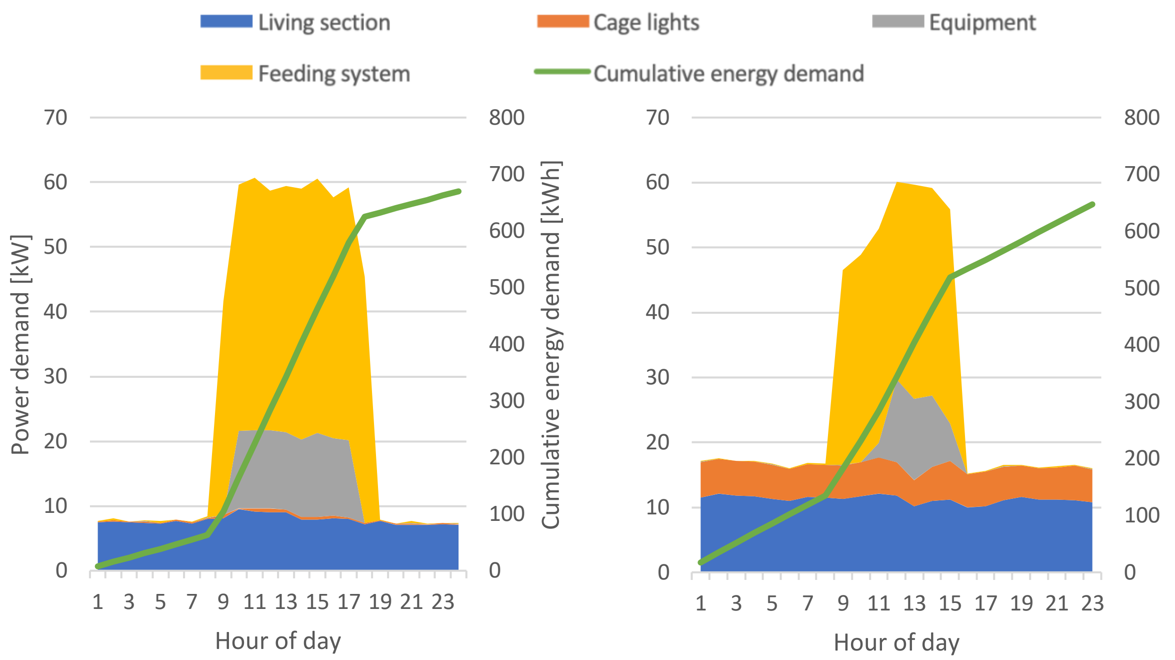


Figure 6a: Consumption profile for one typical day in summer for a fish farm with a production capacity of 3120 tonnes. The consumption profile is shown for the second year in the production cycle.

Figure 6b: Consumption profile for a typical day in winter for a fish farm with a production capacity of 3120 tonnes. The consumption profile is shown for the second year in the production cycle.

The energy demand of the feed barge varies between summer and winter. The growth rate of the salmon is strongly correlated to sea water temperatures and the salmon grow at a higher rate in summer (Hermansen & Heen, 2012). This leads to longer feeding hours and thereby a higher CED of the feeding system in the summer. Lights and residential systems have decreased energy use in the summer due to the longer light hours and increased temperatures. The use of equipment will vary depending on the amount of dead-fish and other challenges for the locality. The dead-fish increases with salmon lice which reproduces fastest in the summer when its warm in the sea (Mattilsynet, 2016). This leads to higher energy demand of the equipment in the spring and summer. The total cumulative energy demand of the locality is dominated by the feeding system and is highest in the summer.

The energy demand of a salmon farming feed barge does not only vary between seasons, but also varies throughout the production cycle. The energy demand of a salmon farm increases as the feed intake increases with the size of the salmon (Marafioti, Alfredsen, & Alver, 2012). The increased feed intake leads to a higher energy demand of the feeding system and thereby an increased energy demand for the feed barge. The consumption profiles shown above are for the second year in the production cycle, the same year the salmon are slaughtered.

The consumption profile for a locality is similar for all salmon farms, however the power demand will vary depending on the production capacity of the locality. When the production capacity of a locality increases the number of pens increases linearly. This leads to an increased power demand of cage lights and feeding system as one feed blower is required per feeding line. The power demand of the living section will also increase with the size of the feed barge. The power demand of the equipment is more constant between localities as there are few variations in the power demand of the equipment on the market (Heinesen, 2019).

A salmon farming locality also requires operations from two locality specific vessels and other vessels hired for specific operations. The scope of this study includes the locality specific vessels which are the transport and work vessel. The consumption profile for the work vessel will vary between localities and specific demand. The work vessel is energy demanding both during transport and when it's docked to the pens. The power demand of the work operations is 100 kW and the vessel has operating hours between 7.30-17.30 (DNV-GL, 2018; Stensvold, 2017).

2.4 Energy efficiency improvements on the feed barge

The energy demand of a salmon farming locality can be reduced through energy efficiency improvements on the feed barge. Efficiency improvements reduces the power demand of components which is also beneficial with regards to electrification. This section describes energy efficiency improvements available on the market today.

Underwater feeding

Underwater feeding has been in development by Akvagroup since 2013/14. In the underwater feeding system, the fish are fed at 7 meters deep where they are less exposed to lice. The feed is transported through regular feeding hoses by pumping deep water into the main pipe. This reduces the energy demand of the underwater feeding system in comparison to the regular feeding system which uses compressed air to transport the feed (AkvaGroup, 2015). In traditional feeding systems one blower of 22 or 30 kW per feeding line is required whereas underwater feeding systems require one pump of 11 kW per feeding line. The power demand is thereby reduced with 50-60 % per feeding line (Erikstad, 2019; Wiken, 2018). The underwater feeding systems also has other benefits as the wear on the feeding hoses is reduced which contributes positively regarding the micro plastic focus in the industry.

LED lights

Metal halogen lights used in today's system can be replaced with LED lights. LED lights have a reduced power demand of 60 % and in addition allows for dimming and has twice the lifetime of metal halogen lights. Several LED lights for pens are available on the market today ranging from 400 W to 1200 W (AkvaGroup, 2019b; Steinsvik, 2019b).

Heat pump

The living system requires light and heating and stands for a substantial amount of the energy demand, especially in winter. The heating system is today delivered by electronic heating in form of panel ovens. The heating system can be replaced with water to water heat pumps. Heat pumps can reduce the installed capacity of the feed barge as they can deliver between 1,5 – 4,5 times the load they require from the grid. The installed capacity is dimensioned for the coldest days when the power factor for the heat pump is reduced (NVE, 2016b). It can be assumed that 75 % of the power demand in the living section is due to the heating system. A heat pump thereby reduces the installed power demand of the living section with 40 % (Haugerud, 2015; NVE, 2016b; VPI, 2019)

Battery storage

In addition to increasing the energy efficiency of the components on the feed barge, the power demand can be reduced through peak shaving with battery packs. The consumption profile for feeding barges follows a flat profile for hours 00:00-08:00 and 16:00-24:00. Between 08:00-16:00 the power demand increases due to the feeding system and equipment being used (Figure 6a and Figure 6b). To reduce the peak load the battery pack can charge at hours with lower demand and be used between 08:00-16:00 when the power demand is high. This enables power consumption over the capacity ceiling of the grid and thereby no constraints are put on electrification of equipment and charging infrastructure for vessels. Batteries can also be used for non-electrified feed barges which wishes to reduce their diesel use. The batteries can then charge during feeding hours and deliver electricity outside the feeding hours when the load is lower (ABB & Bellona, 2018).

Lithium-ion battery packs of 120 kW with a storage capacity of 158,4 kWh are made available from e.g. Akvagroup (AkvaGroup, 2019a). For the locality depicted in Figure 6a and Figure 6b the battery can deliver 23% of the energy demand, if one battery pack is installed. The fraction will increase for smaller localities and decrease for larger localities. Larger localities can increase the number of battery packs on the feed barge to decrease their energy demand.

2.5 The Norwegian electricity grid

Availability of grid power is a prerequisite for electrification. In order to analyse the electrification potential of salmon farming localities the barriers of the power grid must be understood. The electricity grid enables transport of electricity from generation sources to households and other end users. The electricity grid in Norway is split between three voltage levels and can be seen in Figure 7.

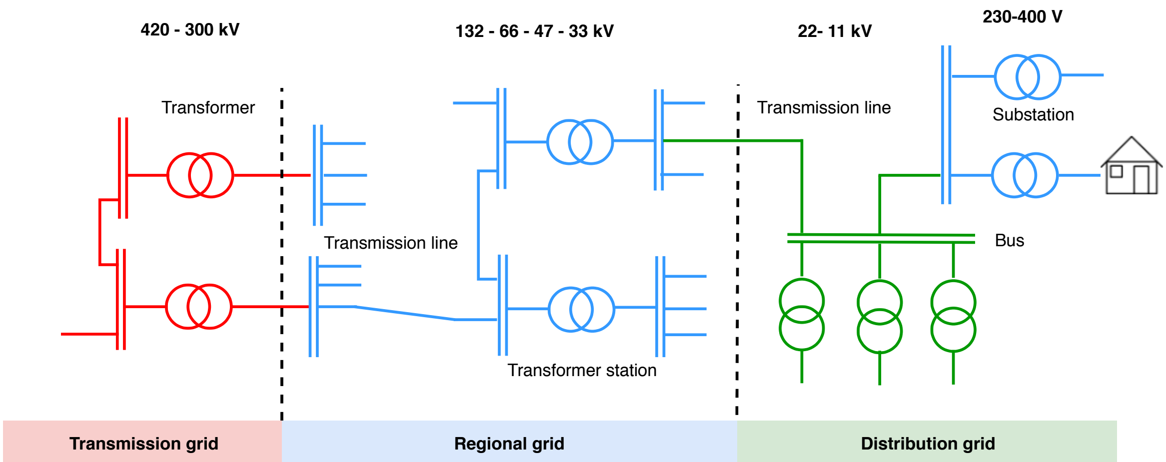


Figure 7: Visualisation of the electricity grid structure in Norway. Formatted from Energi Norge (Energi Norge, 2019b)

The transmission grid is the backbone of the Norwegian power grid and allows for transport of electricity over large distances. The regional grid has a lower voltage level and is the interconnection between the transmission and the distribution grid. The distribution grid supplies end users with electricity and is divided into high and low voltage segments (Energi Norge, 2019b). The high voltage segments have a voltage level of 1-22 kV and the low-voltage distribution has a voltage level of 230 or 400 V (NVE, 2019). The grid levels are interconnected with transformers which reduces and increases the voltage. Substations are small transformer stations which reduced the voltage to 230-400 V. From the transformer stations several transmission lines emerge and distribute power to suppliers.

Norway is divided into geographical areas where different grid companies own and operate the electrical distribution networks with voltage up to 22 kV. The grid companies have monopoly on transmission of electricity in an area, and this monopoly is matched by a delivery obligation (NVE, 2015b; Olje- og energidepartementet, 1990). When new customers connect to the grid, the required power of their load must be known, as power is the dimensioning factor for the grid (NVE, 2016a).

Customers are not entitled to free access to the power grid and the grid companies will require an investment contribution for the cost that are a result of the new connection (NVE, 2015a). The investment costs of a new connection are dependent on how the new connection reduces the power grid companies' ability to continuously supply end users with electricity of a specified quality. The supplied electricity must maintain a specified quality identified by the supply quality regulation [1] .The supply quality regulation includes specifications for how much the voltage and frequency can deviate from the standard value before the grid companies must implement actions to reduce the deviations (Olje- og energidepartementet, 2004).

A new grid connection will influence the security of the supply for the customers connected to the same transmission line (H. R. Næss, 2019). The impact the new connection has depends on the power demand of the connection and the quality of the grid at the connection point. Most challenges occur for connection points far away from a transformer, connections with a high power demand and connection points in areas where the grid is weak (Grindheim, 2015). When the connection point is far from a transformer a voltage drop in the transmission line will occur. The voltage drop is proportional to the power demand and length of the line. Grid investment are needed if this voltage drop surpasses the specified allowed level in the supply quality regulation (Olje- og energidepartementet, 2004).

When a connection point is in an area where the grid is weak, several challenges such as low voltage, instantaneous voltage changes and excessive loads can occur (Torsæter & Kirkeby, 2017). The impact a new connection point has on the grid increases with the power demand as this can increase the losses and voltage changes. The grid is often weak in areas far from the generating sources and transformers, typically in less populated areas close to the shore.

New connection points can also trigger grid investments if the power demand of the new connection is not available from the grid. There is no shortage of energy supply in Norway, however, the transmission infrastructure set's a boundary for the amount of energy which can be used in a moment. If a load is connected to an area where this threshold is reached, new grid investments are needed. This can typically be on islands which are not dimensioned for high loads (Garbe, 2018).

Salmon farming localities are situated along the coastline, often in rural areas with weak grids. In addition, the production cycle requires energy demanding equipment described in Chapter 2.3.2. These factors can contribute to triggering grid investments if the localities are connected to the mainland grid.

2.6 Electrification potential

If salmon farming localities don't trigger significant grid investment, electrification can be an efficient way to reduce the onsite emissions (Møller, 2018). Electrification of the aquaculture industry is an established practise and approximately 50 % of the salmon farming localities are today electrified (ABB & Bellona, 2018). An electrified locality is defined as a locality which has a feed barge connected to the mainland grid.

[1] Forskrift om leveringskvalitet i kraftnettet (Olje- og energidepartementet, 2004)

The operations of interest to electrify are the marine operations which are today heavily based on fossil fuels. The feed barge is the most central process when it comes to electrification as it allows for further electrification of the locality specific vessels. The feed barge can be electrified through connection to the mainland power grid if the new connection does not threaten the security of supply for the remaining customers. Figure 8 shows the technical aspects of connecting the feed barge to the mainland grid. A subsea cable of 1 or 22 kV, depending on the voltage loss, is pulled from the feed barge to fitting infrastructure on land. The cable is here connected to a transformer where the voltage is transformed to the correct level. The transformer is then connected to the regional distribution grid (Hide, 2019).

Most feed barges have a TN-S (Terra Neutral-Switch) system meaning the line to line voltage is 400 V whereas the line to neutral is 230 V making it possible to connect both one and three phase loads to the barge (Holt, 2017). The subsea cable is connected to switchgear which ensures isolation of the electrical equipment. The switchgear is again connected to a transformer which transforms the voltage of the subsea cable (1/22 kV) to the used voltage on the feed barge (400 V) (Hide, 2019). If the subsea cable is 22 kV the feed barge requires a high voltage room where access to the room is limited to high voltage qualified personnel (Heinesen, 2019). The voltage level of the subsea cable is set depending on the voltage loss through the cable. The voltage loss should not exceed 5 % and increases with the length of the cable and power demand of the locality (Draka, 2010).

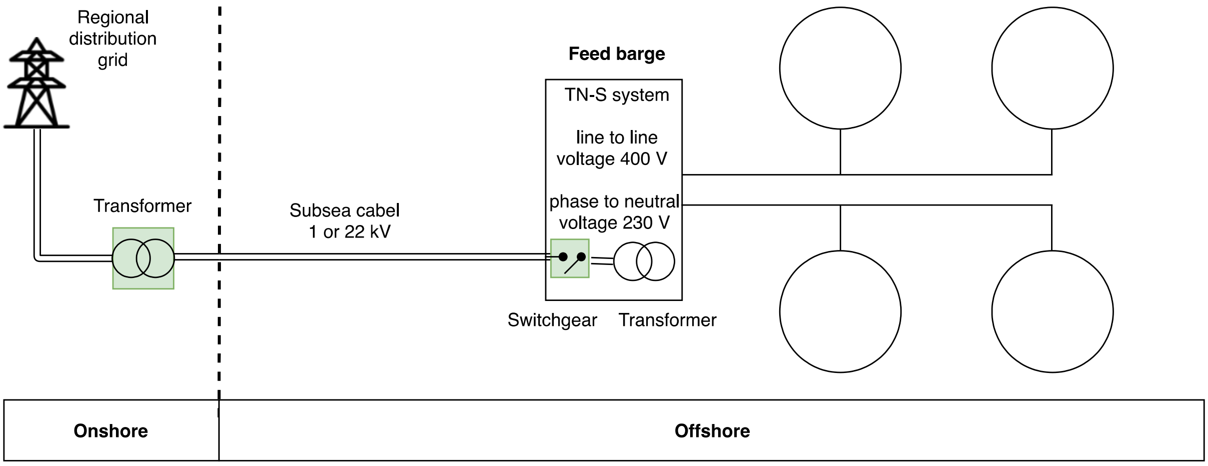


Figure 8: Technical aspects of electrification of the feed barge of a salmon farming locality.

DNV-GL have considered the costs from electrification of feed barges and found that 80 % of the localities in Norway can be electrified profitably (DNV-GL, 2018). The profitability is strongly dependent on the distance from the feed barge to the local grid as well as other factors including diesel and electricity price and the size of the feed barge.

The feed barges which have large barriers for electrification can be electrified through renewable energy production such as wind or PV installations on the locality (Holt, 2017; Syse, 2016; Wiken, 2018). A hybrid system, with a battery pack and diesel generator can also contribute to reducing emissions as the battery can charge during feeding hours and supply electricity at lower loads (ABB & Bellona, 2018).

In addition to the feed barge, the locality specific vessels can reduce its emissions through electrification. Electrification of the work vessels has been demonstrated by Elfrida which is the first electric work vessel used for aquaculture. Elfrida was seaborne in 2017 and is owned by Salmar. The vessel has a permanent magnet motor of 146 kWh as well as battery packs of 160 kWh (Soltveit, 2017). Even though electrification of the vessels is possible, the investment costs are high. The investment cost of Elfrida were 30 % higher than a regular work vessel (Soltveit, 2017). These costs have the potential of being reduced in the future, especially due to the rapid cost decrease in batteries.

The work vessel requires charging possibilities on the feed barge or circumference of the pens if the vessel is to become fully electrified. Fully electrified work vessels are thereby restricted to electrified localities. For non-electrified localities, the work vessel can become hybrid electric with charging possibilities on land. This can reduce the fuel use with 43 % (ABB & Bellona, 2018)

The energy demand of the transport vessel is substantially lower than the work vessel and the transport vessel can be electrified regardless of the energy carrier of the feed barge. Outboard engines and battery packs available today can electrify the transport vessel and charging stations on land are sufficient (ABB & Bellona, 2018).

Salmon farming also consists other marine operations based on fossil fuels such as the well boat and feed vessel. These vessels are hard to electrify due to the high power demand and duration time and have thereby been left out of the scope of the study. Other mitigation measures such as speed optimization, alternative fuels and vessel size can be considered for these operations (Bouman, Lindstad, Rialland, & Strømman, 2017).

Technology is available on the market to electrify the onsite operations of salmon farming. In order to allow for electrification grid power must be available at a specified quality. To test the availability of grid power the energy and power demand of the salmon farming localities must be understood as power demand is the dimensioning factor for the grid.

3 Methodology

Chapter 3 will describe the methodology used when analysing the energy demand, power demand, carbon footprint of onsite energy use and electrification potential of salmon farming in Trøndelag. The methodology firstly describes the goal and scope as well as the system boundary. Thereby, the work methodology is shown and the modelling of four major results are defined in more detail (energy demand model, carbon footprint of energy use, power demand model, and electrification potential).

3.1 Goal and scope

The main goal of the study is to map the electrification potential of the salmon farming localities in Trøndelag. Mapping the energy and power demand of the localities in Trøndelag is the second goal of the study as this is an immature field and a prerequisite when analysing the electrification potential. The locality specific energy demand includes the energy demand of the feed barge, work vessel and transport vessel. The results of the study can be used to identify the low hanging fruits of emission reduction in the salmon farming industry in Trøndelag. The results can be directly implemented by the salmon farming industry in Trøndelag and contribute to emission reduction of the industry.

The geographical scope of the study is set to Trøndelag, a county in mid Norway shown in Figure 9. The scope was set to allow for collection of real energy demand data as published data is lacking. The scope of the study when assessing the carbon footprint is scope 1 and 2 as the carbon footprint will consider purchased electricity (GHG Protocol, 2004). For the energy demand only direct energy demand is considered.

Figure 9: Trøndelag highlighted on a map of Norway (Finansdepartementet, 2018)

3.2 System boundary

The system boundary is focused around the onsite activities (feed barge, transport and work vessel) and is shown in Figure 10. This system boundary was set as electrification of the feed barge opens up for further electrification of the marine operations and is thereby the process electrification must be focused around. The marine operations are the main contributors to carbon emissions and the work and transport vessel are natural processes to electrify if the feed barge can be electrified (Møller, 2018). The system boundary is used throughout the study when analysing the electrification potential, the energy and power demand and the associated emissions with the onsite energy use.

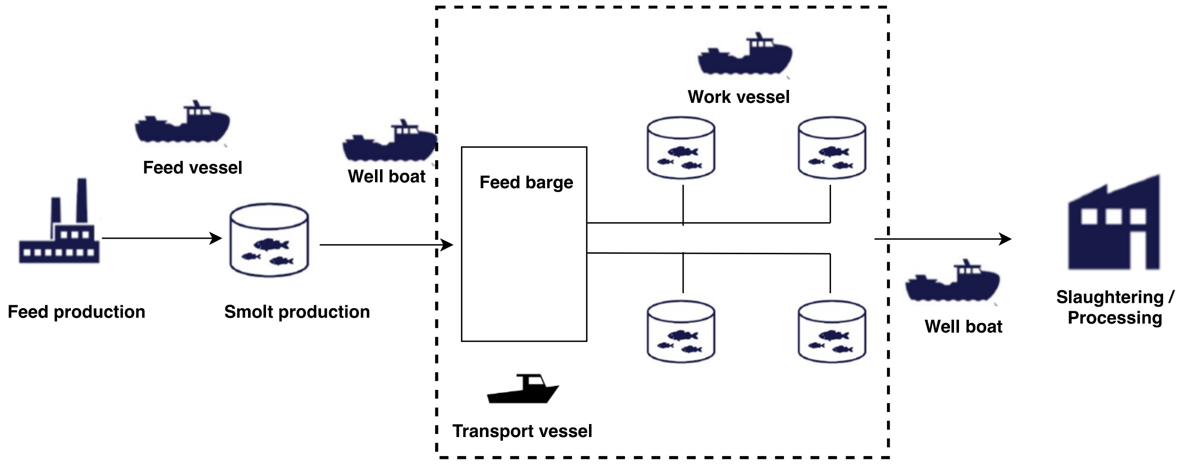


Figure 10: System boundary when analysing the electrification potential, energy and power demand. Icons from Enova.

3.3 Work methodology

The work methodology of this study is summarised in Figure 11. The work methodology consists of data collection, data analysation (mapping, modelling, calculation) and the use of analysed data from other companies. The study has been dependent on data collection from salmon farming companies as published data on energy demand for salmon farming localities is lacking (Møller, 2018). This resulted in a bottom up approach being used in the analysation.

The results are dependent on each other and have been analysed incrementally. First, a mapping of the localities in Trøndelag and their energy carrier was conducted in order to understand which localities has the potential for electrification. Second, data on the energy demand of the localities was collected and used to analyse which processes contributed to the energy demand. Third, the carbon footprint was calculated to understand which processes contribute to the direct onsite emissions. Fourth, data on the power demand of feed barges was collected as this is the dimensioning factor for the power grid and must be known if localities are to electrify. Fifth, efficiency improvements for the feed barge was studied to understand how the power demand could be reduced. Sixth, the power demand of all feed barges was modelled and mapped for all non-electrified localities for an efficiency and base case scenario. These results were handed over to power grid companies with area concession in Trøndelag whom analysed which localities could be electrified without triggering grid investment. The carbon footprint results for the onsite energy use and the results from the power grid companies were thereby used to calculate the emission reduction potential of electrification and energy efficiency improvements in Trøndelag. These results were compared to the national mitigation goals.

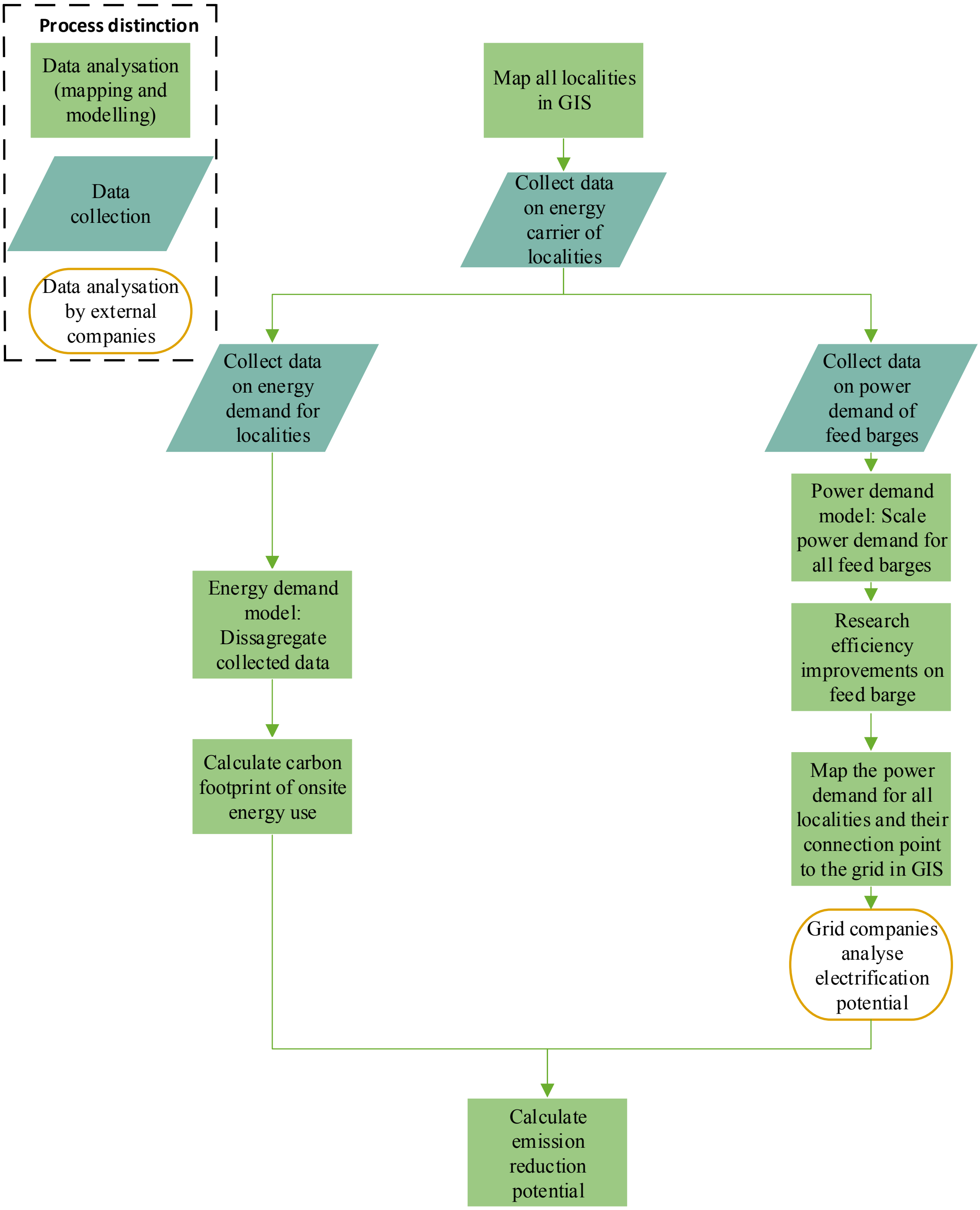


Figure 11: Work methodology

3.4 Energy demand model

The energy demand model is used to disaggregate the energy demand data which has been collected from salmon farming companies to get a better understanding of the distributed energy consumption on the locality.

3.4.1 Data

Data on the energy demand of salmon farming localities has been gathered from all large salmon farming companies in Trøndelag. The data collection includes the energy demand of the feed barge, work vessel and transport vessel. There are 139 salmon farming localities in Trøndelag, of which 106 are in use. All salmon farming companies were contacted and specific data was gathered for 51 localities which is 48 % of the localities in use in Trøndelag. Of these were 36 electrified and 15 were not. The localities for which no data was gathered for belong to smaller companies which either don’t collect energy demand data or did not have the capacity to withdraw the data.

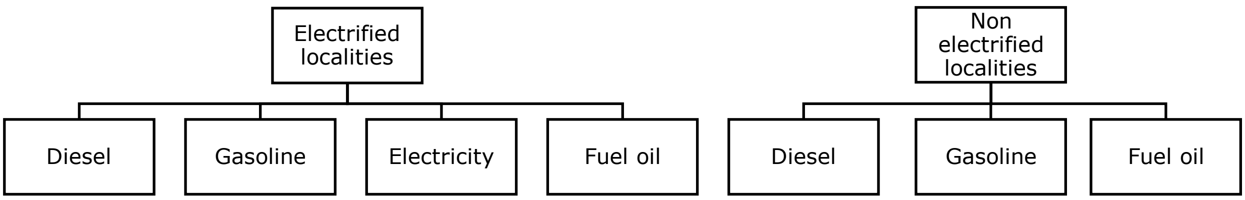


Figure 12: Detail level of collected data. The energy demand was distinguished between electrified and non-electrified localities and divided between their energy carriers.

The collected data has been distinguished between electrified and non-electrified localities, presented on a kWh basis split between energy carriers. The electrified localities have a feed barge connected to the mainland grid whereas the non-electrified localities use diesel generators for electricity supply. The data has been collected on a detail level shown in Figure 12. The collected energy demand data included the energy demand of the feed barge and locality specific vessels for one production cycle of one salmon generation which is approximately 2 years (Marine Harvest, 2018). The collected data is for production cycles with start in spring or autumn 2016 or 2017, and slaughter in 2018 or 2019.

The energy use depends on the production capacity of the locality. To make the energy use between localities comparable the salmon farming companies have also provided data on the production volume for the same time-period as the energy data was measured. This makes the energy demand of localities comparable on a kWh/kg produced basis.

3.4.2 Assumptions

To further understand the energy consumption, the collected data has been disaggregated to a more detailed level than the data was collected for. It is desirable with an aggregation level showing which components (feed barge, transport vessel, work vessel) consume energy as well as an even more detailed disaggregation for the feed barge (feeding system, cage lights, equipment, living section). The desirable aggregation level consists of 4 levels and is shown in Figure 13.

Level 1 is the distinction between electrified and non-electrified localities, level 2 is the distinction between the energy carriers, level 3 is the distinction between the components on the locality and level 4 is the distinction between components on the feed barge. The data has been given on detail level 2. Assumptions have been made to reach level 3 and detailed information given by one specific company has been used to reach level 4.

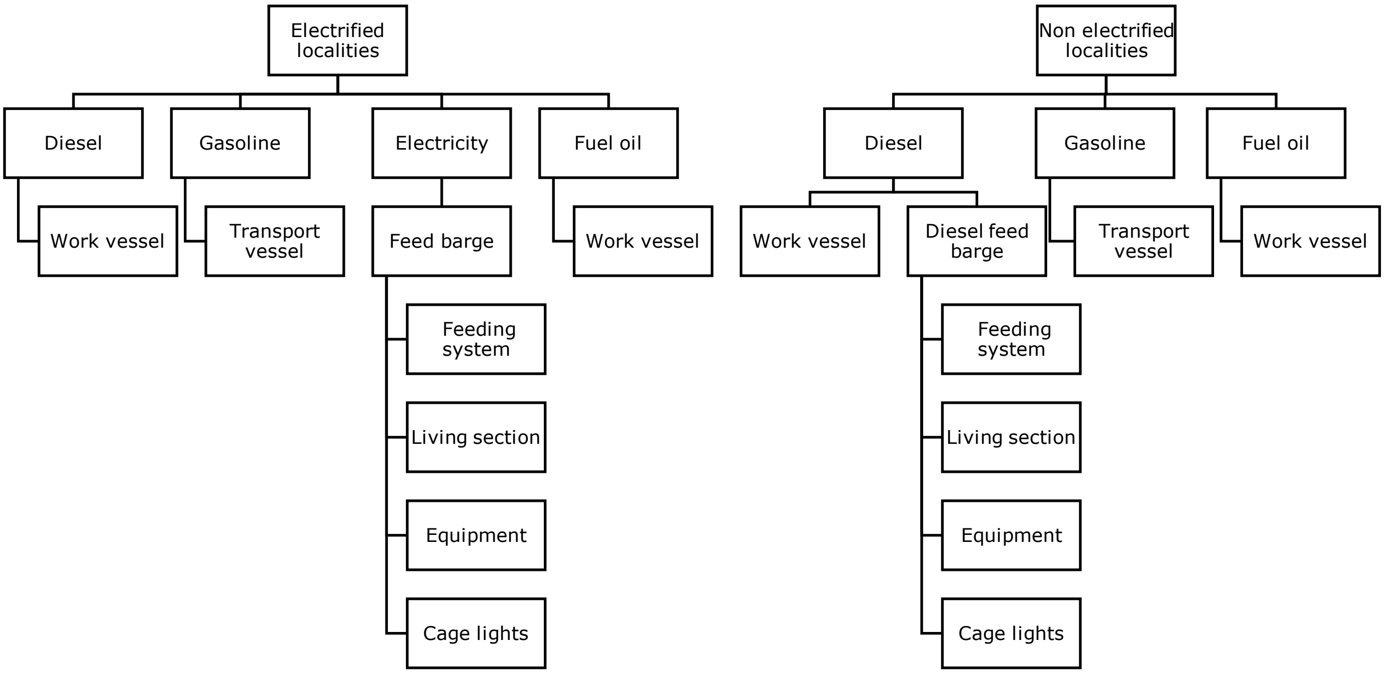


Figure 13: Detail level the energy demand data has been disaggregated to.

The assumptions made to reach level 3 are described in Table 3.

Table 3: Assumptions made for the energy demand model

Energy carrier	Electrified localities	Non-electrified localities
Diesel	All diesel is attributed to the work vessel	The diesel consumption is split between the work vessel and feed barge. The same amount (kWh/kg produced) of diesel which is used for the work vessel for the electrified localities is assumed for the non-electrified. The remaining diesel is attributed to the feed barge.
Gasoline	All gasoline is attributed to the transport vessel	All gasoline is attributed to the transport vessel
Electricity	All electricity demand is attributed the feed barge.	No electricity demand
Fuel oil	All fuel oil is attributed to the work vessel	All fuel oil is attributed to the work vessel

The energy consumption on the feed barge has been further disaggregated to distinguish the energy requiring components (level 4). This distribution was found using average data over one production cycle from one specific company.

3.5 Carbon footprint of onsite energy use

The carbon footprint of the onsite energy use has been calculated from the collected energy demand data and the carbon intensities of the energy carriers. Table 4 lists the carbon intensities used. The operational boundaries of the fossil fuels have been set to scope 1, direct GHG emissions (GHG Protocol, 2004). These emissions only account for the direct combustion emissions of gasoline, fuel oil and diesel. The operational boundary of electricity is set to scope 2. These emissions account for the indirect GHG emissions of the purchased electricity (GHG Protocol, 2004). Other emissions which occur as a consequence of the activities of the salmon farming industry are not accounted for.

Table 4: Carbon intensities for the different energy carriers of the operations studied.

Energy carrier	kg CO_2eq /kWh	Source	Specification
Electricity	9,00E-03	(Wernet et al., 2016)	Electricity, production mix NO
Diesel	2,65E-01	(Miljødirektoratet, 2016)	Direct emissions from combustion
Gasoline	2,57E-01	(Miljødirektoratet, 2016)	Direct emissions from combustion
Fuel oil	2,63E-01	(Miljødirektoratet, 2016)	Direct emissions from combustion

3.6 Power demand model

The power demand of localities has been modelled in order to analyse the electrification potential. The power demand of two scenarios have been analysed. Scenario 1 is the base case scenario which is a locality with a feed barge as it is today. In scenario 2, the efficiency scenario, several components are replaced with more efficient components described in Chapter 2.4. Feed barges for both scenarios are dimensioned for charging work vessels and the components are described in Table 5.

Table 5: The components on the feed barge for the base case scenario and efficiency scenario.

Component	Scenario 1: Base case	Scenario 2: Efficiency
Feeding system	Traditional feeding system	Underwater feeding system
Underwater lights	Metal halogen	LED lights
Living section (heating system)	Panel ovens	Heat pump
Overall system	No storage	Battery storage

The dimensioning power of a feed barge is modelled based on the maximum load of the locality. The maximum load occurs when all components are run at their peak load simultaneously. The power demand of the feed barge varies based on the production capacity of the locality. The non-electrified localities range from production capacities of 780 tonnes – 7020 tonnes. The dimensioning power has therefore been modelled for all production capacities of non-electrified localities.

The dimensioning power is calculated in kilo volt-ampere (kVA) which is the unit used when calculating apparent power. Through multiplying the apparent power with the power factor, the energy transfer (kW) is found and the power factor accounts for the efficiency level in the system. A high power factor indicates that most of the power is absorbed by the load, not circulating in the electric system and thereby a high efficiency of the system (Nilsson & Riedel, 2011)

The equation for calculating the total power demand is shown below where η is the efficiency of the component and $\cos\varphi$ is the power factor. The total power demand is multiplied by a safety factor giving the dimensioning power.

$$Total\ \ power\ demand = \frac{Peak\ power * Concurrency * Utilization\ factor}{\eta * \cos\varphi}$$

The peak power is the power the components are modelled for and the concurrency is a number between 0-1 indicating the simultaneousness the components must be modelled after. The feeding system must be modelled with a concurrency of 1 in the event where all feed blowers are used simultaneously, however the living section is modelled with a concurrency of 0,6 as all components are never used simultaneously (Heinesen, 2019). The utilization factor is a number between 0-1 indicating the percentage of the peak power the component is to be modelled after. Most components are modelled after their peak power, thereby with a utilization factor of 1.

3.6.1 Data

Specific data for two feed barges with a production capacity of 3120 tonnes and 6240 tonnes has been collected from a supplier of feed barges. The data includes the specific power demand of all components on a feed barge as well as the modelling factors; utilization factor, power factor, efficiency and safety factor. This data has been used for scaling the power demand of all non-electrified feed barges and various assumptions have been made in doing so.

3.6.2 Assumptions

The power demand of the feed barge has been split into 4 categories; the feeding system, lights for cages, living section and equipment. In addition, the power demand of the locality specific operations of the work vessel is included. The transport vessel is excluded as it can be electrified with outboard engines and battery packs and does thereby not require charging possibilities on the feed barge (ABB & Bellona, 2018). Table 6 gives a description of the assumptions made when scaling the power demand for the feed barge. A full inventory as well as the modelling factors can be seen in Table B 2, Table B 3, Table B 4, and Table B 5 in appendix B.

Table 6: Assumptions made for the base case and efficiency scenario when modelling the power demand of salmon farming localities. Table 5 describes the components included in each scenario.

Component	Scenario 1: Base case	Scenario 2: Efficiency	Source
Feeding system	Localities with production capacity 780-4680 tonnes use blowers of 22 kW with an efficiency of 0,938, the larger localities use 30 kW blowers with an efficiency of 0,941. One blower per feeding line is required. Additional load from cabinet, sluices and augers give an additional 15 %.	Subsea feeding reduced the power demand to 11 kW pumps where one pump is required per feeding line. Additional load from cabinet, sluices and augers give an additional 15 %.	(Erikstad, 2019; Heinesen, 2019)
Lights in cages	The power demand of lights is proportional to the production capacity of the feeding barge and is scaled using data from existing barges.	LED lights reduces the power demand from scenario 1 with 60 %.	(AkvaGroup, 2019b; Steinsvik, 2019b)
Living section barge	The power demand of the living section is scaled proportionally to the production capacity of the feeding barge and is scaled from data from existing barges.	75 % of the power demand in the living section is due to heating. A heat pump can reduce the total power demand of the living section with 40 %.	(Haugerud, 2015; Heinesen, 2019; NVE, 2016b; VPI, 2019)
Equipment	All localities have the same power demand for equipment which is found from data for existing barges.	Power demand of equipment is identical to scenario 1.	(Heinesen, 2019)
Work vessel	The work vessel is assumed to demand 100 kW from the feed barge. A power factor of 0,9 is set which is a conservative estimate	Identical to scenario 1.	(DNV-GL, 2018; IOTA; Soltveit, 2017; Stensvold, 2017)
Battery	No battery storage	The peak power in scenario 2 is reduced by a battery pack of 120 kW.	(AkvaGroup, 2019a)
Safety factor	A safety factor of 1,5 is added	The safety factor is reduced to 1,2 as the battery works as a safety factor in itself.	(Heinesen, 2019)

3.7 Method for assessing the electrification potential

The modelled power demand for the localities has been used to analyse the electrification potential based on local technical barriers of the power grid. The electrification potential has been analysed in collaboration with the power grid companies with area concession in Trøndelag.

A map of the power demand for each locality in addition to their connection point to the grid has been distributed to the power grid companies. The power demand for both the base case and efficiency scenario was included. It has been tested whether the load from each non-electrified locality can be delivered without triggering grid investments. For the load to not trigger grid investment enough power must be available on the transmission line. The new connected load must also stay within a given allowed voltage drop level and not cause disturbances on the grid in form of voltage or frequency variations (NVE, 2018; Olje- og energidepartementet, 2004) .

Individual and simultaneous electrification has been tested for. For northern Trøndelag the localities have been tested for both individual and simultaneous electrification. Southern Trøndelag has only been tested for individual electrification. The analysis has been conducted by different companies for the north and south (NTE and Trønder Energi) which resulted in the analysis being conducted differently. When testing for individual electrification a load flow analysis has been conducted for each locality one by one. The results only indicate if one locality can be electrified, disregarding the loads of the remaining localities. The electrification of one locality will affect the electrification potential of the other localities with connection points on the same transmission line (Ellingsen et al., 2009; Grindheim, 2015). When testing for simultaneous electrification the load of all localities is tested simultaneously and thereby gives results on the electrification potential of an area. Figure B 1 and Figure B 2 in appendix B shows the loads connected to the different transmission lines.

The electrification potential has been analysed for the two scenarios, base case and efficiency, described in Chapter 0. In all cases the base case scenario has been tested first. In the events where the base case scenario triggered grid investments the efficiency scenario was tested.

3.8 Sensitivity analysis

Sensitivity analysis is a method for dealing with uncertainties in a model or system. A sensitivity analysis shows which parameters are most sensitive to change (Brunner & Rechberger, 2016). The sensitivity of the electrification potential has been analysed by the grid companies. Information has been given on how well within the limit the load flow analyses have been and thereby how sensitive the results are to a change in power demand.

A sensitivity analysis has also been conducted on the carbon footprints sensitivity to the emission factors for the electrified feed barge. Relative sensitivity has been used to conduct the analysis.

Relative sensitivity is defined as

$$Relative\ sensitivity = \frac{\Delta y/y}{\Delta x/x}$$

and shows the relative change of variable y in relation to a change of delta x in variable x (Saltelli et al., 2008). The sensitivity analysis is done at the normal operating point. In this study, the sensitivity analysis is conducted for the total CO_2 emissions tested against the emission factors of the electricity mix. If the relative sensitivity is 1, the value is directly proportional to the parameter.

4 Results and discussion

This chapter presents the results of the energy demand, carbon footprint of onsite energy use, power demand and electrification potential. The results are presented and discussed incrementally as the results are dependent on each other. Chapter 3.3 describes the order the results are conducted in, which is the same order they are presented in. The results on the energy use of localities in Trøndelag are the first results presented.

4.1 Energy use of salmon farming localities in Trøndelag

There are 139 localities in Trøndelag of which 53 are electrified, 53 are not electrified and 33 are not in use. An electrified locality is defined as a locality with a feed barge connected to the mainland grid whereas a non-electrified locality gets its energy supply from diesel generators. The fraction of electrified localities in Trøndelag is 50 %, when only considering the localities in use. A mapping of the localities and their energy carriers is shown in Figure 14. The majority of electrified localities are located in southern Trøndelag, which can indicate a resilient power grid in the area.

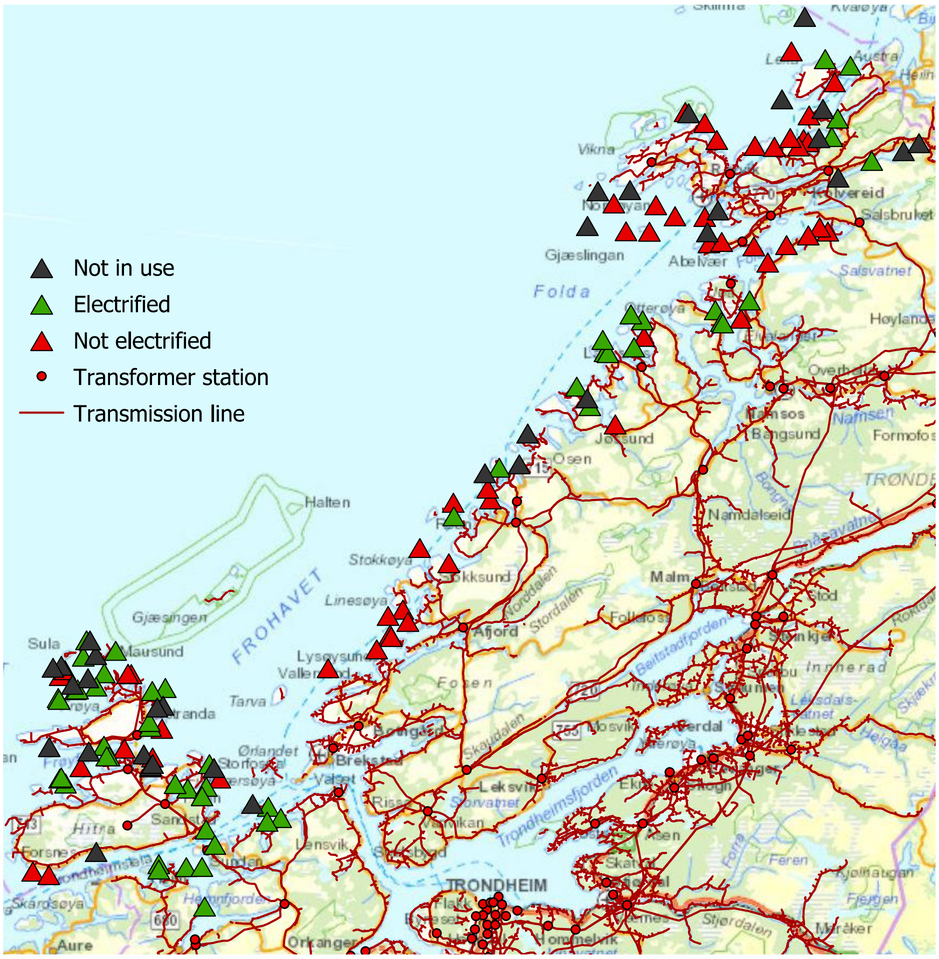


Figure 14: Salmon farming localities in Trøndelag distinguished between their energy carriers. The electrified localities have feed barges connected to the mainland grid and the non-electrified localities have an energy supply from diesel generators

Figure 15a shows the distribution of the onsite energy demand of 48 % of the localities in Trøndelag. The energy demand includes the energy demand of the feed barge, work vessel and transport vessel. The electrified localities have an average energy demand of 0,26 kWh/kg salmon produced, whereas non-electrified localities have an average energy demand of 0,44 kWh/kg produced salmon. The energy demand of the non-electrified localities is almost twice as high as the electrified localities which is due to the low energy efficiency of diesel as an energy carrier (ICF International, 2017).

50 % of the localities are electrified, making the average energy demand per kg produced salmon in Trøndelag 0,35 kWh/kg produced. In 2018, Trøndelag had a production of 318 873 tonnes whole fish equivalents (WFE) making the annual energy demand of onsite salmon farming operations 119 GWh. This corresponds to the energy demand of approximately 600 households (Fiskeridirektoratet, 2019).

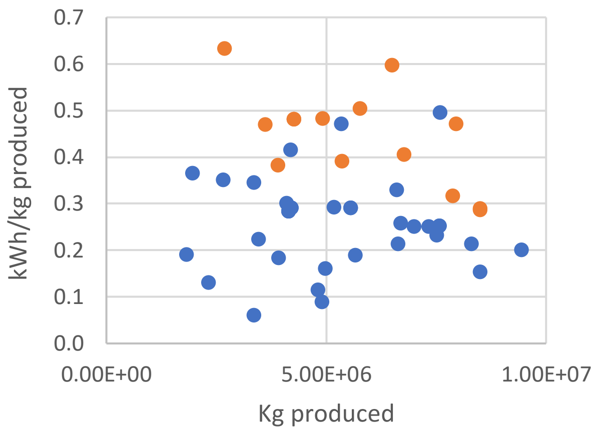


Figure 15a: Energy demand of localities in Trøndelag. The blue dots are electrified localities and the orange dots are non-electrified localities.

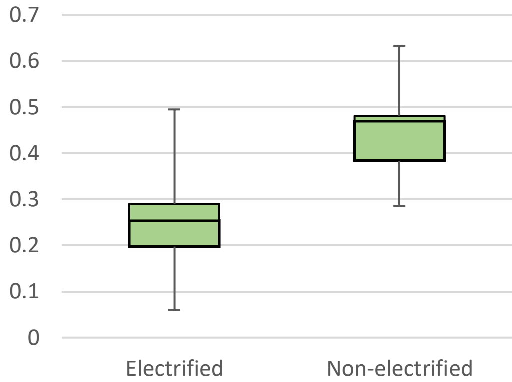


Figure 15b: Variations in energy demand for salmon farming localities in Trøndelag. The box shows quartile 2 and 3 where the line indicates the median. The whiskers show the minimum and maximum

There are large variations in the energy demand of the localities. This is presented in Figure 15b. The collected data on energy demand of the electrified localities varied from 0,06 to 0,49 kWh/kg produced salmon with a median of 0,25 kWh/ kg produced salmon. The non-electrified localities varied from 0,28 to 0,63 kWh/kg produced salmon with a median of 0,47 kWh/kg produced. The non-electrified localities have a smaller range of variation and a downward going trend as production increases. This can be due to the diesel generators running at a constant load unaffected by the real-time energy demand (Issa, Dubé, Mobarra, Fiset, & Ilinca, 2017). Increased production will thereby decrease the average energy use as more salmon are produced at the same load.

It is unknown if the variations in the energy demand are due to uncertainties in the data or if it reflects the situation in the aquaculture industry. Several factors can cause variations in the energy demand between localities, of which some are discussed below.

- **Energy reporting**

Energy reporting is an immature field in the aquaculture industry. There are few systems in place to ensure sound reporting of the energy use of aquaculture localities. Enova states that companies should on their own initiative implement energy management systems to understand and reduce their energy use (Enova, 2019). The lacking standardisation in reporting leads to differences in how the energy demand is reported between localities, both in the level of detail, and the system boundary of the reporting. Few companies seem to establish disaggregated data for their energy use, and only report data on the total energy demand, distinguished between energy carriers. There is thereby little understanding of which components contribute to energy consumption on a locality. The lack of standardised energy reporting systems also increases the uncertainty in the collected data. It has been emphasised by the salmon farming companies whom have distributed the data that the numbers contain uncertainties.

The variations in the energy demand of the electrified localities stems from differences in the diesel demand. The localities which have reported the lowest energy demand has reported no diesel use. This must be a result of differences in reporting, and not the actual case, as all salmon farming localities require work vessels which run on diesel. This indicates that the diesel demand of work vessels can be reported at different localities and the real diesel demand of a locality is thereby not reflected in the energy reporting (Sæternes, 2019).

The electrified localities which have a high energy demand can be localities where diesel generators have been run for parts of the year due to low capacity on the grid.

- **Energy management**

Variations in the energy demand between localities can also be due to actual differences in the energy use between localities. Enova offers financial support to companies whom wish to implement an ISO 50001 certified energy management system (Enova, 2019). Salmon farming companies can implement energy management systems for individual localities. This will reduce the energy demand of these localities through energy efficient behaviour and targeted actions. The localities with the lowest energy demand per kg produced salmon can thereby be localities which have implemented energy management systems.

- **Lice and other biological factors**

Variations in the energy demand between localities can also be due to locality specific biological factors such as lice and disease outbreaks which affects the energy demand of a locality. Lice can have a strong impact on the energy demand due to energy requiring treatment methods and reduced production volume. Several treatment methods exist in the event of a lice outbreak where medicinal treatment and the use of cleaner-fish are the most common (Cerbule, 2018). For medicinal treatment, well boats are hired to perform chemical treatment on the salmon. This leads to high energy use in the form of diesel use of the well boat. However, this energy demand is not within the system boundary of this thesis. The energy use of the feed barge will be affected by the use of cleaner-fish such as wrasse and lumpfish which in addition to lice, eat a substantial amount of pellets and thereby increases the energy demand of the feeding system (Reynolds et al., 2015). Disease and lice outbreak will also increase the energy demand of the dead fish handling system and thereby increasing the energy demand of the locality. In addition, the reduced production of fish will increase the energy demand per kg produced fish.

The energy demand of one year for localities was tested against the number of weeks the locality has used cleaner fish as a measure against salmon lice that year. A correlation value of $r\ (44) = 0{,}37$, $p < 0{,}05$ between energy use per kg produced and output of cleaner-fish was found. This shows that the variation in energy demand between localities is dependent on specific biological conditions such as lice. The localities with a high energy demand can thereby be localities which have had a large amount of disease and lice that year.

4.1.1 Contribution analysis of onsite energy demand

A contribution analysis of the onsite energy demand is presented in Figure 16. The energy demand of the electrified localities is dominated by the diesel demand of the work vessel whereas the non-electrified localities are dominated by the diesel demand of the feed barge and work vessel. The feed barge of non-electrified localities has an energy demand which is 3,8 times higher than the energy demand of the feed barge for the electrified localities. This is due to diesel being an inefficient energy carrier with low efficiencies (ICF International, 2017). The transport vessel and fuel oil for the work vessel has very low impact on the energy demand.

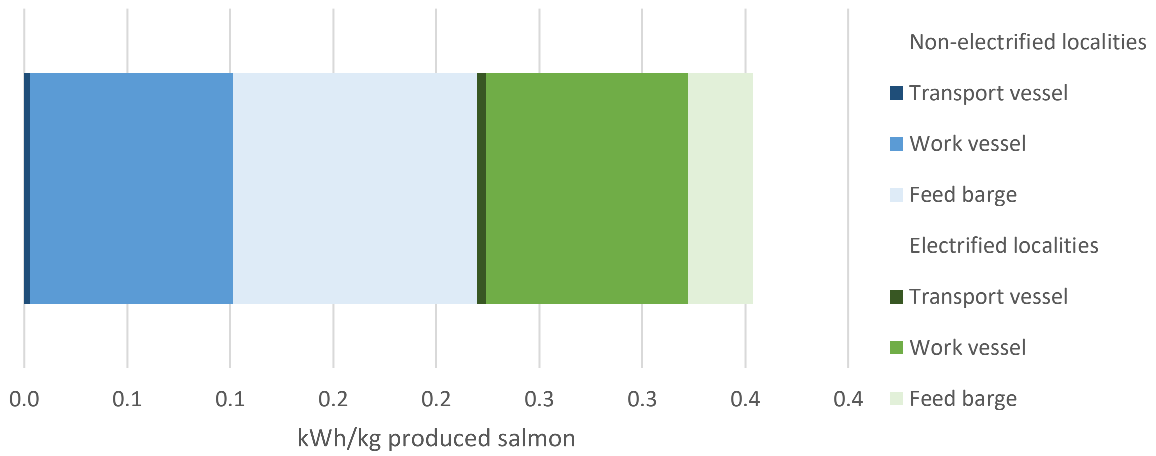


Figure 16: Contribution analysis of the energy demand for onsite processes on a salmon farming locality in Trøndelag.

The contribution analysis of the onsite energy demand is based on assumptions, as disaggregated energy demand data is unavailable. For the electrified localities, the diesel use has been attributed to the work vessel as the feed barge is supplied energy from the mainland grid. For the non-electrified localities, diesel is used as an energy carrier for both the feed barge and the work vessel. Assumptions was thereby made to distinguish the amount used for the two processes. The analysis has been dependent on these assumptions as little detailed data is available in the industry. To better understand the operations that drives the energy demand and decrease the uncertainty of the results, standardised reporting and disaggregated energy demand data is needed.

The energy demand of the feed barge has been further disaggregated to a detail level for the components on the feed barge. Figure 17 shows the distribution of the average energy demand over a year on the feed barge and is assumed to be identical for both electrified and non-electrified localities.

Figure 17: Distribution of the energy demand of components on feed barge.

The feeding system is the most energy requiring component of the feed barge (Syse, 2016; Wiken, 2018). This is due to the high power demand of the feed blowers. The power demand of the living section is quite low, but the use is constant making it the second most energy demanding component on the feed barge (Heinesen, 2019). The cage lights also contribute with a substantial power demand but is mostly used in the winter. The average energy use of the lights is thereby reduced by the low energy requirement in the summer. The equipment has a relatively high power demand but is not used as constantly as the other components which explains the low contribution to the energy demand of a feed barge.

4.2 Carbon footprint of onsite energy use

The carbon footprint of the onsite energy demand of an average kg produced salmon in Trøndelag was found to be 0,086 kg CO_2eq per kg produced salmon, when the Norwegian electricity mix is used. This corresponds to a carbon footprint of 27 400 tonnes CO_2eq in 2018 which is equivalent to the annual emissions from approximately 6000 passenger vehicles (EPA, 2018; Fiskeridirektoratet, 2019).

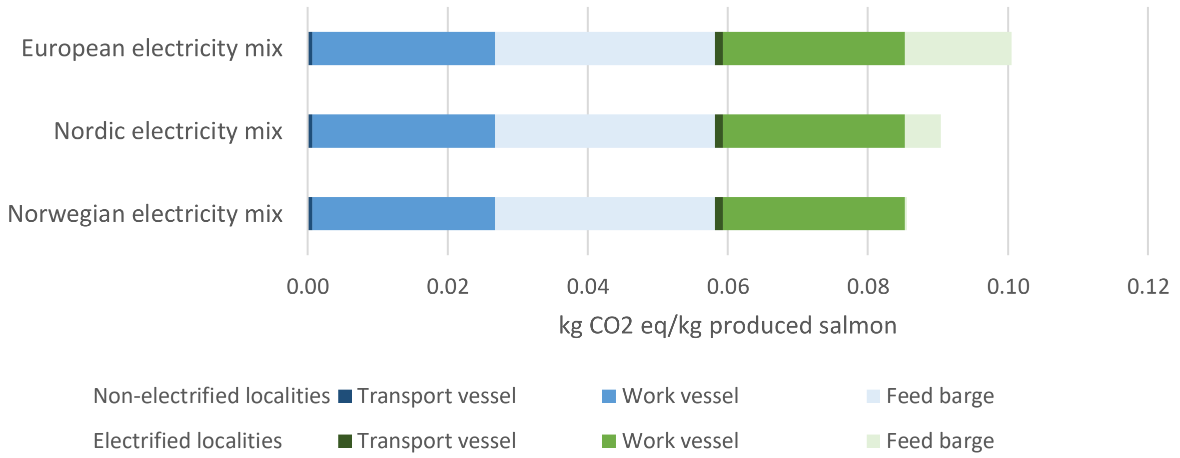


Figure 18: Carbon footprint of onsite energy use of an average kg produced salmon in Trøndelag.

The contribution analysis of the carbon footprint of the onsite energy demand is presented in Figure 18. The work vessel is the process which dominates the carbon footprint of the onsite energy demand and contributes with 61 % of the total carbon footprint. The work vessel is therefore the most important process for achieving emission reduction. The carbon footprint is strongly correlated to the energy demand and mainly stems from the non-electrified localities. The non-electrified localities contribute with 68 % of the total onsite carbon footprint and is dominated by the work vessel and feed barge. For the electrified localities, the carbon footprint of the work vessel contributes to 96 % of the total carbon footprint.

The carbon footprint of the onsite energy demand is shown for three different electricity mixes in Figure 18. The relative sensitivity for the total carbon footprint with respect to the carbon intensity for the electrified feed barge was found to be 0,003. This implies that the change in the carbon intensity of the electricity mix does not cause a great change in the total carbon footprint. The carbon footprint increases when the Nordic and European electricity mixes are used, however, the electrified feed barge has a lower carbon footprint than the non-electrified feed barge, regardless of the electricity mix used. This is due to the efficiency improvements which is a co-benefit of electrification. Electrification will thereby reduce the carbon footprint of the onsite energy demand, even if a less carbon efficient electricity mix is assumed. This demonstrated that there is a large emission reduction potential through electrification of salmon farming localities.

The uncertainty of the results can be discussed by comparing the results to previous research on the carbon footprint of the onsite energy demand in salmon farming. Very little research exists on this topic and the existing research has results with high variability (Møller, 2018). However, a few studies exist on the carbon footprint of the direct energy demand of the whole value chain of salmon farming where the feed barge process is included, but vessels excluded. The results of the feed barge can thereby be compared to other studies and the total results can be compared to the results of ABB and Bellona (2018). The carbon footprint results found in this study is compared to the existing data in Table 7.

Table 7: Carbon footprint results of this study compared to other research. All numbers in kg CO2eq/kg produced salmon

Component	This study	(ABB & Bellona, 2018)	(Nyhus, 2014)	(Nathan Pelletier et al., 2009)	(Winther et al., 2009)
Transport vessel	1,83E-03	1,43E-02			
Work vessel	5,20E-02	9,57E-02			
Electrified feed barge	2,82E-04	0,00E+00	2,34E-04	1,81E-04	2,16E-04
Non-electrified feed barge	3,14E-02	1,80E-01	6,71E-02	4,19E-02	4,76E-02
Total	8,56E-02	2,90E-01			

The carbon footprint found by ABB is much higher than the carbon footprint of salmon farming in Trøndelag, found in this study. The largest differences in results are caused by the non-electrified feed barges. The vessels have smaller differences even though the results from ABB are consistently higher. When comparing the carbon footprint of the feed barge to the research of Nyhus (2014), Pelletier et al. (2009) and Winther et al. (2009) the results are quite comparable. This can indicate that the data used or assumptions made by ABB & Bellona are unrealistic as it gives continuously higher results than earlier research. The results of Nyhus (2014), Pelletier et al. (2009) and Winther et al. (2009) are all based on collected data from salmon farming companies whereas the results of ABB & Bellona (2018) are based on energy demand data from one company and assumptions.

The low carbon footprint results of onsite energy demand found in this study can also be explained by specific biological factors for the years the energy demand data has been collected for. The collected data for the energy demand analysis is for salmon generations which started their growth phase in sea in the spring or autumn of 2016-17. These years have quite low lice levels shown in Figure 19 (Fiskeridirektoratet, 2017a). The low lice levels can contribute to reducing the energy demand of the onsite operations.

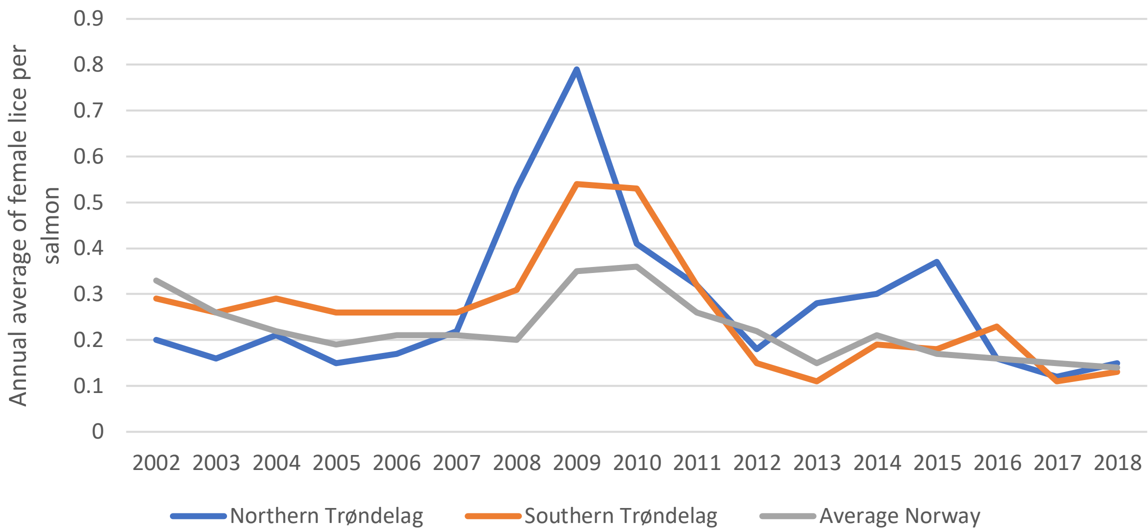


Figure 19: Annual lice development in Norway (Fiskeridirektoratet, 2017a)

4.3 Power demand of locality specific operations

The carbon footprint studied in the previous section can be reduced through electrification of the different processes. For a process to be electrified the power demand must be known as this is the dimensioning factor for the power grid (Energi Norge, 2019b). The power demand of the non-electrified localities has been modelled in order to analyse the electrification potential of the localities and is presented in this subchapter.

Figure 20 shows the dimensioning power for the different components on a locality and how it varies based on the production capacity of the locality. The power demand of the feeding system is dominant for the larger localities. The feeding system requires one feed blower per feeding line of 22 or 30 kW (Heinesen, 2019; Holt, 2017; Wiken, 2018). The larger feed barges require 30 kW feed blowers which causes a jump in the power demand of the feeding system at a production capacity of 4680 tonnes. For the smaller localities the work vessel contributes with the highest power demand. The work vessel is modelled to meet a 100 kW power demand for all localities and is thereby unaffected by the production capacity (DNV-GL, 2018). The power demand of the equipment is also constant for all locality sizes as the equipment from the suppliers to a little degree varies in power demand. The power demand of the cage lights and living section increases linearly with the production capacity of the locality (Heinesen, 2019).

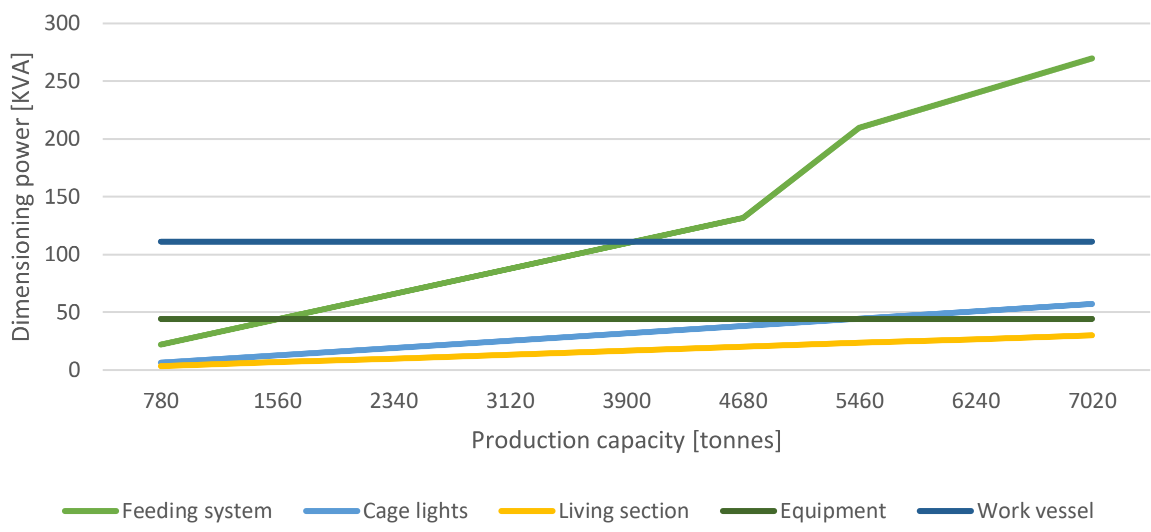


Figure 20: Dimensioning power for the different components on a salmon farming locality and how the dimensioning power changes based on the production capacities.

The power demand has in addition to the original feed barge, been dimensioned for an efficiency scenario where subsea feeding, LED lights, a heat pump and battery storage is installed. A further description of the scenarios can be seen in the methodology section, in Chapter 0. The dimensioning power of localities for both scenarios is presented in Figure 21.

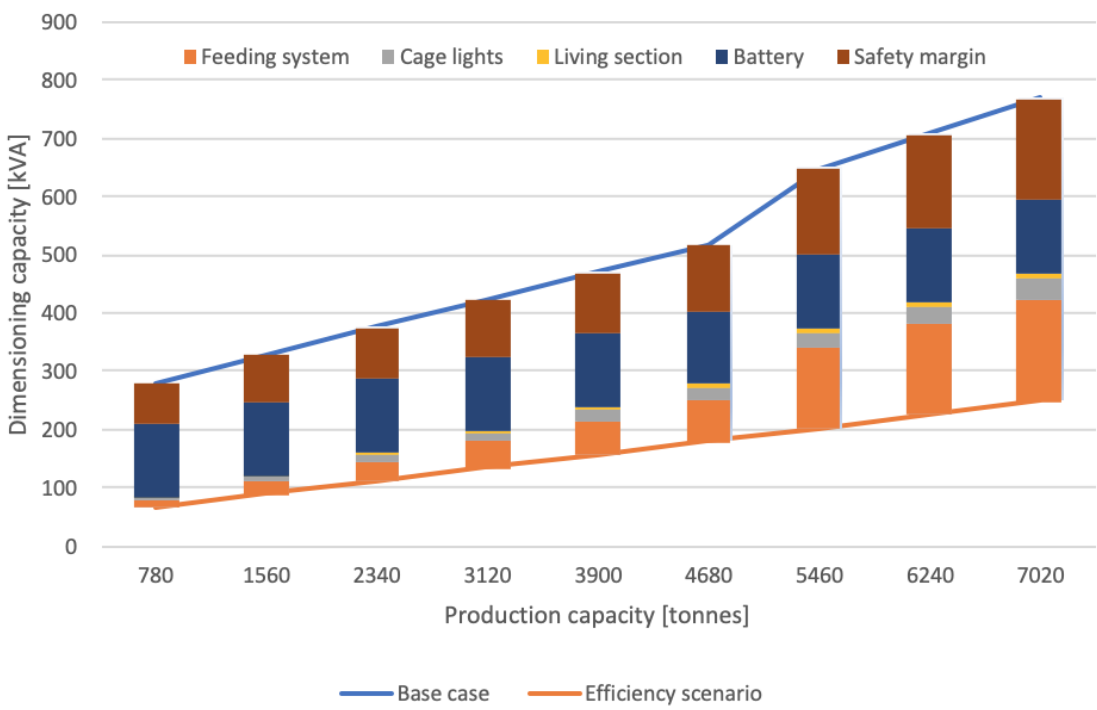


Figure 21: Difference in dimensioning capacity before and after efficiency improvements on a feed barge. The stacked columns in between the trend lines show to which extent the different components contribute to the power reduction

Efficiency improvements on the feed barge reduces the power demand with 68-76 % depending on the production capacity of the locality. Battery storage and subsea feeding are the most important contributors to the power demand reduction. Battery storage contributes by reducing the total power demand of the feed bare while additionally reducing the need for a safety margin. The feeding system is the most energy requiring component on the feed barge and the power demand increases with the production capacity of a locality. The power reduction caused by the subsea feeding system is thereby largest for the localities with a high production capacity.

The power demand of the localities has been used to analyse the electrification potential of the non-electrified localities in Trøndelag which is presented in the next chapter.

4.4 Electrification potential

Today, 50 % of the localities in operation in Trøndelag are electrified and these localities stand for 53% of the installed production capacity. Increasing the fraction of electrified localities can contribute to reducing the emissions of the salmon farming industry. The electrification potential is dependent on the quality of the grid as electrification can become costly in areas where the security of supply is challenged by new connections to the grid.

The next subchapters present the results of the electrification potential of salmon farming localities in Trøndelag when considering local technical barriers of the grid. The electrification potential is tested for feed barges with additional capacity for charging of the work vessels. The transport vessel can be electrified without charging possibilities on the feed barge and is therefore not included in the analysis.

The electrification potential for northern Trøndelag where Nord Trøndelag Energi (NTE) have area concession is firstly presented. Chapter 4.4.2 presents the electrification potential in southern Trøndelag, where Trønder Energi and Fosen Nett have area concessions. More detailed maps can be seen in Appendix A.

4.4.1 Electrification potential in northern Trøndelag

The electrification potential has been analysed for individual and simultaneous electrification and the results are shown in Figure 22a and Figure 22b respectively. For individual electrification, 72 % of the localities in northern Trøndelag can be electrified for the base case scenario without triggering grid investment. Efficiency improvements further increases the electrification potential to 76%. The two localities which need a power reduction before being electrified have connection points on islands which are not dimensioned for high loads. The localities which cannot be electrified without triggering grid investments are located far from grid infrastructure causing voltage drops over the permitted level of the supply quality regulation (Olje- og energidepartementet, 2004)

The electrification potential is high when testing for individual electrification as the load of one locality has little impact on the security of supply for the grid. When testing for simultaneous electrification, the localities with connections points at the same transmission line will affect the electrification potential of each other (H. R. Næss, 2019). Simultaneous electrification is the result of most interest as the emissions are further reduced for each locality that is electrified. The results of the simultaneous electrification are presented in Figure 22b. The figure defines six areas which illustrate transmission lines with more than one locality connected to it. Out of the six areas, only one area can be electrified for the base case scenario. When including the localities which are connected outside an area, a total of seven localities (24%) can be electrified for the base case scenario without triggering grid investments. The barriers for electrification are thereby greatly increased when all localities are to be connected at once. Efficiency improvements for the localities contributes to increasing the electrification potential to 58 % and allows for three more areas to be electrified without triggering grid investments. There are however, still 12 localities which cannot be electrified without triggering grid investments.

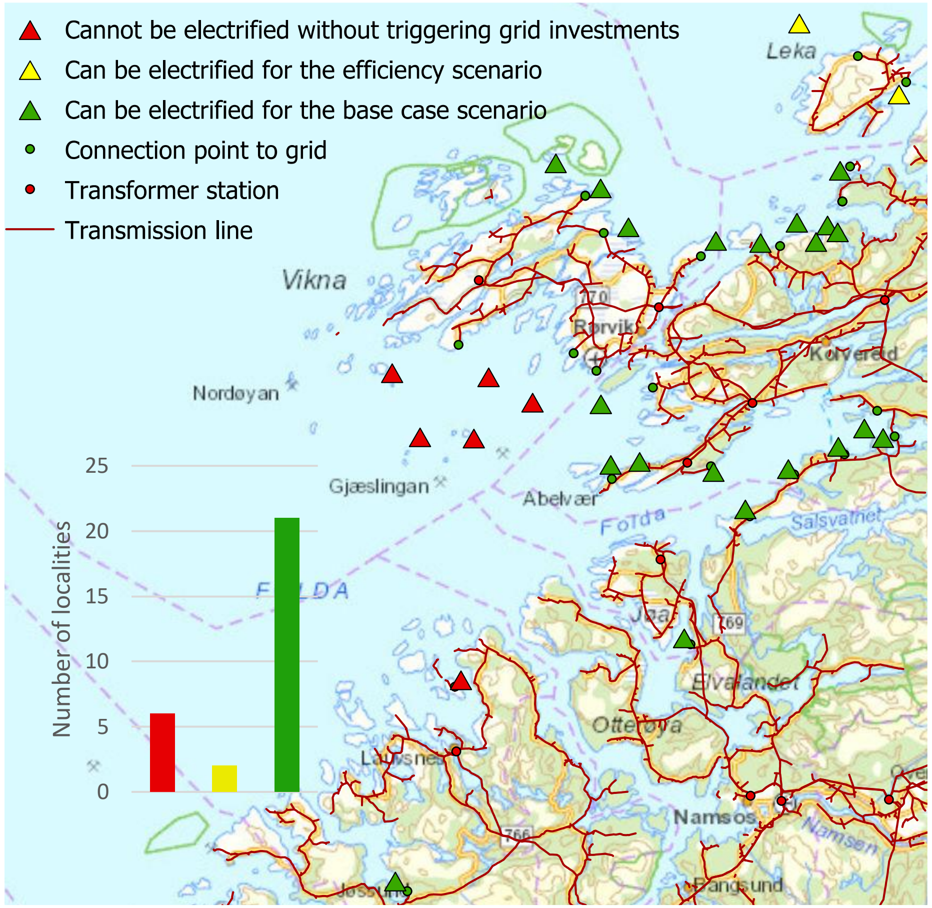


Figure 22a: Electrification potential of localities in Trøndelag when testing the localities individually

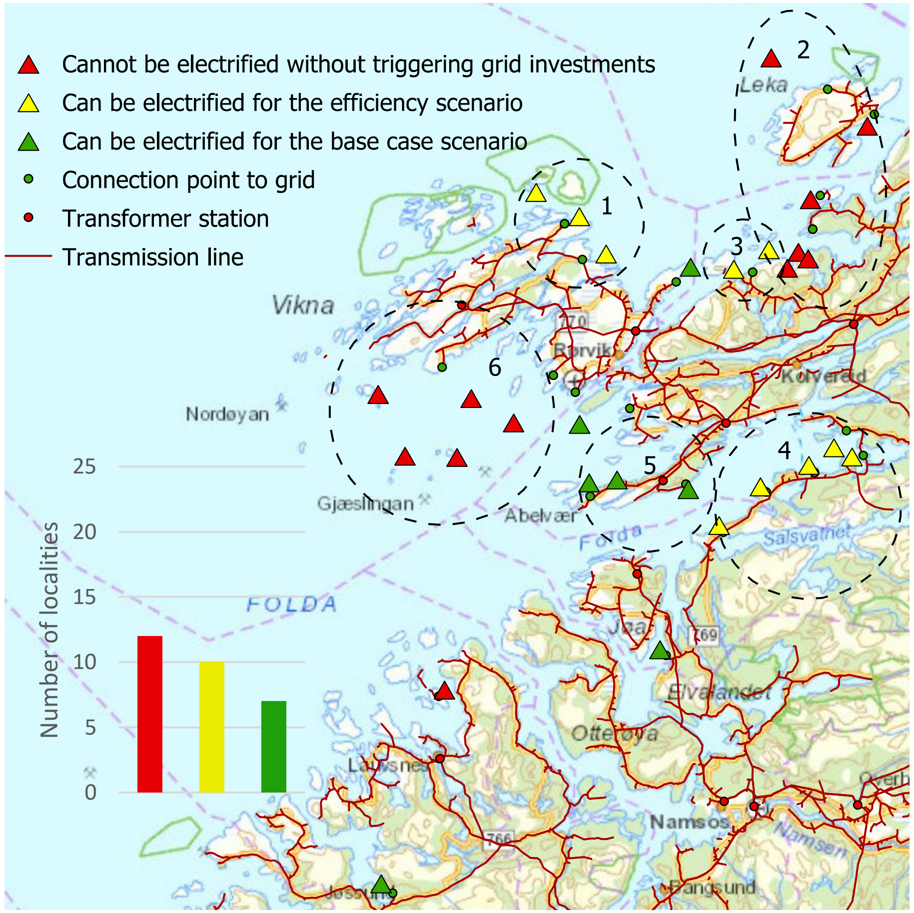


Figure 22b: Electrification potential of localities tested simultaneously. Dotted lines encircle sites considered for simultaneous electrification

The power demand for the individual localities has been modelled based on existing feed barges and thereby been scaled to the different production capacities of the localities. The power demand of the localities contains uncertainties which can influence the results of the electrification potential. Table 8 summarises the results and challenges faced by each area and discusses how sensitive the results are to changes in the power demand of the localities.

Table 8: Challenges of simultaneous electrification and sensitivity of the results

Area no. (refers to number used in Figure 22b)	Electrification possibility	Challenge	Sensitivity to changes in power demand of localities
1	Efficiency scenario	Instantaneous voltage changes	The efficiency scenario is well within the limit and the area is not sensitive to changes in power demand.
2	Cannot be electrified without triggering grid reinforcements	Low voltages	The area has challenges with the voltage level even without all the localities connected. Electrification of all localities will therefore require a considerable power demand reduction or grid reinforcements, even seen in relation to the efficiency scenario. The area is therefore not very sensitive to changes in power demand.
3	Efficiency scenario	Instantaneous voltage changes	The instantaneous voltage changes are high and the area is not sensitive to changes in power demand.
4	Efficiency scenario	High voltages and instantaneous voltage changes	The efficiency scenario is well within the limit and the power reduction does not need to be as considerable. The area is not so sensitive to change in power demand.
6	Cannot be electrified without triggering grid reinforcements	Distance to infrastructure	Not sensitive to changes in power demand as the distance is the constraining factor.

The main challenges faced by the power grid in the event of electrification in northern Trøndelag is related to the voltage level or voltage changes caused by the load on the grid. These are typical challenges which occur when connection high loads to weak grids (Torsæter & Kirkeby, 2017). The sensitivity of the results is low for all areas meaning the uncertainty in the power demand for the localities does not affect the electrification potential to a large degree.

Two areas (2 and 6) cannot be electrified without triggering grid investments. The localities in area 6 are situated far from shore and will thereby have high costs if electrified. For area two the challenges lies in the voltage level due to the long distance to the transformer (Grindheim, 2015). The results are not sensitive to changes in power demand and the power demand of the localities must be greatly reduced to allow for simultaneous electrification of the area. To reduce the barriers of electrification for the area the connection point can be moved to the same transmission line as area 3 which has fewer loads and is closer to the transformer station. This is visualised in Figure B 3 in appendix B. Even though the length of the subsea cable will increase, the total costs of the electrification will be reduced as grid investments are avoided.

For area 6 the costs will be high even if the power demand is reduced due to the long distances to the infrastructure. These localities can reduce emissions through installation of batteries which can be charged during feeding hours and deliver electricity outside of feeding hours. This can reduce the diesel demand with 43 % (ABB & Bellona, 2018). Another possibility is to produce electricity on the feed barge through wind or solar power (Grindheim, 2015; Holt, 2017; Syse, 2016; Wiken, 2018)

4.4.2 Electrification potential in southern Trøndelag

Figure 23 shows the electrification potential of the localities situated in southern Trøndelag. Trønder Energi has area concession of the entire area except from the localities connected to Fosen, where Fosen Nett has area concession.

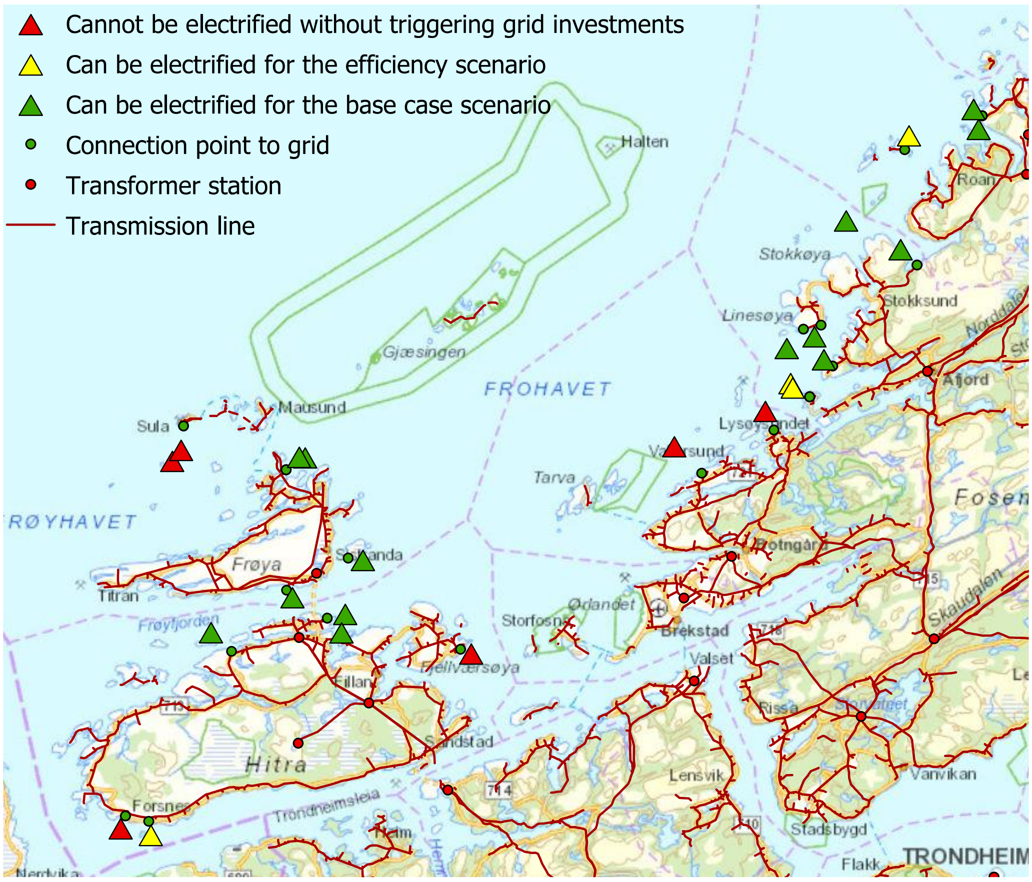


Figure 23: Electrification potential of localities in southern Trøndelag when tested for individual electrification

The electrification potential has been tested for all localities individually, meaning the load of the localities are tested one by one. 75 % (18 localities) of the localities in southern Trøndelag can be electrified without triggering grid investments when testing for individual electrification. 4 localities must reduce their power demand before electrification is possible. The remaining 25 % (6 localities) cannot be electrified without triggering grid investment due to challenges of the grid. Four of the localities which cannot be electrified without triggering grid investments are located at Hitra and Frøya. The area specific constraints in the grid is voltage drops occurring. This occurs due to high loads connected far from transformer stations. The challenges can be reduced through reducing the load of the localities. The two remaining localities which cannot be electrified without triggering grid investments are located with connection points at Fosen. The power grid at Fosen is not dimensioned for high loads and the available power demand is the constraining factor (Jakobsen et al., 2019).

The electrification potential has not been tested for simultaneous electrification. If all localities are electrified simultaneously, the power demand of the localities connected to the same transmission line will inflict on each other and might cause barriers that will reduce the electrification potential in comparison to the individual electrification results. Figure 24 have encircled the localities which would connect to the same transmission line in the event of simultaneous electrification. The localities in southern Trøndelag have connection points divided between more transmission lines than in northern Trøndelag, and only one area (area 6) has more than two localities with electrification potential connected to the same transmission line. This indicates that the results of the simultaneous electrification most likely will be similar to the results of individual electrification.

In area 3, one of the localities needs a reduced power demand and one cannot be electrified when testing for individual electrification which symbolises an area with constraints. This area could therefore be problematic for simultaneous electrification. Area 6 has three localities connected to the same transmission line where the connection points are on an island. This has shown to be challenging in northern Trøndelag as the power grid on islands are not dimensioned for high loads. However, if the power demand is reduced for all localities the area has a high potential of being electrified without triggering grid investments. The results therefore indicate that the electrification potential for simultaneous electrification will be similar to the results of the individual electrification.

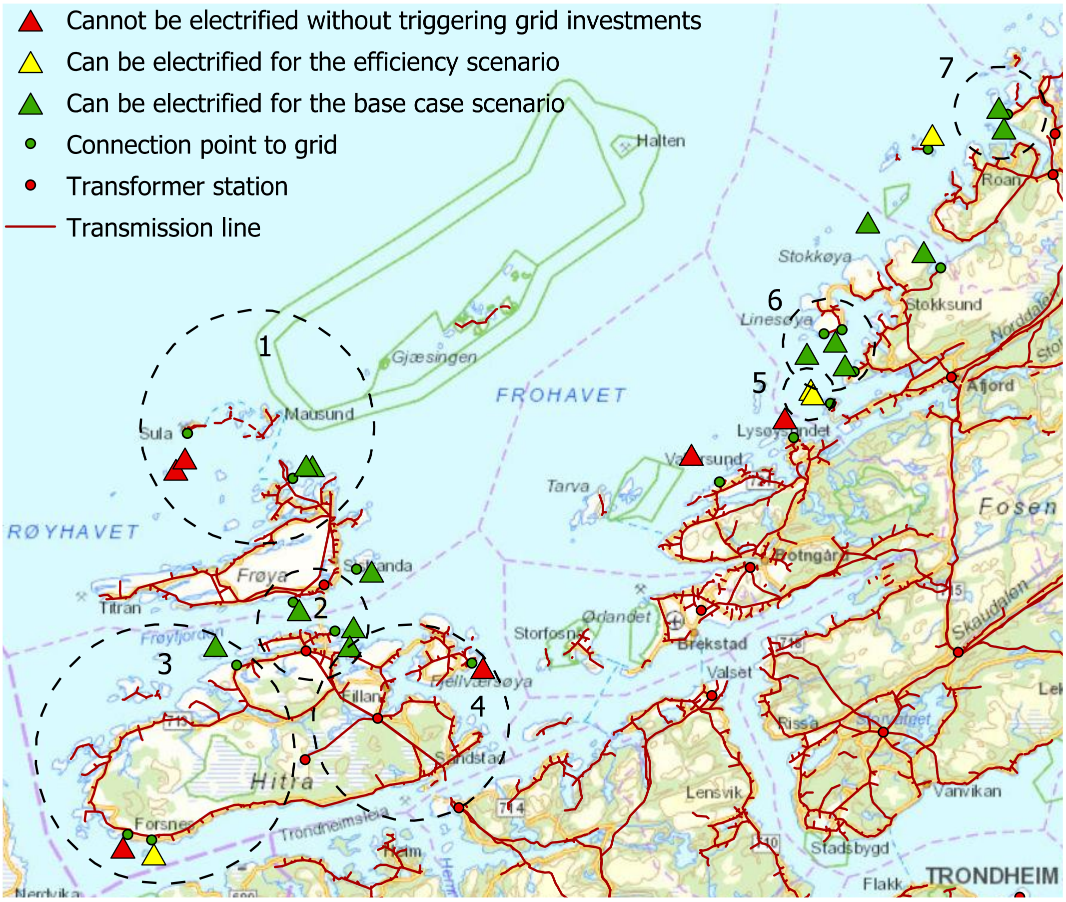


Figure 24: Categorisation of the localities which will connect to the same transmission line in the event of simultaneous electrification in southern Trøndelag

4.5 Barriers for electrification

If the results from the electrification potential for simultaneous electrification in northern Trøndelag is combined with the results of the electrification potential studied in southern Trøndelag the fraction of electrified localities in Trøndelag can be increased from 50% to 83%, when only considering the local technical possibilities of the power grid. There is thereby a large potential for electrification of the salmon farming industry in Trøndelag, and energy efficiency improvements are vital in reaching the transition. The numbers of electrified localities in Trøndelag is today below its potential. This suggests that other barriers are hindering the decarbonisation of the aquaculture industry. This section will discuss economic, technical and structural barriers of electrification as well as propose solutions to reduce these barriers.

4.5.1 Economic barriers

The costs of electrification are greatly reduced when grid reinforcements are avoided, however, the main barrier of electrification is still the costs. Electrification has high investment costs where 40-90 % can be attributed the cable and the remaining costs are due to the substation installation. The cost savings potential of electrification lies in the saved energy costs occurring due to the lower energy demand of electrified localities and low prices of electricity in comparison to diesel (DNV-GL, 2018). The cost savings potential decreases with decreased energy use and it is therefore more unlikely for smaller localities to electrify as their present value savings are much lower than for larger localities with higher energy demand

Figure 25a and Figure 25b show a visualisation of the production capacities of the different localities and their electrification potential. Several of the localities which have electrification potential considering local technical barriers have low production capacities and will thereby have little economic incentive to electrify. In addition, there is a correlation between the size of a locality and the electrification potential. The localities which cannot be electrified without triggering grid investments are also the localities with the highest power demand. This is especially true for southern Trøndelag. This means that the localities with the lowest barriers for electrification often are the localities with the lowest power demand, which also has the least economic incentive to electrify. Other benefits of electrification should be studied to increase the willingness to electrify for localities with low production capacities.

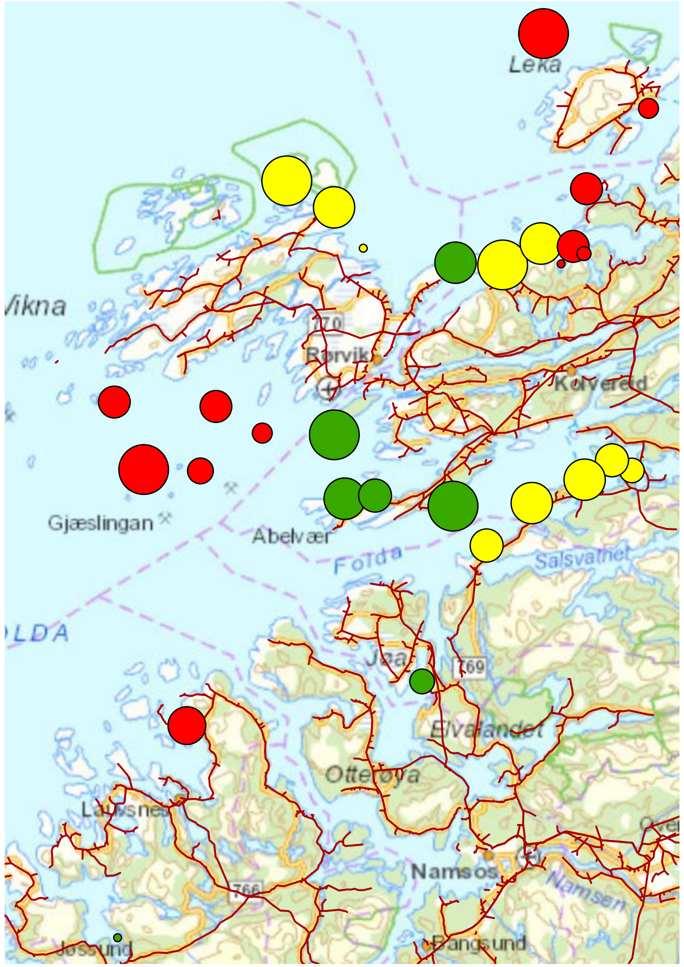


Figure 25a: The circles indicate salmon farming localities in Trøndelag and the colours shows the simultaneous electrification potential. The red circles cannot be electrified without triggering grid investments, the yellow can be electrified for the efficiency scenario and the green for the base case scenario. The size of the circles indicates the production capacity of the localities

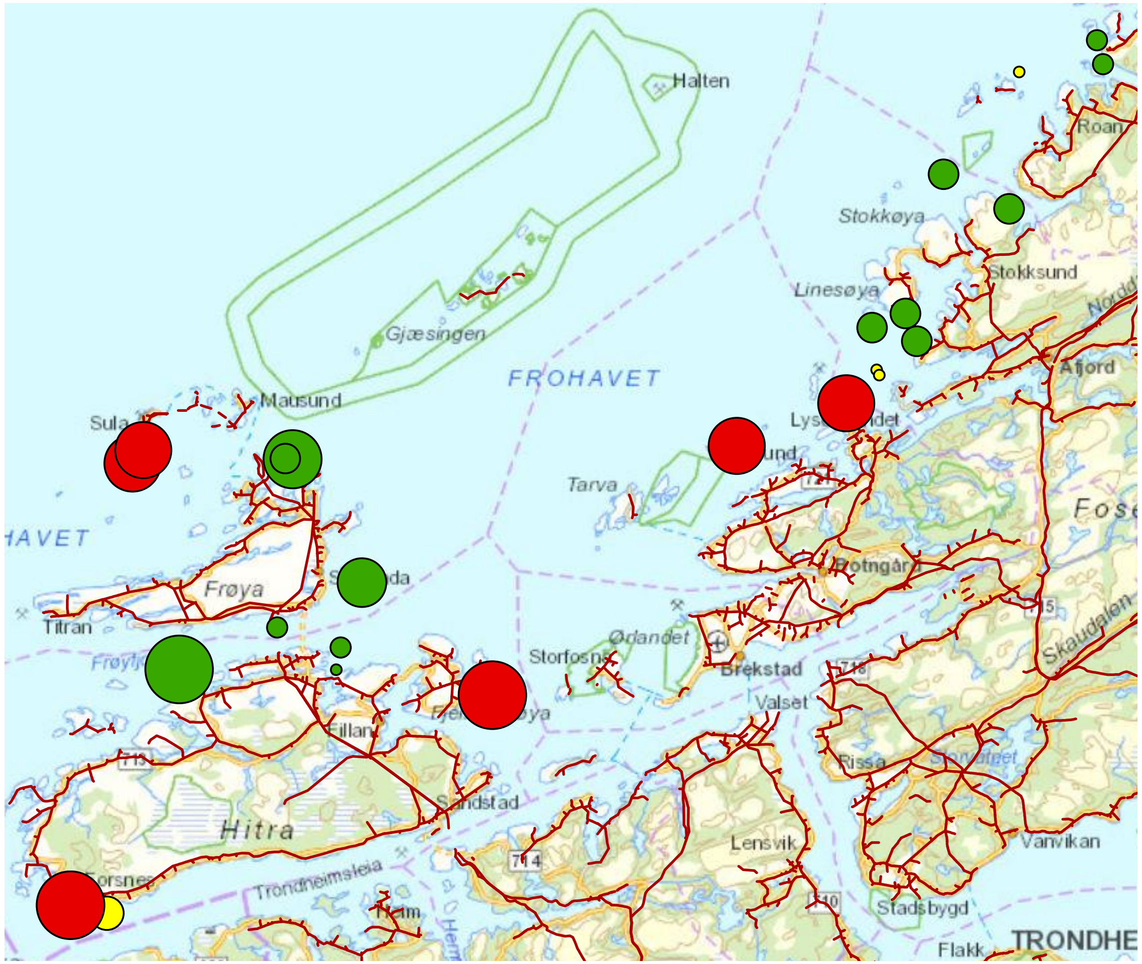


Figure 25b: The circles indicate salmon farming localities in Trøndelag and the colour of the circles show the individual electrification potential. The red circles cannot be electrified without triggering grid investments, the yellow can be electrified for the efficiency scenario and the green for the base case scenario. The size of the circles indicates the production capacity of the localities where the circles increases with the production capacity.

One way to increase the electrification potential for localities with little incentive to electrify is to reduce the economic barriers of electrification. The economic barriers of electrification can be reduced through collaboration with nearby salmon farms. The salmon farms this is possible for are shown in Figure B 4a and Figure B 4b in appendix B. These localities can share a subsea cable and thereby reduce the cable costs. Some of the localities which can collaborate are owned by different companies and it is thereby a prerequisite that electrification is a goal for both.

Economic barriers from grid investments may also be reduced in the future due to planned wind sites in Trøndelag. Fosen wind is establishing Europe's largest land-based wind power project with six wind parks in Trøndelag with a total of 1057 MW installed power. The construction work started in 2016 and is to be finished in 2020 (Statkraft, 2016). New installed wind power will reinforce several bottlenecks in the transmission network. For most areas wind power construction leads to local grid investments in the transmission grid and thereby strengthens the grid in the area (Jakobsen et al., 2019). Thereby, the localities which cannot be electrified without triggering grid investments today have increased electrification potential in the future due to planned grid investments.

Figure 26a and Figure 26b shows the planned wind sites in southern and northern Trøndelag respectively. The wind sites are divided into areas which have been given concession to build wind power sites and wind sites which have started their construction. Southern Trøndelag has eight planned wind sites where five are under construction. Northern Trøndelag has four planned wind sites where one is under construction. The wind sites are in locations where salmon farming localities are situated and will thereby contribute to reducing the barriers of electrification in the area.

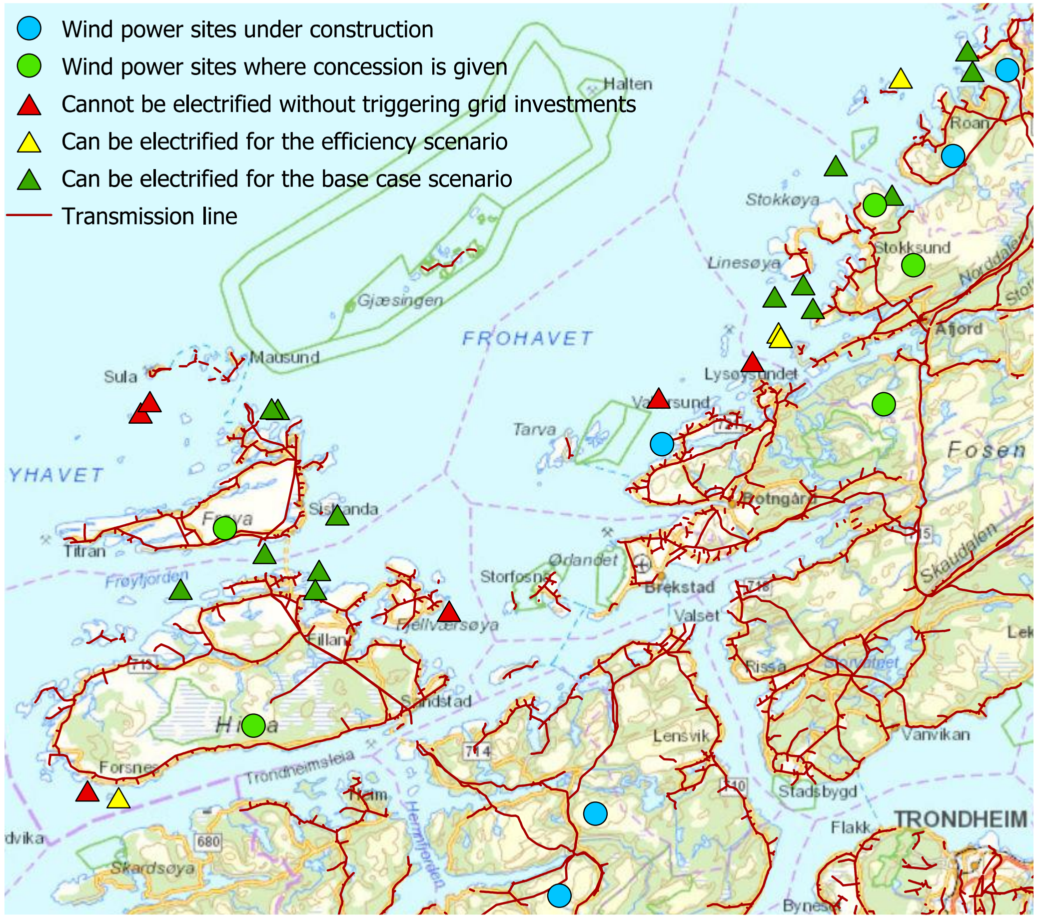


Figure 26a: Planned wind power sites in southern Trøndelag. Electrification potential is shown for individual electrification

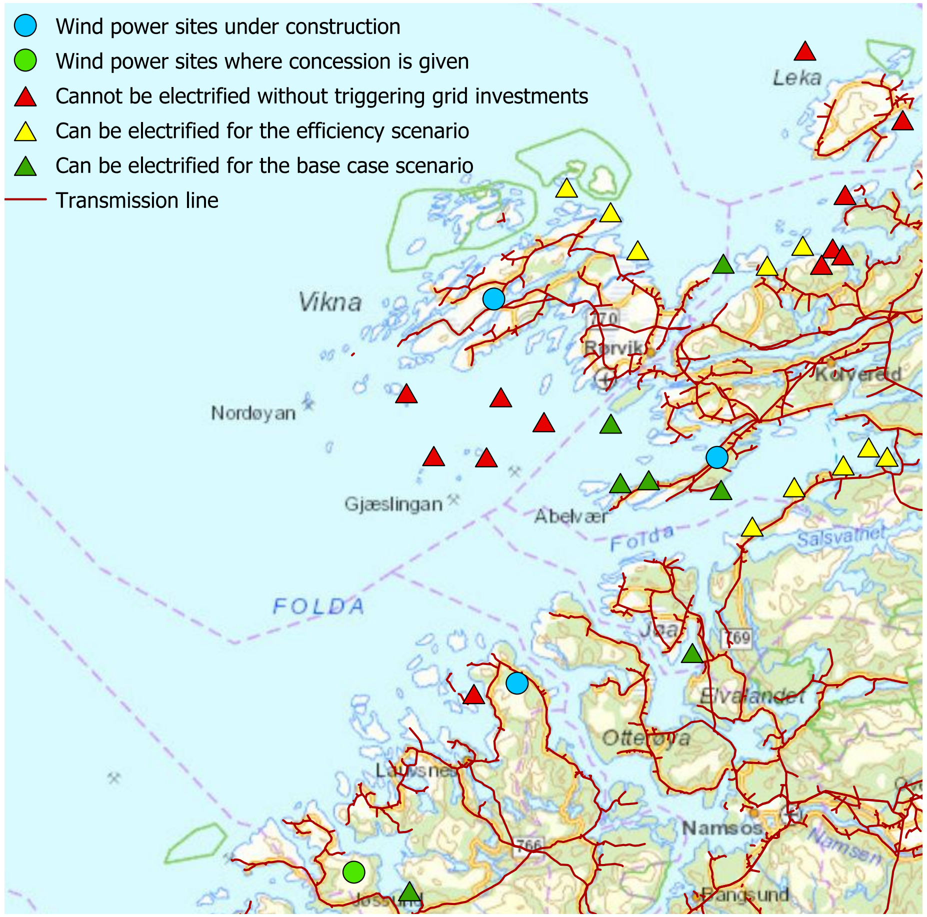


Figure 26b: Planned wind power sites in northern Trøndelag. Electrification potential is shown for simultaneous electrification

4.5.2 Technical barriers

This study has only considered the technical barriers of the existing power grid, however, other technical barriers can hinder electrification of the salmon farming industry. The voltage level needed for the subsea cable can be a constraining factor for electrification. The voltage level of the subsea cable is dependent on the voltage loss. The voltage loss should not exceed 5 % and is dependent on the length and area of the cable in addition to the power and voltage demand of the feed barge (Draka, 2010; M. Næss, 2019). If the voltage level of the subsea cable is over 1 kV it is classified as high voltage and thereby a high voltage room must be built on the feed barge with limited access to authorised personnel (Heinesen, 2019). This can lead to long periods without electricity in the event of a power outage which can have severe consequences for the production. For the base case scenario all non-electrified localities need a higher voltage than 1 kV to restrict the voltage loss to under 5 %. For the efficiency scenario the power demand is greatly reduced and 19 localities can electrify at low voltage. The localities are visualised in Figure B 5 and Figure B 6 in appendix B.

4.5.3 Structural barriers

Besides from costs and high voltage infrastructure, structural barriers can hinder the electrification transformation. Today, the interface between the power grid and salmon farming company is set on the on-land transformer. The salmon farming company must therefore purchase individual components to ensure their own energy supply. Energy supply is not necessarily the core knowledge or focus of salmon farming companies which may lead to non-optimal solutions. This creates a barrier for the salmon farming companies to electrify.

An alternative is for energy to be delivered as an integrated system solution based on the demand. That is, for example, for the providers of feed barges to deliver an integrated power system with connection to the mainland grid and energy management systems based on the specified demand of the locality.

A less used model is for energy to be delivered as a service. The interface between the salmon farming company and power grid company is then moved to the feed barge where the consumption happens, and it is up to the provider of energy to optimize the solutions and provide the demanded power. This enables both the salmon farming and energy companies to work with their core knowledge and thereby optimize the best solutions (Svendgård, 2019).

4.6 Emission reduction potential of electrification and efficiency measures

If the barriers discussed above are reduced, a large emission reduction potential can be achieved through increased electrification. The potential emission reduction is dependent on which processes within the system boundary that are electrified. The results have shown that up to 83 % of the localities in Trøndelag can be electrified without triggering grid investments. The already electrified localities (50%) can electrify their work vessel without triggering grid investments as batteries available on the market for feed barges (120 kW) can deliver the required power demand for vessels on the locality (100 kW) (AkvaGroup, 2019a; DNV-GL, 2018). The remaining localities (17%) can implement energy efficiency improvements and the vessel can be made hybrid-electric with charging possibilities on land (ABB & Bellona, 2018).

Figure 27 shows the potential emission reduction which can be achieved per kg produced salmon in Trøndelag based on the limitations of the existing power grid. A total emission reduction of 86 % can be achieved through electrification and energy efficiency measures. The greatest emission reduction occurs from fully electrifying the work vessel for the localities that are already electrified or have the potential of being electrified considering local grid barriers.

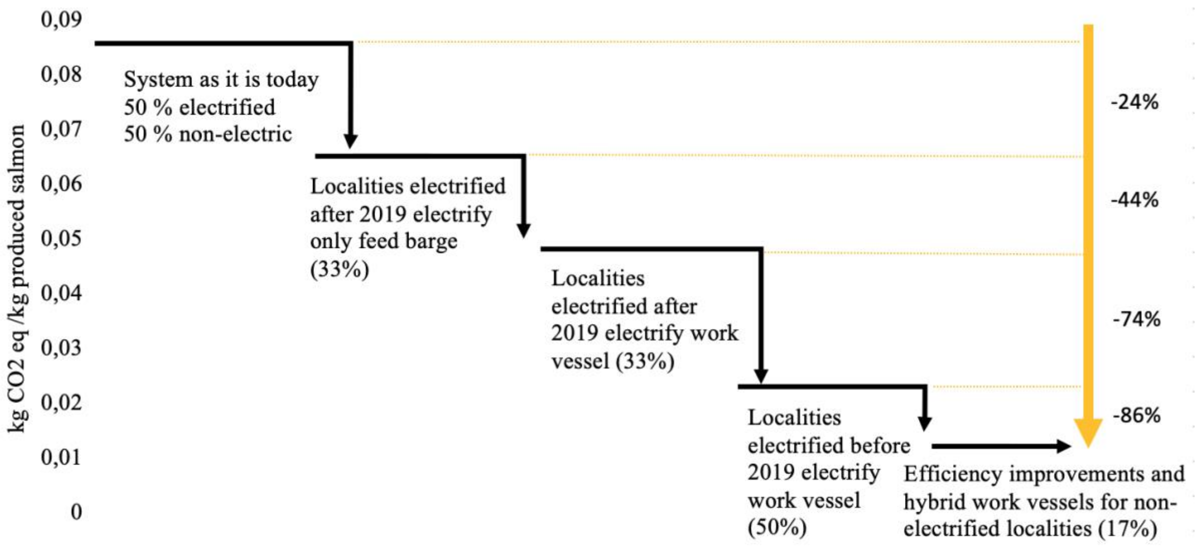


Figure 27: Emission reduction potential through electrification and efficiency improvement of the onsite energy related emissions of salmon farming

If the industry is to reduce its emissions in line with the national mitigation target an emission reduction of 40 % in 2030 and 80-95% in 2050 compared to 1990 levels must be reached. This emission reduction is to occur alongside a fivefold increase in production towards 2050 (Olafsen, Winther, Olsen, & Skjermo, 2012). As the emission level of the aquaculture industry in 1990 is not known and the emission reduction potential has been compared to 2018 levels as this is the last full year where data has been collected.

Table 9 shows the change in emissions in 2030 and 2050 compared to 2018 levels, when implementing the measures in Figure 27. An annual 4 % increase in production is assumed as this reaches a fivefold increase in production by 2050.

Table 9:Emission reduction potential of electrification and efficiency improvements in 2030 and 2050 when an annual 4 % increase in production is assumed.

Scenario	Change in emissions 2030	Change in emissions 2050
Base case	60 %	251%
Localities electrified after 2019 electrify feed barges within 2020	22%	167 %
Localities electrified after 2019 electrify work vessels within 2025	-10%	10%
Localities electrified before 2019 electrify work vessel within 2025	-58%	-7 %
Non-electrified localities implement efficiency improvements and hybrid work vessels	-77%	-50%

An emission reduction of the onsite energy demand can be decreased in line with national mitigation target in 2030 if all localities which are already electrified or have the potential of electrifying with the existing power grid, electrify both their feed barge and work vessel. This gives an emission reduction of 58 % in 2030 compared to 2018 levels when assuming an annual 4 % increase in production. The analysis only considered the direct energy related emissions within the system boundary of this study. Whether this is enough to reduce the total territorial emissions of the whole industry is unknown as the system boundary of this research does not include processes such as the well boat and feed vessel.

In 2050, the emissions are decreased with 50 % when implementing all measures shown in Figure 27. Further emission reduction measures outside the scope of this study is thereby needed to reach an emission reduction of 80-95% within 2050. Such measures can include renewable electricity production through wind or solar cells on the locality or low carbon fuels such as hydrogen or biofuels for vessels (Bouman et al., 2017; Syse, 2016; Wiken, 2018; Ystgård). It is also possible that the national mitigation target can be reached if the increase in production is lower than what has been foreseen.

4.7 Strengths and weaknesses of this work

This study has used collected energy demand data from the industry which is a strength of this work as published data is lacking and has high variability (Møller, 2018) However, the collected data contains uncertainties due to lacking standardisation for energy use reporting. This is a consequence of energy use not being the main focus of the industry. The collected data has been distinguished between energy carriers without further information on which systems and components that use the energy. Further assumptions have thereby been made to disaggregate the data to a detail level where the energy demand of the main processes on the feed barge is known. The assumptions made to reach this detail level leads to uncertainties in the results. However, these assumptions had to be made to further understand the driver of the energy use. Improvements in energy reporting is needed to reduce the uncertainties of the results as well as energy measurement for individual components, not only for energy carriers.

The power demand for each locality has been modelled based on the production capacity and it is assumed that all localities with the same production capacity has the same power demand. These assumptions were made due to lacking data on the power demand of components and feed barges. The power demand is modelled based on the power demand of two existing feed barges of 6240 and 3120 tonnes and thereby scaled to the production capacities of the other feed barges. This is a weakness of the study as the power demand of feed barges can have individual variations even though the localities have the same production capacity. The power demand modelling is based on assumptions on how the power demand of components vary based on the size of the locality. This leads to uncertainties of the results. The power demand results were used to analyse the electrification potential of the different localities. The sensitivity analysis from the electrification potential of the salmon farming localities showed a very low sensitivity to changes in power demand of the localities. This implies that even though there is uncertainty in the power demand the final results of the electrification potential would remain relatively unchanged.

The electrification potential has been evaluated by Trønder Energi for the localities in southern Trøndelag and NTE for the localities in northern Trøndelag. NTE has evaluated the electrification potential for all localities individually as well as testing the potential if all localities were to electrify simultaneously. For electrification to contribute to substantial emission reduction in line with the national mitigation targets as many localities as possible must electrify. Testing for simultaneous electrification is thereby the result which is of most interest. The localities in southern Trøndelag have only been tested for individual electrification. The fraction of localities which can be electrified without triggering grid investments may thereby be reduced if several localities which are connected to the same transmission line electrify simultaneously. It is thereby a weakness of the study that this has not been analysed in southern Trøndelag.

This study has only included direct emissions of the onsite energy use when considering the carbon footprint of the system and how electrification can contribute to reaching the national mitigation targets. Electrification consist of infrastructure such as transformers, cable lines and subsea cables which require large amounts of steel and copper which production should be accounted for (Hauan, 2014). A full carbon footprint analysis should thereby include the background emission of production and demolition of all components included in an electrification process. It is a weakness of the study that not all impacts of electrification are accounted for. If these impacts were included the total emission reduction potential of electrification would decrease. These impacts have not been included as the main goal of the study has been to analyse the electrification potential and analysing background emissions fall outside the scope of the study. In addition, electrification is an established mitigation measure and the impact of electrification infrastructure will thereby most likely not surpass the emission reduction potential of changing the energy carrier from diesel to hydro based electricity (Hertwich et al., 2014)

In the project thesis leading up to this work the carbon footprint of the onsite energy demand was studied for the whole value chain of salmon farming. The results revealed the transport operations of the well boat to be the process with the highest direct carbon footprint (Møller, 2018). A weakness of this research is thereby that the system boundary has been set to only include the locality specific processes of salmon farming. This system boundary was chosen as electrifying the feed barge is a prerequisite in electrifying the processes connected to the feed barge. In addition, the focus of this study has been electrification and efficiency measures. The well boat is a power demanding process which is hard to electrify. Other mitigation measures are most likely more relevant for this process and should be studied in future research. Other mitigation measures can include low carbon fuels such as hydrogen, biofuels and liquefied natural gas or speed and voyage optimization (Bouman et al., 2017).

The results found in the study are highly relevant for decision makers in salmon farming companies in Trøndelag. The system boundary has been set so that all the processes within the system boundary are run and owned by the same actor. This makes the results relevant for the industry. The maps presented in the study, show which localities can be electrified without triggering grid investments. The results therefore highlight the low hanging fruits and may be directly integrated in the company's strategies for electrification and emission reduction. This is a strength of the work as the results have high relevancy and use potential.

4.8 Further work

The results of this report have shown that the local technical barriers of electrification are low and the fraction of electrified localities can be increased from 50% to 83 % without triggering grid investments. This indicates that other structural, economic or technical barriers are hindering the decarbonisation of the aquaculture industry. Future research should focus on identifying a wider range of barriers which are slowing down the electrification transformation and identify how these barriers can be reduced.

The barriers of electrification can also be reduced through identifying co-benefits of electrification. This report has considered electrification as a mitigation tool for the salmon farming industry. However, there are several co-benefits of electrification and efficiency improvements which have not been studied and will contribute to reducing the barriers of electrification (IEA, 2014). The main benefits identified by IEA are presented in Table 10. Further work should identify if some of the listed benefits are significant for the salmon farming industry.

Table 10: Multiple benefits of efficiency improvements as defined by IEA (IEA, 2014)

Topic	Benefit	Description
Enhancing energy system security	Energy security	Reduced energy demand increases the energy security
	Energy delivery	Better service delivered by energy providers
	Energy prices	Decreased energy demand decreases energy prices
Economic development	Macroeconomic development	Positive macroeconomic impacts through boosting GDP and employment
	Industrial productivity	Enhanced production and capacity for energy providers
Social development	Poverty alleviation	Electricity can be provided to more households
	Health and well-being	Reduced noise, better indoor environment etc.
	Employment	Efficiency generates gain in employment
Environmental sustainability	Local air pollution	Less energy use is strongly correlated to local emissions
	Resource management	Lower energy demand reduces use of resources per kWh
Increased prosperity	Public budgets	Reduced government expenditures on energy or increased tax through economic activity
	Disposable income	Reduced energy bills

	Asset values	Willingness to pay increases with increased energy efficiency

The scope of this study has been set around Trøndelag due to the time limit of the research period. Salmon farming localities are scattered along the whole Norwegian coast and Trøndelag only stands for 25 % of the salmon production in Norway (Fiskeridirektoratet, 2019). In Trøndelag 50 % of the localities are electrified, but there is no information on the state of the aquaculture industry in the remaining production areas in Norway. It is of interest to map the energy demand and the electrification potential of the whole salmon farming industry in Norway. Such a mapping should include multi-layers where not only the carbon emission and energy demand is mapped, but other co-benefits defined above are emphasized. A multi-layer model can also include the economic savings potential of each locality as well as specific structural barriers. This will contribute to mapping several benefits and barriers for individual localities and can be used by the aquaculture industry to identify which emission reduction measure should be implemented for each locality.

Further work should also focus on better understanding the variations in energy demand between the localities. The collected data on energy use per kg produced salmon showed large variations. The variations in energy demand can have several explanations, one being the implementation of energy management systems for some localities. It should be studied in further work whether the localities with the lowest energy demand are localities which have implemented energy management systems. This can contribute to understanding why there are variations in the energy demand of salmon farming localities.

Further work should analyse whether other emission reduction measures are relevant for the industry. While this study has focused on electrification and efficiency improvements as measures for decarbonising the aquaculture industry other measures exist which can be more suitable for some operations. Research has found small scale wind turbines integrated with diesel generators to be a feasible low carbon system for feed barges (Haakull, Askeland, & Frugaard, 2016; Holt, 2017; Justad, 2017; Oppegård & Wendelborg, 2018; Skov & Andreassen, 2018; Wiken, 2018; Ystgård). It should be studied in further detail if other renewable solutions can be integrated, especially for the localities which cannot be electrified without triggering grid investments.

The feed barge, work and transport vessel are not the only emitting processes in the aquaculture industry. There are several other energy requiring processes based on fossil fuels such as the well-boat and feed vessel. Further work should expand the system boundary set in this study to include the whole value chain of salmon farming when analysing the emissions and emission reduction potential. The lack of data on carbon emissions in the industry and the numerous actors involved can make such an analysis difficult. Using a top down approach could allow for data gathering for the processes with unavailable data. Such work can contribute to understanding how emissions of the whole value chain can be reduced, not only the onsite energy related emissions.

In order for electrification to be a beneficial mitigation measure the full life cycle emissions of connecting to the on-land grid should be lower than the life cycle emissions of the current system. A full LCA should be conducted on connecting the non-electrified localities to the mainland power grid. Conduction an LCA allows for inclusion of other impact categories such as metal depletion and particulate matter which can be influential when considering the full environmental impact (Hertwich et al., 2014)

5 Conclusions

To ensure alignment with national mitigation targets, a decarbonisation of the aquaculture industry is required. This study has mapped the electrification potential of the onsite operations of salmon-farming in Trøndelag, considering local technical barriers of the existing power grid. The energy and power demand of the localities have been mapped and it has been analysed how the identified electrification potential can contribute to reduce emissions in the industry in line with the national mitigation targets.

A mapping of the energy carriers for salmon farming in Trøndelag found 50 % of the localities to be electrified. The average energy demand of the onsite operations is 0,35 kWh/kg produced salmon and the associated emissions are 0,086 kg CO_2eq/kg produced salmon. The work vessel is the process dominating both the energy demand and carbon footprint of onsite energy use. This study has shown that detailed energy use data is lacking in the salmon farming industry. To be able to reduce the energy related CO_2 emissions efficiently, detailed and consistent energy reporting must be deployed broadly in the industry.

The emissions from the industry can be reduced through electrifying the locality specific operations. The fraction of electrified localities in Trøndelag can be increased from 50 % to 83 % without triggering grid investments. This includes electrification of the work vessel and feed barge. Energy efficiency improvements in the form of subsea feeding, LED lights, heat pump and battery storage can contribute to reduce the power demand of a locality with 68-76 % and are fundamental for increased electrification. 40 % of the localities which can be electrified without triggering grid investments need a reduced power demand before being electrified. The localities which cannot be electrified without triggering grid investments are either situated far from grid infrastructure or have connection points in areas where the grid is weak.

Electrification and efficiency measures can reduce the carbon footprint of the onsite energy demand with 86 %, without triggering grid investments. The work vessel is the most important process for reaching this emission reduction and an electrified feed barge is a prerequisite when electrifying the work vessel. Implementation of these measures will contribute to reducing emissions in line with the national mitigation targets. An emission reduction of 58 % in 2030 compared to 2018 levels can be reached if the electrification share is increased to 83%. This is within the national mitigation target of 40% reduction in 2030 when considering the energy related emissions within the system boundary of this study. This holds even with an expected annual 4% increase in production. For the 2050 mitigation target to be reached, emission reduction outside the scope of this study is needed.

Overall, there is a large potential for electrifying the salmon farming localities in Trøndelag with the existing grid. Energy efficiency improvements are needed to avoid triggering grid investments and battery storage and subsea feeding are the most promising contributors to a reduced power demand.

Despite this study showing an electrification potential of 83 % considering local technical barriers only 50 % are electrified today. This indicates that there is a large unutilized emission reduction potential through readily available electrification. Whether this is due to a lack of knowledge or other essential barriers discussed in this study should be assessed in further work. This study does however show that there are low hanging fruits which could easily reduce the energy related emissions of the salmon farming industry.

References

ABB, & Bellona. (2018). *Grønt skifte i havbruk*. ABB / Bellona, Billingstad/Oslo, Norway. Retrieved from: http://bellona.no/nyheter/havbruk/2018-05-20480

AkvaGroup. (2015). *AKVA Subsea Feeder*. AKVAgroup, Trondheim, Norway. Retrieved from: https://www.akvagroup.com/Downloads/Aqua Subsea Feeder engelsk EN.pdf

AkvaGroup. (2017). *Cage Farming Aquaculture* AKVAgroup, Trondheim, Norway. Retrieved from: https://www.akvagroup.com/Downloads/Cage Cat_E - 3_1-18.pdf

AkvaGroup. (2019a). Batteripakker. Retrieved from https://www.akvagroup.com/merdbasert-oppdrett/batteripakker

AkvaGroup. (2019b). Metal Halogen. Retrieved from https://www.akvagroup.com/pen-based-aquaculture/lights/metal-halogen

Berge, A. (2013). Bygger verdens største fôrbåt. Retrieved from https://ilaks.no/bygger-verdens-storste-forbat/

Bjørndal, T., Holte, E., Hilmarsen, Ø., & Tusvik, A. (2018). *Analyse av lukka oppdrett av laks - landbasert og i sjø: Produksjon, økonomi og risiki*. NTNU, SINTEF Ocean, SNF, Trondheim, Norway. Retrieved from: https://fhf.no/prosjektdetaljer/?projectNumber=901442&fileurl=https%3a%2f%2ffhfno.sharepoint.com%2fsites%2fpdb%2fPublisertedokumenter%2f287287Sluttrapport+-+FHF+901442+-+landbasert+oppdrett.PDF&filename=Sluttrapport%3a+Analyse+av+lukka+oppdrett+av+laks+%e2%80%93+landbasert+og+i+sj%c3%b8%3a+Produksjon%2c+%c3%b8konomi+og+risiko

Bouman, E. A., Lindstad, E., Rialland, A. I., & Strømman, A. H. (2017). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review. *Transportation Research Part D: Transport and Environment, 52*, 408-421. doi:https://doi.org/10.1016/j.trd.2017.03.022

Brunner, P. H., & Rechberger, H. (2016). *Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers*: CRC press Florida, USA.

Cerbule, K. (2018). *Salmon lice control method effectiveness in Atlantic salmon aquaculture.* (Master's thesis in International Fisheries Management), The Arctic University of Norway, Tromsø, Norway. Retrieved from https://munin.uit.no/bitstream/handle/10037/14180/thesis.pdf?sequence=2&isAllowed=y

Curran, M. A. (2016). Life Cycle Assessment. *In Kirk‐Othmer Encyclopedia of Chemical Technology, John Wiley & Sons, Inc (Ed.)*. doi:10.1002/0471238961.lifeguin.a01.pub2

DNV-GL. (2018). *Fullelektrisk fiskeoppdrett*. A project for Energi Norge and Sjømat Norge, DNV-GL, Oslo, Norway. Retrieved from: https://www.energinorge.no/contentassets/ef7f99cb7a954aa99393156203f764ad/fullelektrisk-fiskeoppdrett_endeligversjon.pdf

Draka. (2010). *Teknisk håndbok kraftkabel* (Report no.4). Draka. Retrieved from: http://media.draka.no/2016/07/Teknisk-Handbok-2010_final-til-web.pdf

Ellingsen, H., Olaussen, J. O., & Utne, I. B. (2009). Environmental analysis of the Norwegian fishery and aquaculture industry—A preliminary study focusing on farmed salmon. *Marine Policy, 33*(3), 479-488. doi:https://doi.org/10.1016/j.marpol.2008.11.003

Energi Norge. (2019a). Kraftproduksjon. Retrieved from https://energifaktanorge.no/norsk-energiforsyning/kraftforsyningen/

Energi Norge. (2019b). Nettstruktur og organisering. Retrieved from https://www.energinorge.no/fagomrader/stromnett/kraftsystemet/nettstruktur-og-organisering/

Enova. (2019). *Veileder for etablering av energiledelse i virkshomheten*. https://www.enova.no/bedrift/industri-og-anlegg/tema/det-starter-med-energiledelse/

EPA. (2018). Greenhouse gas emissions from a typical passanger vehicle. Retrieved from https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle

Erikstad, J. R. (2019). [Product Manager Feed Systems, Akva Group]. Personal Communication.

EY. (2017). *The Norwegian aquaculture analysis 2017* (Report no. B1801no). EY, Norway. Retrieved from: https://www.ey.com/Publication/vwLUAssets/EY_-_The_Norwegian_Aquaculture_Analysis_2017/$FILE/EY-Norwegian-Aquaculture-Analysis-2017.pdf

FAO. (2018). National Aquaculture Sector Overview - Norway. Retrieved from http://www.fao.org/fishery/countrysector/naso_norway/en

Finansdepartementet. (2018). Trøndelag. Retrieved from https://www.statsbudsjettet.no/Statsbudsjettet-2018/Fylkesoversikt/Trondelag/

Fiskeridirektoratet. (2017a). *Nøkkeltall fra norsk havbruksnæring*. https://www.fiskeridir.no/Akvakultur/Statistikk-akvakultur/Statistiske-publikasjoner/Noekkeltall-for-norsk-havbruksnaering

Fiskeridirektoratet. (2017b). Tildelingsprosessen. Retrieved from https://www.fiskeridir.no/Akvakultur/Tildeling-og-tillatelser/Tildelingsprosessen

Fiskeridirektoratet. (2019). Biomassestatistikk. Retrieved from https://www.fiskeridir.no/Akvakultur/Statistikk-akvakultur/Biomassestatistikk

Forseth, T., Barlaup, B. T., Finstad, B., Fiske, P., Gjøsæter, H., Falkegård, M., . . . Wennevik, V. (2017). The major threats to Atlantic salmon in Norway. *ICES Journal of Marine Science, 74*(6), 1496-1513. doi:10.1093/icesjms/fsx020

Garbe, E. M. (2018). *Analyse av kraftnett ved tilkobling av ladestasjon for elektriske ferge.* (Bachelor, Electrical Power Engineering), NTNU, Trondheim,Norway.

GHG Protocol. (2004). *A Corporate Accounting and Reporting Standard*. World Business Council for Sustainable Development, Switzerland and World Resource Institute, USA. Retrieved from: https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf

Grindheim, K. M. E. (2015). *Spenningsforhold og Tiltak i Distribusjonsnett med Betydelig Innslag av Småskala Distribuert Produksjon og Elektriske Energilagre.* (MSc Department of Energy and Process Engineering), NTNU, Trondheim.

Haakull, A. W., Askeland, J. V., & Frugaard, L. T. (2016). *Fornybare energikilder til oppdrettsanlegg.* (Bachelor, Maskin, Marin Konstruksjonsteknikk), Høgskolen Stord/Haugestund, Haugesund, Norway.

Hauan, I. B. (2014). *Life Cycle Assessment of Electricity Transmission and Distribution.* (MSc, Energy and Environmental Engineering), NTNU, Trondheim, Norway. Retrieved from https://brage.bibsys.no/xmlui/bitstream/handle/11250/235701/748579_FULLTEXT01.pdf?sequence=3&isAllowed=y

Haugerud, L. L., Ingvild. (2015). *Analyse av feltmålinger av varmepumper i boliger* (32074-00054-0.1). Oslo, Norway. Retrieved from: https://www.enova.no/upload_images/A39CCBB0659E45289D1FFC54EBF71CFA.pdf

Heinesen, L. E. (2019). [Senior Electrical Engineer, Steinsvik]. Personal Communication.

Hermansen, Ø., & Heen, K. (2012). NORWEGIAN SALMONID FARMING AND GLOBAL WARMING: SOCIOECONOMIC IMPACTS. *Aquaculture Economics & Management, 16*(3), 202-221. doi:10.1080/13657305.2012.704617

Hertwich, E., Gibon, T., Bouman, E., Arvesen, A., Suh, S., Heath, G., . . . Shi, L. (2014). *Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies* (Vol. 112).

Hide, G. H. (2019). *Elektrifisering av havbruk gir økt bærekraft og omdømme. Presentation held at Hjort-seminaret 21.mars 2019*. ABB, Tromsø. Retrieved from: https://uit.no/Content/623463/cache=20192503152257/ABB.pdf

Hognes, E., Ziegler, F., & Sund, V. (2011). *Carbon footprint and area use of farmed Norwegian salmon*. Trondheim, Norway. Retrieved from:

Hognes, E. S. N., Katarina; Sund,Veronica; Ziegler, Friederike. (2014). *LCA of norwegian salmon production 2012*. SINTEF Fiskeri og havbruk. Retrieved from: https://brage.bibsys.no/xmlui/handle/11250/2458163

Holt, M. (2017). *Feasibility Studies on a Stand-Alone hybrid Wind-Diesel System for Fish Farming Applications.* (MSc thesis), NTNU, Trondheim, Norway.

ICF International. (2017). *Diesel Generators: Improving efficiency and emission performance in India*. SHAKTI Sustainable Energy Foundation,New Delhi, India,. Retrieved from: https://shaktifoundation.in/wp-content/uploads/2017/06/ICF-2014-Diesel-Generators-Improving-Efficiency-and-Emission-Performance-in-India.pdf

IEA. (2014). *Capturing the Multiple Benefits of Energy Efficiency*. IEA Publications, Paris, France. Retrieved from: https://www.iea.org/publications/freepublications/publication/Multiple_Benefits_of_Energy_Efficiency.pdf

IOTA. Power Factor Correction in Battery Chargers. Retrieved from https://www.iotaengineering.com/pplib/IOTA_Tech_PFC in Battery Chargers.pdf

Issa, M., Dubé, E., Mobarra, M., Fiset, J., & Ilinca, A. (2017). *Modeling and optimization of the energy production based on Eo-Synchron application* (Technical paper 620). Québec, Canada. Retrieved from: http://www.genset-synchro.com/pdf/IDGTE.pdf

Jakobsen, S. B., Mindelberg, S. K., Østenby, A. M., Dalen, E. V., Lundsbakken, M., Bjerkestrand, E., . . . Berg, M. (2019). *Forslag til nasjonal ramme for vindkraft*. NVE, Oslo, Norway. Retrieved from: http://publikasjoner.nve.no/rapport/2019/rapport2019_12.pdf

Justad, A. A. (2017). *Wind turbines for the power supply for offshore fish farms.* (Master thesis, Engineering Sciences), University of Agder, Bergen, Norway.

Lov om klimamål, LOV-2017-06-16-60 C.F.R. § 1-5 (2017).

Liu, Y., & Bjelland, H. v. (2014). Estimating costs of sea lice control strategy in Norway. *Preventive Veterinary Medicine, 117*(3), 469-477. doi:https://doi.org/10.1016/j.prevetmed.2014.08.018

Lysbassen, A., Haltbrekken, L., Kaski, K. E., Nævra, A., & Fylkesnes, T. K. (2017). *Representantforslag 16 S*. https://stortinget.no/globalassets/pdf/representantforslag/2017-2018/dok8-201718-016s.pdf

Marafioti, G., Alfredsen, J. A., & Alver, M. O. (2012). *Estimation of growth in farmed salmon based on dynamic energy budget model. Poster presentation at Havbruk 2012*. Department of Engineergin Cybernetics and SINTEF Fisheries and aqaculture, Trondheim, Norway. Retrieved from: https://www.sintef.no/contentassets/231bb9f9d45047e09ff0bf5e03d32284/giancarlo_model.pdf

Marine Harvest. (2018). *Salmon Farming Industry Handbook 2018*. Marine Harvest ASA, Norway. Retrieved from: http://marineharvest.com/about/news-and-media/news_new2/marine-harvest-osemhg-2018-salmon-industry-handbook-/

Mattilsynet. (2016). Fakta om lakselus of lakselusbekjempelse. Retrieved from https://www.mattilsynet.no/fisk_og_akvakultur/fiskehelse/fiske_og_skjellsykdommer/lakselus/fakta_om_lakselus_og_lakselusbekjempelse.23766

Miljødirektoratet. (2015). Fiskeoppdrett. Retrieved from https://www.miljostatus.no/fiskeoppdrett

Miljødirektoratet. (2016). *Greenhouse Gas Emissions 1990-2017, National Inventory Report* (Report No. M-1271). Miljødirektoratet, Oslo, Norway. Retrieved from: http://www.miljodirektoratet.no/no/Publikasjoner/2016/April-2016/Greenhouse-Gas-Emissions-1990-2014-National-Inventory-Report/

Møller, S. (2018). *Energy demand and electrification potential of the atlantic salmon farming industry in Norway.* Unpublished project thesis, NTNU, Trondheim, Norway.

Næss, H. R. (2019). [Senior Engineer, NTE]. Personal Communication.

Næss, M. (2019). [Sales Manager Industry, Nexans]. Personal Communication.

Nilsson, J. W., & Riedel, S. A. (2011). *Electric Circuits*: Pearson Education, Prentice Hall, New Jersey, USA.

NVE. (2015a). Anleggsbidrag. Retrieved from https://www.nve.no/reguleringsmyndigheten-for-energi-rme-marked-og-monopol/nettjenester/nettilknytning/leveringsplikt/

NVE. (2015b). Leveringsplikt. Retrieved from https://www.nve.no/reguleringsmyndigheten-for-energi-rme-marked-og-monopol/nettjenester/nettilknytning/leveringsplikt/

NVE. (2016a). Energi og effekt. Retrieved from https://www.nve.no/energibruk-og-effektivisering/energibruk-i-norge/energi-og-effekt/

NVE. (2016b). *Varmepumper i energisystemet*. NVE. Retrieved from: http://publikasjoner.nve.no/rapport/2016/rapport2016_60.pdf

NVE. (2018). Spenningskvalitet. Retrieved from https://www.nve.no/reguleringsmyndigheten-for-energi-rme-marked-og-monopol/nettjenester/leveringskvalitet/spenningskvalitet/

NVE. (2019). Nett. Retrieved from https://www.nve.no/energiforsyning/nett/

Nyhus, O. J. (2014). *Life Cycle Assessment of Farmed Salmon, Comparing a Closed with an Open Sea Cage System.* (MSc, Marine Technology), NTNU, Trondheim, Norway.

OED. (2019). The electricity grid. Retrieved from https://energifaktanorge.no/en/norsk-energiforsyning/kraftnett/

Olafsen, T., Winther, U., Olsen, Y., & Skjermo, J. (2012). *Verdiskapning basert på produktive hav i 2050*. Report from a work group by DKNVS & NTVA, Norway. Retrieved from: https://www.sintef.no/globalassets/upload/fiskeri_og_havbruk/publikasjoner/verdiskapning-basert-pa-produktive-hav-i-2050.pdf

Lov om produksjon, omforming, overføring, omsetning, fordeling og bruk av energi (Energiloven), LOV-1990-06-29-50 C.F.R. § 3.3 (1990).

Forskrift om leveringskvalitet i kraftsystemet, FOR-2004-11-30-1557 C.F.R. (2004).

Oppegård, E., & Wendelborg, M. (2018). *Elektrifisering av oppdrettsanlegg ved bruk av vindkraft-batteri hybrid systemer.* (BSc, Department of Energy and Process Engineering), NTNU, Trondheim, Norway.

Pelletier, N., & Tyedmers, P. (2007). Feeding farmed salmon: Is organic better? *Aquaculture, 272*(1), 399-416. doi:https://doi.org/10.1016/j.aquaculture.2007.06.024

Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjo, A., . . . Silverman, H. (2009). Not All Salmon Are Created Equal: Life Cycle Assessment (LCA) of Global Salmon Farming Systems. *Environmental Science & Technology, 43*(23), 8730-8736. doi:10.1021/es9010114

Forskrift om produksjonsområder for akvakultur av matfisk i sjø av laks, ørret of regnbueørret, FOR-2017-01-16-61 C.F.R. § 1-13 (2017).

Regjeringen. (2019). *Havbruk til havs*. https://www.regjeringen.no/no/dokumenter/havbruk-til-havs/id2625352/

Reynolds, P., Eliassen, G., Anders Elvergård, T., Arne Hangstad, T., Foss, A., Vikingstad, E., . . . Imsland, A. (2015). Rognkjeks i merd spiser det meste. doi:10.13140/RG.2.1.4808.4968

Sæternes, R. (2019). [FoU Coordinator, SinkabergHansen AS]. Personal Communication.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., . . . Tarantola, S. (2008). *Global sensitivity analysis: the primer*: John Wiley & Sons Ltd, West Sussex, England.

Sandbakk, M. (2018). [Senior Adviser, Enova, Personal Communication].

SjømatNorge. (2018). *Sjømat 2030, Et blått taktskifte*. SjømatNorge, Oslo, Norway. Retrieved from: https://sjomatnorge.no/sjomat-2030/

Skov, H. K., & Andreassen, A. I. (2018). *Bruk av fornybar energi til energiproduksjon på fiskeoppdrettsanlegg.* (Bachelor), Høgskulen på Vestlandet, Haugesund, Norway.

Soltveit, T. (2017). Verdens første elektriske arbeidsbåt overlevert til Salmar. Retrieved from https://www.kyst.no/article/verdens-foerste-elektriske-arbeidsbaat-overlevert-til-salmar-1/

Statkraft. (2016). Fosen Vind. Retrieved from https://www.statkraft.no/om-statkraft/Prosjekter/norge/fosen/

Steinsvik. (2019a). Dead fish handling. Retrieved from https://www.steinsvik.no/en/products/e/seaculture/seaculture-equipment/dead-fish-handling

Steinsvik. (2019b). Lys. Retrieved from https://www.steinsvik.no/no/produkter/n/seaculture/havbruksutstyr/lys

Stensvold, T. (2017). Batterier slår ut diesel:- Det er ingen revolusjon, men en evolusjon. Retrieved from https://www.tu.no/artikler/oppdrettsnaeringen-vil-ha-elektriske-bater-det-beste-arbeidsmiljoet-i-verden/403737

Svendgård, O. (2019). [Cluster leader, Renewable Energy Cluster, Personal Communication].

Syse, H. (2016). *Investigation Off-Grid Energy Solutions for the Salmon Farming Industry.* (Master of Science), University of Strathclyde, Glasgow, Scotland.

Taranger, G. L., Karlsen, Ø., Bannister, R. J., Glover, K. A., Husa, V., Karlsbakk, E., . . . Svåsand, T. (2015). Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. *ICES Journal of Marine Science, 72*(3), 997-1021. doi:10.1093/icesjms/fsu132

Terjesen, B. (2017). *30 år med settefisk, 1986 til 2016 – hva nå? (Thirty years with smolt production, 1986 to 2016 - what now?). Keynote at TEKSET 2017*.

Torsæter, B. N., & Kirkeby, H. (2017). *Simuleringsstudie av spenningskvalitet i lavspentnett med plusskunder*. SINTEF Energi AS, Trondheim, Norway. Retrieved from: https://www.sintef.no/globalassets/project/nef-tm-2017/rapporter-2017/sesjon-4-2---21---bendik-nybakk-torsater-og-henrik-kirkeby---simuleringsstudie-av-spenningskvalitet-i-lavspenningsnett-med-plusskunder.pdf

VPI. (2019). Væske-til-vann-varmepumpe. Retrieved from https://www.varmepumpeinfo.no/varmepumpetyper/vaske-til-vann-varmepumpe

Werkman, M., Green, D. M., Murray, A., & Turnbull, J. F. (2010). The effectiveness of fallowing strategies in disease control in salmon aquaculture assessed with an SIS model. *98*, 64-73. doi:10.1016/j.prevetmed.2010.10.004

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). *The ecoinvent database version 3. The international Journal of Life Cycle Assessment* [online]. pp1218-1230. Retrieved from: http://link.springer.com/10.1007/s11367-016-1087-8

Wiken, L. S. (2018). *Akvakultur og Små Vindturbinar: Eit moglegheitsstudie av i kva grad små vindturbinar kan dekkje energiforbruket ved norske oppdrettsanlegg.* (M.Sc), Universitetet i Bergen, Bergen, Norway.

Winther, U., Ziegler, F., Hognes, E., Emanuelsson, A., Sund, V., & Ellingsen, H. (2009). *Carbon footprint and energy use of Norwegian seafood products* (SFH80 A096068). SINTEF. Retrieved from: https://www.sintef.no/globalassets/upload/fiskeri_og_havbruk/fiskeriteknologi/filer-fra-erik-skontorp-hognes/carbon-footprint-and-energy-use-of-norwegian-seafood-products---final-report---04_12_09.pdf

Ystgård, E. R. *Småskala vindkraft i fiskeopdrettsnæringen - en løssnom løsning?* , In collaboration with National Wind Center, Ås, Norway.

Ziegler, F., & Hornborg, S. (2014). *Aquaculture and energy use: a desk top study*. https://swemarc.gu.se/digitalAssets/1536/1536133_publication---energy-use-in-aquaculture.pdf

Ziegler, F., Winther, U., Hognes, E. S., Emanuelsson, A., Sund, V., & Ellingsen, H. (2013). The Carbon Footprint of Norwegian Seafood Products on the Global Seafood Market. *17*(1), 103-116. doi:doi:10.1111/j.1530-9290.2012.00485.x

Appendix A

Appendix A gives a more detailed visualisation of the electrification potential of non-electrified localities in Trøndelag. Table A 1 shows the modelled power demand of the non-electrified localities and to which degree they can be electrified when testing for individual and simultaneous electrification. Figure A 1 to Figure A 8 shows more detailed maps of the individual electrification potential. Figure A 8 to Figure A 12 shows more detailed maps of the simultaneous electrification potential.

Table A 1: Electrification potential of all non-electrified localities in Trøndelag based on the modelled power demand of the localities. Results for individual and simultaneous electrification

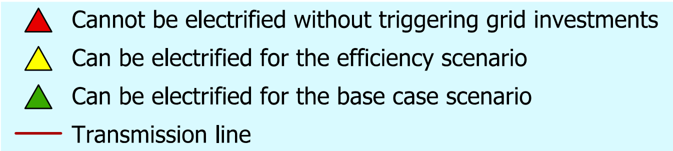
Locality name	Production capacity [tonnes]	Dimensioning power: base case [KVA]	Dimensioning power efficiency scenario [KVA]	Electrification potential individual electrification	Electrification potential simultaneous electrification
Persflua	6240	709	226	No scenario ok	Not analysed
Tristeinen	6240	709	226	No scenario ok	Not analysed
Brattvika Ii	1560	328	89	Scenario 1 ok	Scenario 1 ok
Feøyvika	5460	649	203	No scenario ok	No scenario ok
Vedøya	3120	423	135	Scenario 1 ok	Scenario 1 ok
Ånholmen	3900	470	157	Scenario 1 ok	Scenario 2 ok
Hofsøya	4680	518	180	Scenario 1 ok	Not analysed
Langskjæra	5460	649	203	Scenario 1 ok	Not analysed
Langskjæra Ii	3120	423	135	Scenario 1 ok	Not analysed
Måøydraga	2340	375	112	Scenario 1 ok	Not analysed
Tennøya	6240	709	226	No scenario ok	Not analysed
Valøyan	6240	709	226	No scenario ok	Not analysed
Flesa	1560	328	89	Scenario 1 ok	Not analysed
Omsøyholman	6240	709	226	Scenario 1 ok	Not analysed

Rauodden	2340	375	112	Scenario 1 ok	Not analysed
Singsholmen	7020	768	248	No scenario ok	Not analysed
Varden	7020	768	248	No scenario ok	Not analysed
Værøya Ø	4680	518	180	Scenario 2 ok	Not analysed
Lekafjorden Ii	3120	423	135	Scenario 2 ok	No scenario ok
Steinflesa	7020	768	248	Scenario 2 ok	No scenario ok
Båfjorden	1560	328	89	Scenario 1 ok	Scenario 2 ok
Båfjordstrand a	4680	518	180	Scenario 1 ok	No scenario ok
Digerneset	3120	423	135	Scenario 1 ok	Scenario 2 ok
Geitryggen	4680	518	180	Scenario 1 ok	Scenario 1 ok
Gjerdinga	5460	649	203	Scenario 1 ok	Scenario 1 ok
Kipholmen	3900	470	157	Scenario 1 ok	Scenario 2 ok
Klungset	5460	649	203	Scenario 1 ok	Scenario 1 ok
Lille Kvitholmen	4680	518	180	Scenario 1 ok	No scenario ok
Ramstadholm en	3900	470	157	Scenario 1 ok	Scenario 1 ok
Risværgalten	4680	518	180	Scenario 1 ok	Scenario 2 ok
Skrubbholme n	5460	649	203	Scenario 1 ok	Scenario 1 ok
Smineset N	4680	518	180	Scenario 1 ok	Scenario 2 ok
Storbukta	2340	375	112	Scenario 1 ok	No scenario ok
Ternskjæret Ii	4680	518	180	Scenario 1 ok	Scenario 2 ok
Brandsfjorde n	2340	375	112	Scenario 1 ok	Not analysed
Drevflesa	3120	423	135	Scenario 2 ok	Not analysed

Sandøya Iii	2340	375	112	Scenario 1 ok	Not analysed
Bondøya	4680	518	180	No scenario ok	No scenario ok
Geitholmen	3120	423	135	No scenario ok	No scenario ok
Harbakholmen	1560	328	89	Scenario 1 ok	Scenario 2 ok
Hjortøya	4680	518	180	Scenario 1 ok	Scenario 2 ok
Humulen	4680	518	180	Scenario 1 ok	Scenario 2 ok
Kråkøya	5460	649	203	Scenario 1 ok	Scenario 2 ok
Kyrøyene	7020	768	248	No scenario ok	No scenario ok
Lyngøy	4680	518	180	No scenario ok	No scenario ok
Nordgjæslingan	3900	470	157	No scenario ok	No scenario ok
Gjæsingen	3120	423	135	Scenario 1 ok	Not analysed
Jektholmen	3120	423	135	Scenario 1 ok	Not analysed
Krabbholmen	3120	423	135	Scenario 2 ok	Not analysed
Krabbholmen Ii	3120	423	135	Scenario 2 ok	Not analysed
Ratvika	3120	423	135	Scenario 1 ok	Not analysed
Seiskjæra	3120	423	135	Scenario 1 ok	Not analysed
Takflua	3120	423	135	Scenario 1 ok	Not analysed

Individual electrification potential

This section shows close-up images of all localities in Trøndelag and their electrification potential when testing for individual electrification. All figures have icons which are described by the same legend displayed below.



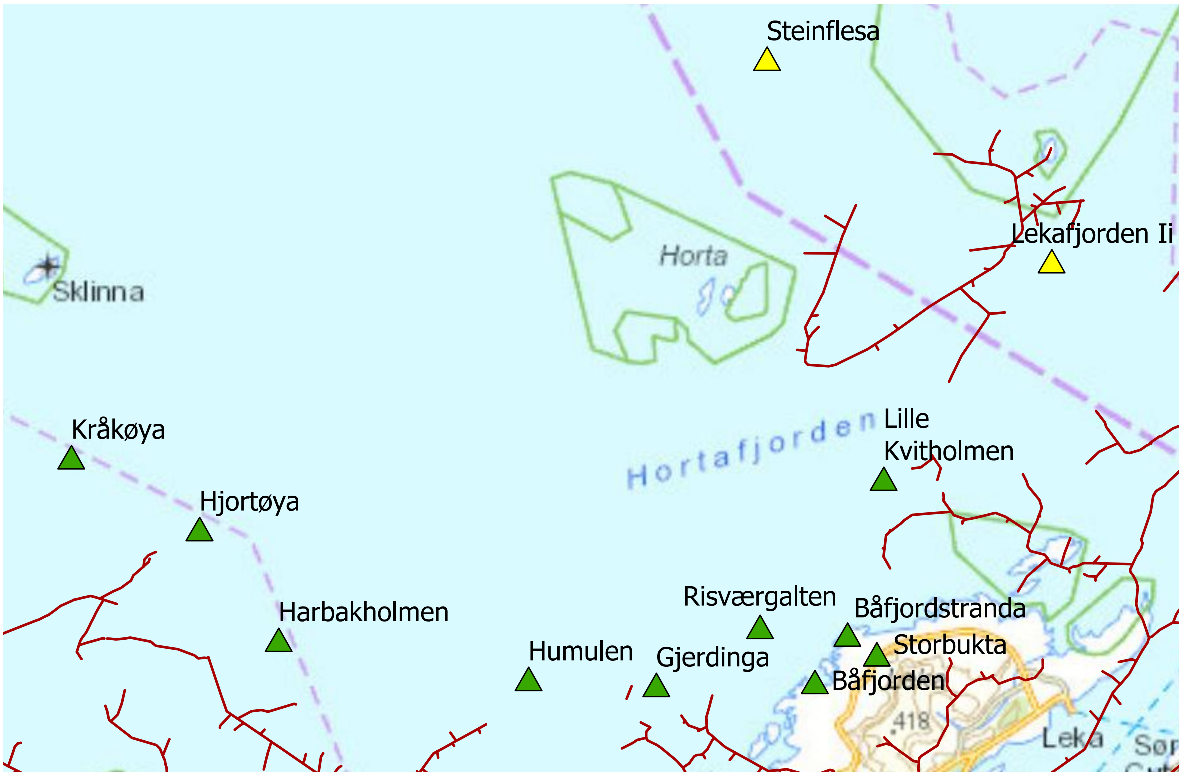


Figure A 1: Electrification potential when tested for individual electrification: Vikna and Nærøy

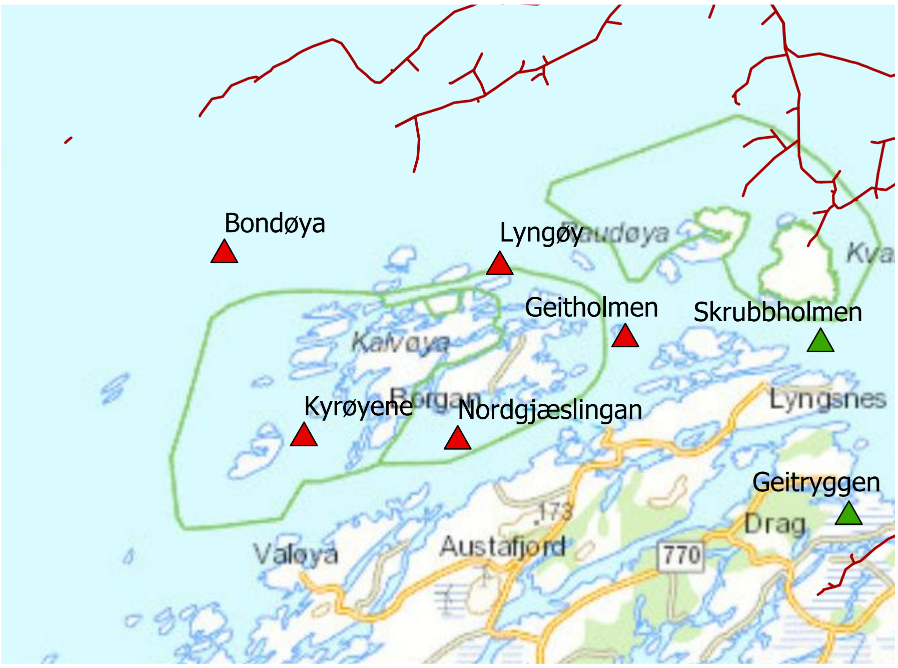


Figure A 2: Electrification potential when testing for individual electrification: Vikna

Figure A 3:Electrification potential when testing for individual electrification: Vikna, Nærøy

Figure A 4: Electrification when testing for individual electrification: Flatanger, Fosnes, Vikna, Nærøy

Figure A 5: Electrification potential when testing for individual electrification: Roan, Åfjord

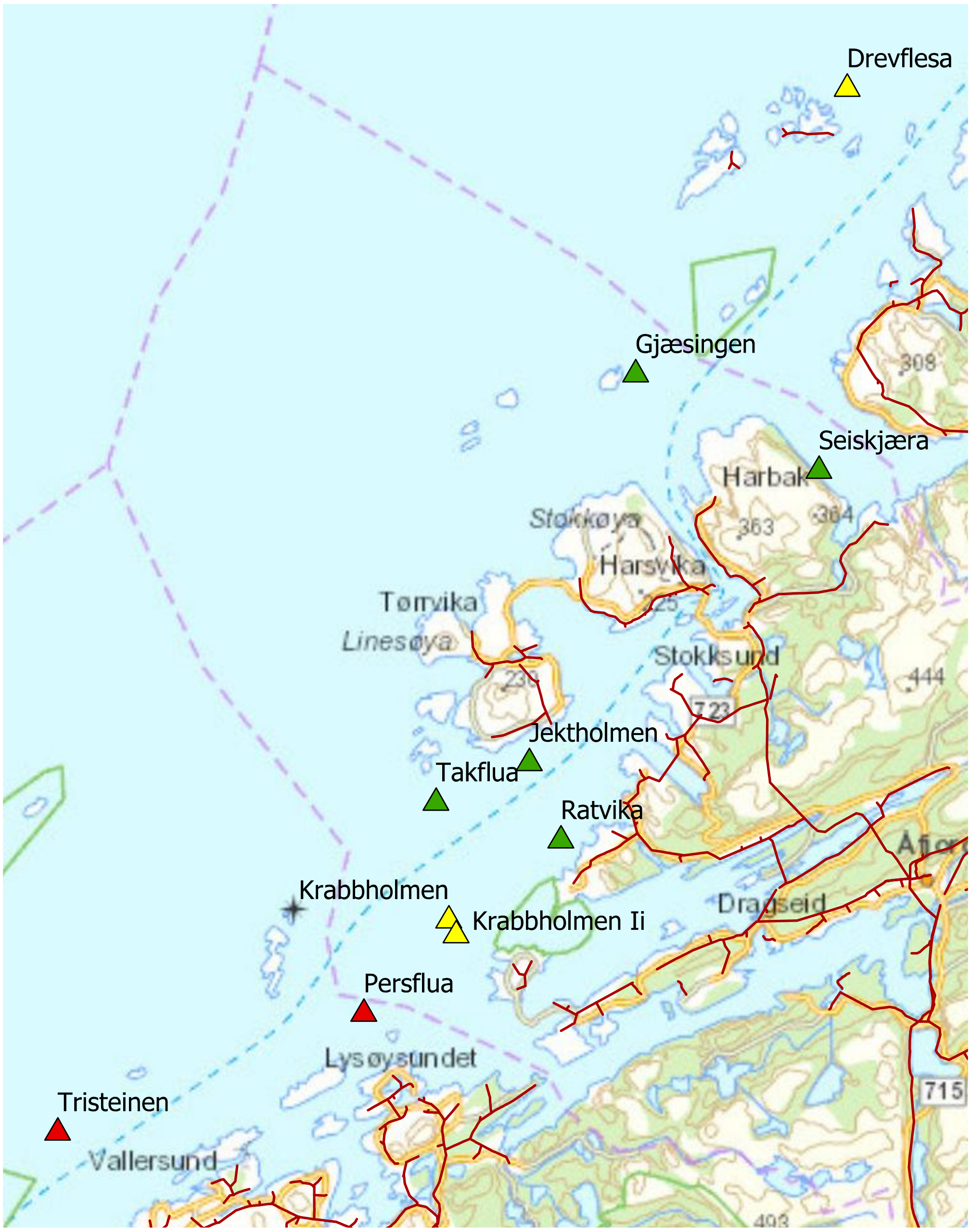


Figure A 6: Electrification potential when testing for individual electrification: Åfjord, Bjugn

Figure A 7: Electrification potential when testing for individual electrification: Hitra, Frøya

Figure A 8: Electrification potential when testing for individual electrification: Hitra, Frøya

Simultaneous electrification

This section shows close-up images of all localities in northern Trøndelag and their electrification potential when testing for simultaneous electrification. All figures have icons which are described by the same legend displayed below.

- ▲ (red) Cannot be electrified without triggering grid investments
- ▲ (yellow) Can be electrified for the efficiency scenario
- ▲ (green) Can be electrified for the base case scenario
- — Transmission line

Figure A 9: Electrification potential when testing for simultaneous electrification: Vikna, Nærøy

Figure A 10: Electrification potential when testing for simultaneous electrification: Vikna, Nærøy, Fosnes

Figure A 11:Electrification potential when testing for simultaneous electrification: Vikna, Nærøy

Figure A 12: Electrification potential when testing for simultaneous electrification: Vikna, Nærøy, Fosnes, Flatanger

Appendix B

Appendix B is divided into four parts. First, a list of the people whom have been of importance for the study is listed. Second, detailed data on the power demand of the localities is presented. Third, methodological figures for the electrification potential are shown. Fourth, several visualisations of GIS maps used when discussing the electrification potential of the localities in Trøndelag are presented.

1 Contact people

Table B 1: People who have been of importance in the study

Name	Company	Discussion points
Rune Paulsen	NTE	Discussion on barriers for electrification as seen from a grid company
Hilde Rollefsen Næss	NTE	Analysation of electrification potential
Oda Andrea Hjelme	NTE	Analysation of electrification potential
Per Osen	Trønder Energi	Analysation of electrification potential
Martin Næss	Nexans	Discussion on cable sizing for subsea cables
Jan Foosnæs	Former director NTE	Discussion on technical aspects of electrification
Edvin Hatlevik	Steinsvik	Discussion on power demand of feed barges
Leon Erik Heinesen	Steinsvik	Discussion on power demand of feed barges
Jan Rune Erikstad	Aquagroup	Discussion on power demand of underwater feeding system
Ragnar Sæternes	Sinkaberg Hansen	Discussion on energy demand of salmon farming localities
Merete Sandberg	Salmar	Provided data on energy demand of localities
Henny Førde	Måsøval	Provided data on energy demand of localities
Monicha Seternes	Måsøval	Provided data on energy demand of localities
Arnt Erik Tronvold	Mowi	Provided data on energy demand of localities
Line Rønning	Lerøy	Provided data on energy demand of localities
Bjørn Egil Sørensen	SalmoNor	Information of electrified localities
Jon Refsnes	Refsnes laks	Information of electrified localities

Frank Øren	Midt Norsk Havbruk	Information of electrified localities
Per Gunnar Knutshaug	Knutshaugfisk	Information of electrified localities
Jens Martin Olsen	Bjørøya	Information of electrified localities
Stian Rakke	Anteo	General discussion of topic
Alf Martin Sollund	Barentswatch	General discussion of topic
Marit Sandbakk	Enova	General discussion of topic
Ole Svendgård	Fornybarklyngen	General discussion of topic
Kari Tyholt	FI	General discussion of topic
Brage Mo	SINTEF Ocean	General discussion of topic

2 Power demand model

The power demand of the different sizes of feed barges has been scaled based on data of two existing feed barges. Table B 2 shows the modelling factors for the different components used in the energy demand model and Table B 3 explains the factors. Table B 4 show the results of the dimensioning power for the different sizes of the localities for the base case scenario and Table B 5 show the results for the efficiency scenario.

Table B 2: Modelling factors for components on feed barge. Identical for scenario 1 and 2.

Components on feed barge	Utilization factor	cos φ	Concurrency
Feeding system	0,7	0,86	1
Lights in cages	1	0,9	1
Living section	1	0,9	0,6
Crane	1	0,9	0,5
Dead fish handling system	1	0,9	1
Camera system	1	0,9	1
Technical outlets	1	0,9	1
Vessel	1	0,9	1
Battery pack	1	0,9	1

Table B 3: Description of the factors used in Table B 2

Factor	Description
Utilization factor	The utilization factor is a number between 0-1 indicating the percentage of the peak power the component is to be modelled after
cos φ	Power factor which indicates the efficiency of the system and shows the relationship between KW and KVA.
concurrency	Concurrency is a number between 0-1 indicating the simultaneousness the components must be modelled after.

Table B 4: Dimensioning capacity for all components on feed barge for the base case scenario. KVA is kilo volt-ampere which is the unit for the dimensioning power. A safety factor of 1,5 is added to the total.

Production capacity [tonnes]	Feeding system [KVA]	Cage lights [KVA]	Living section [KVA]	Equipment [KVA]	Vessel [KVA]	Total
780	22	6	3	44	111	280
1560	44	13	7	44	111	328
2340	66	19	10	44	111	375
3120	88	25	13	44	111	423
3900	110	32	17	44	111	470
4680	132	38	20	44	111	518
5460	210	44	23	44	111	649
6240	240	51	27	44	111	709
7020	270	57	30	44	111	768

Table B 5:Dimensioning capacity for components on feed barge for the efficiency scenario. KVA is kilo volt-ampere which is the unit for the dimensioning power. A safety factor of 1,2 is added to the total.

Production capacity [tonnes]	Feeding system [KVA]	Cage lights [KVA]	Living section [KVA]	Equipment [KVA]	Vessel [KVA]	Battery pack [KVA]	Total
780	10	3	2	44	111	-126	66
1560	21	5	5	44	111	-126	89
2340	31	8	7	44	111	-126	112
3120	41	10	9	44	111	-126	135
3900	51	13	12	44	111	-126	157
4680	62	15	14	44	111	-126	180
5460	72	18	16	44	111	-126	203
6240	82	20	19	44	111	-126	226
7020	93	23	21	44	111	-126	248

3 Electrification potential: Methodology

The electrification potential has been studied for individual electrification where each locality has been tested one by one and for simultaneous electrification where all localities connected to the same transmission line is tested simultaneously. Figure B 1and Figure B 2 show the magnitude of the loads are connected to the same transmission line.

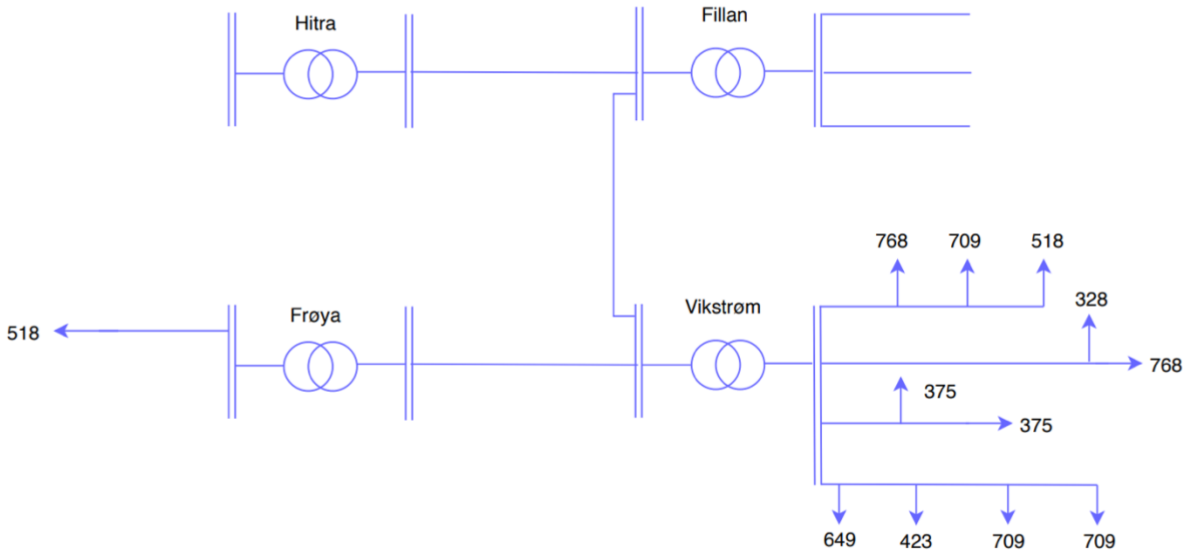


Figure B 1: Visualisation of the power demand connected to which transmission line for Hitra and Frøya in southern Trøndelag. All numbers in KVA

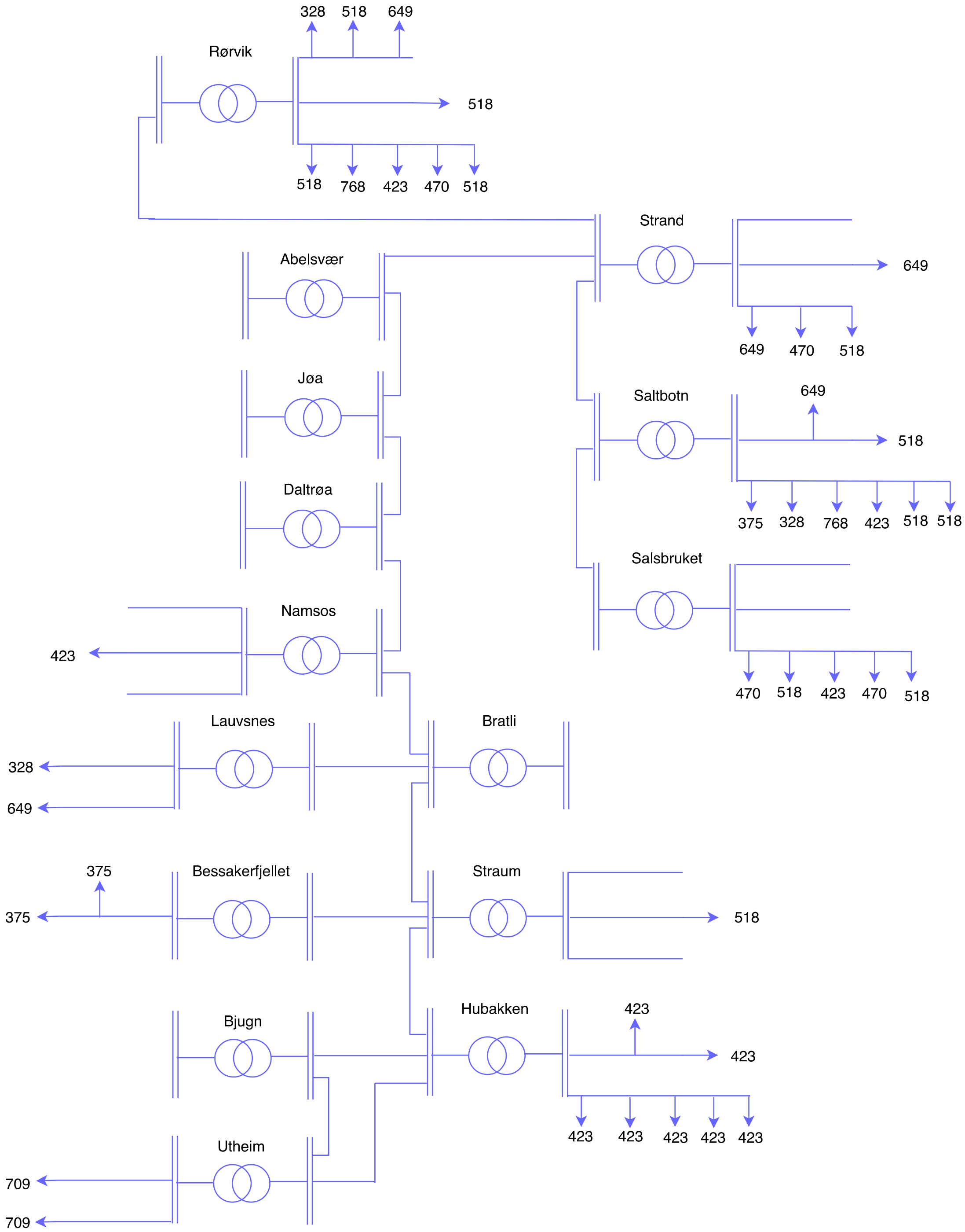


Figure B 2:Visualisation for the power demand connected to which transmission line in Bjugn, Flatanegr, Fosnes, Nærøy, Roan, Vikna and Åfjord. All numbers in KVA

4 Electrification potential: Results

This section shows the figures used in the results and discussion of the electrification potential of the salmon farming localities in Trøndelag.

4.1 Reducing barriers through moving the connection point

Figure B 3 illustrates how the electrification potential can be increased by changing the connection point of some localities. When testing for simultaneous electrification in northern Trøndelag all localities were tested at once. For localities which are connected to the same transmission line the electrification potential is challenged in areas where the grid is weak. A way to increase the electrification potential is to move the connection point of some localities to transmission lines with less challenges. In Figure B 3 Båfjorden, Båfjordstranda and Storbukta all have the same connection point to the grid. In the original analysis, the electrification potential was tested when they were all connected to the point labelled old connection point. This transmission line is located far from a transformer station and had high loads connected to it, which led to the three localities not being able to electrify without triggering grid investments. A way to increase the electrification potential is to move the connection point to the transmission line where Risværgalten and Gjerdinga is connected to the point labelled new connection point. This transmission line has fewer loads connected and is closer to the transformer and thereby has less challenges.

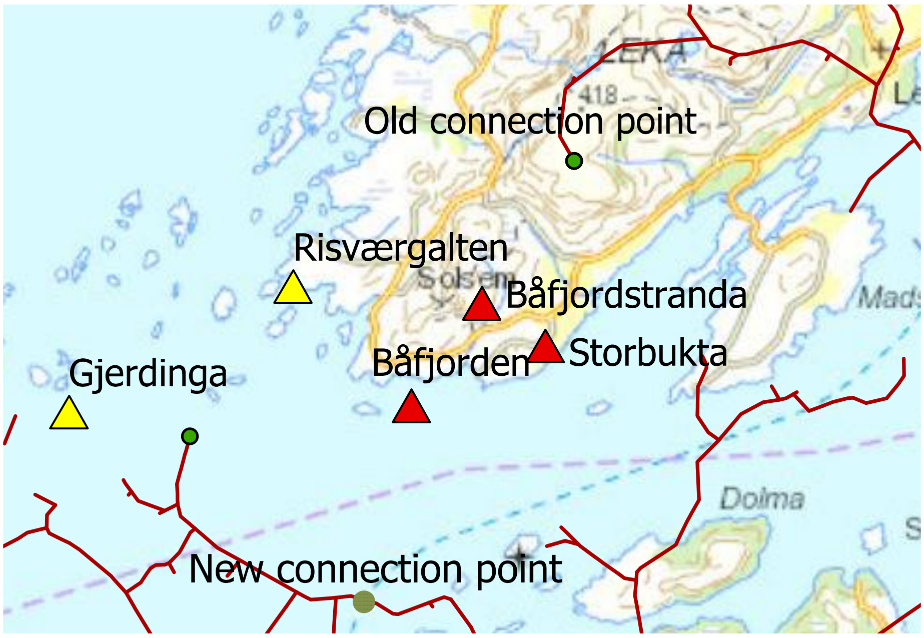


Figure B 3: Original connection point where the encircled red localities originally were connected to the same transmission line. The encircled localities within the ellipse have the connection point to the grid pointed out.

4.2 Collaboration potential

Figure B 4a and Figure B 4b illustrates which localities have the potential of collaborating when connecting to the mainland grid. This can contribute to reducing the costs of electrification.

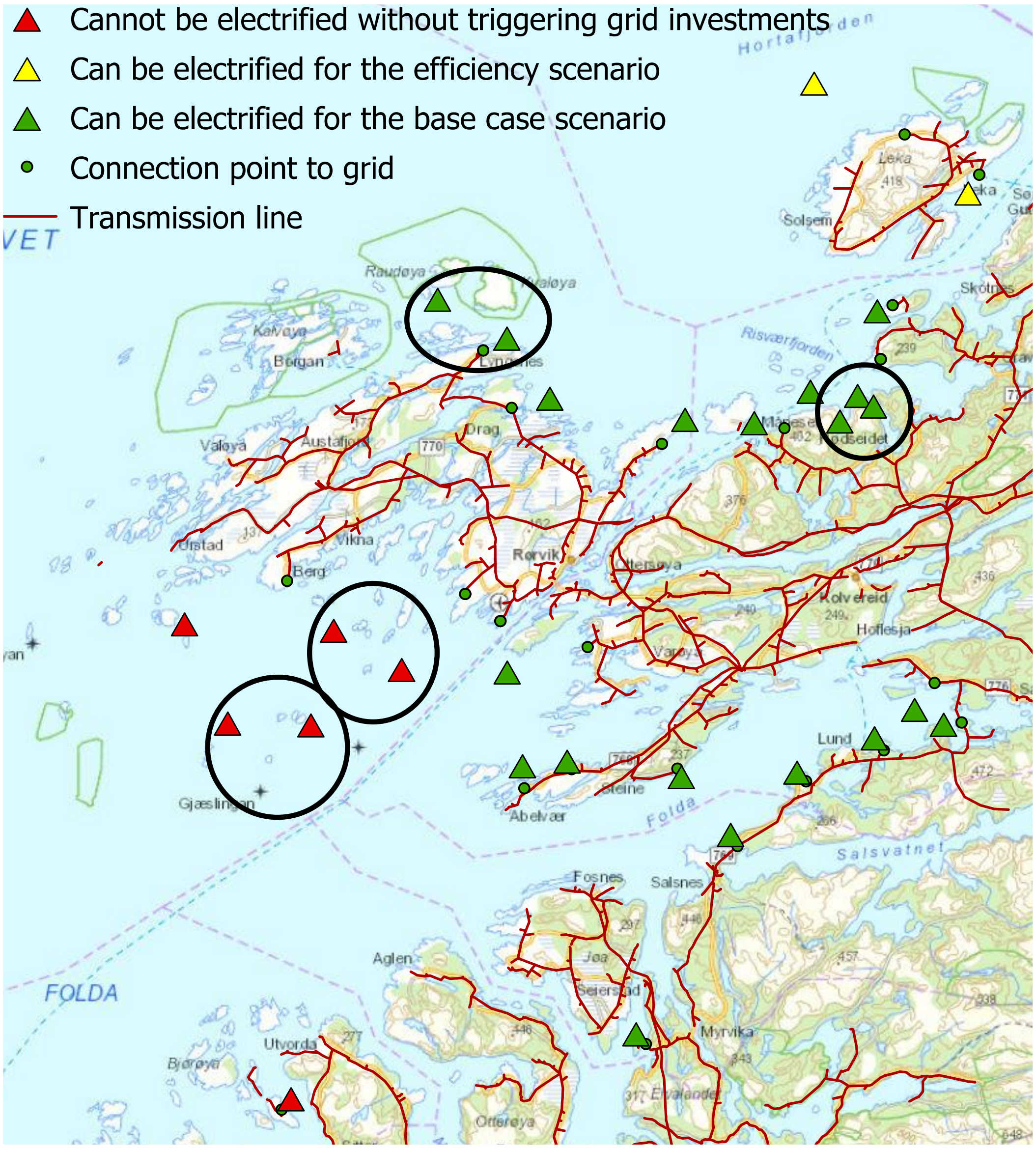


Figure B 4a: Collaboration potential for non-electrified localities in northern Trøndelag. The encircled localities show the localities which has the possibility of sharing parts of the subsea cable used for electrification which can contribute to reducing the costs.

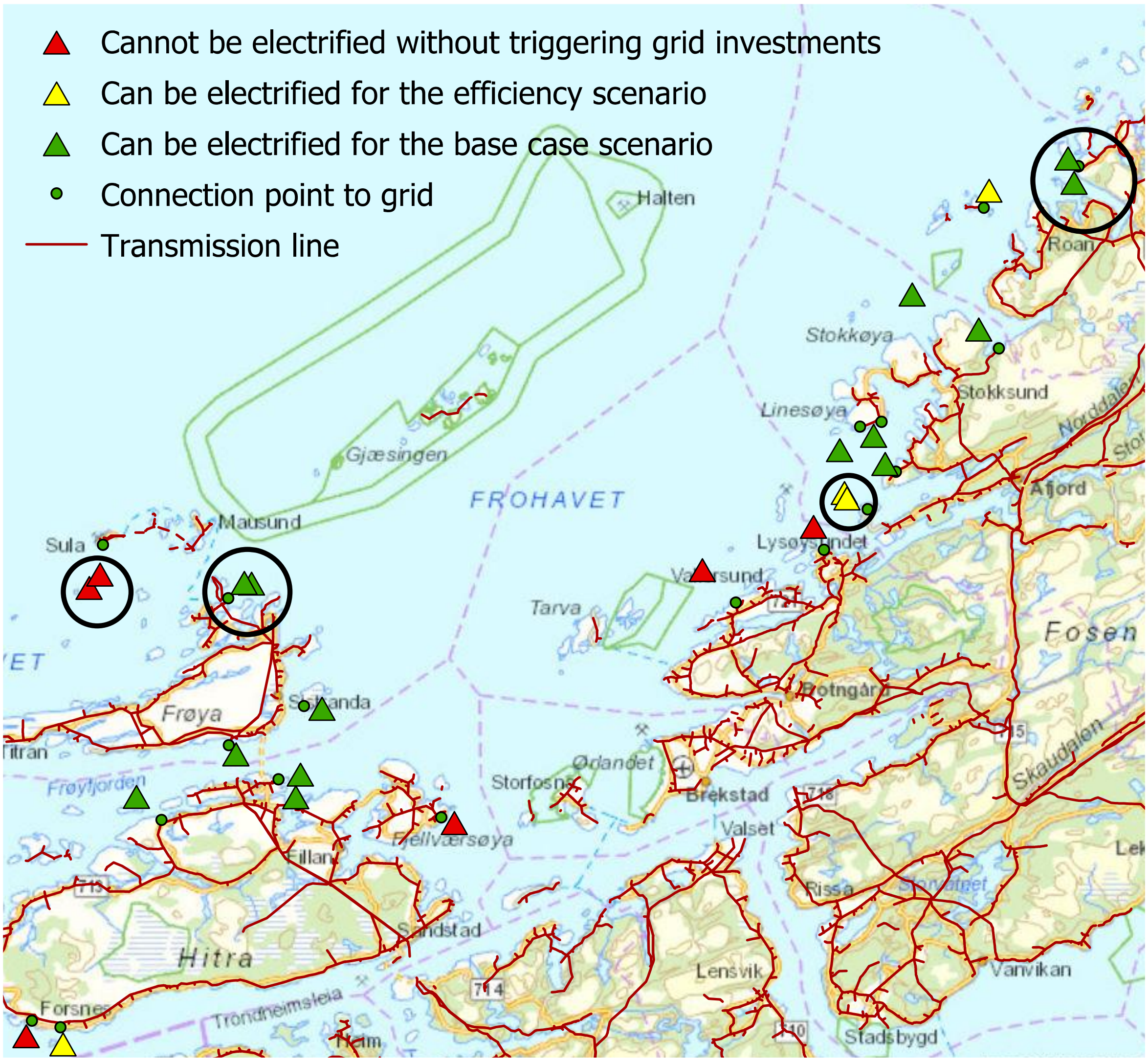


Figure B 4b: Collaboration potential for non-electrified localities in southern Trøndelag. The encircled localities show the localities which has the possibility of sharing parts of the subsea cable used for electrification which can contribute to reducing the costs.

4.3 Voltage connection

The voltage demand of the subsea cables can cause barriers in electrification as the feed barge then requires a high voltage room with permission only for authorised personnel. The localities which require high voltage installations have thereby been studied. For the base case all localities required high voltage subsea cables, the results below are therefore for the efficiency scenario.

The equations below were used to calculate the voltage loss. The voltage loss in the cable cannot surpass 5%. All voltages over 1000 V are considered as high voltage, and it was thereby tested for which localities had a voltage loss under 5 % with a subsea cable of 1000 V.

$$R = \rho * \frac{l}{A}$$

$$I = \frac{1000 * P}{\sqrt{3} * \cos\varphi * V_{L-L}}$$

$$\Delta U = R * I * \sqrt{3} * cos\varphi$$

Table B 6: Explanation of factors used in calculating of the voltage loss of the subsea cable for non-electrified localities in Trøndelag

Symbol	Description	Value
ρ	Resistivity of cable	0,029
l	Length of cable	Varies for each locality based on their distance to the electricity grid
A	Area of cable	240 mm^2
P	Power	Power demand of feed barge as shown in Table B 4 and Table B 5
$\cos\varphi$	Power factor	0,9
V_{L-L}	Line to line voltage	1000 V
I	Current	Calculated for all localities
R	Resistance	Calculated for all localities

Figure B 5 and Figure B 6 show which localities that can be connected to the grid with a low voltage subsea cable and which demand a high voltage cable. All results are shown for the efficiency scenario as all localities need a high voltage connection for the base case scenario.

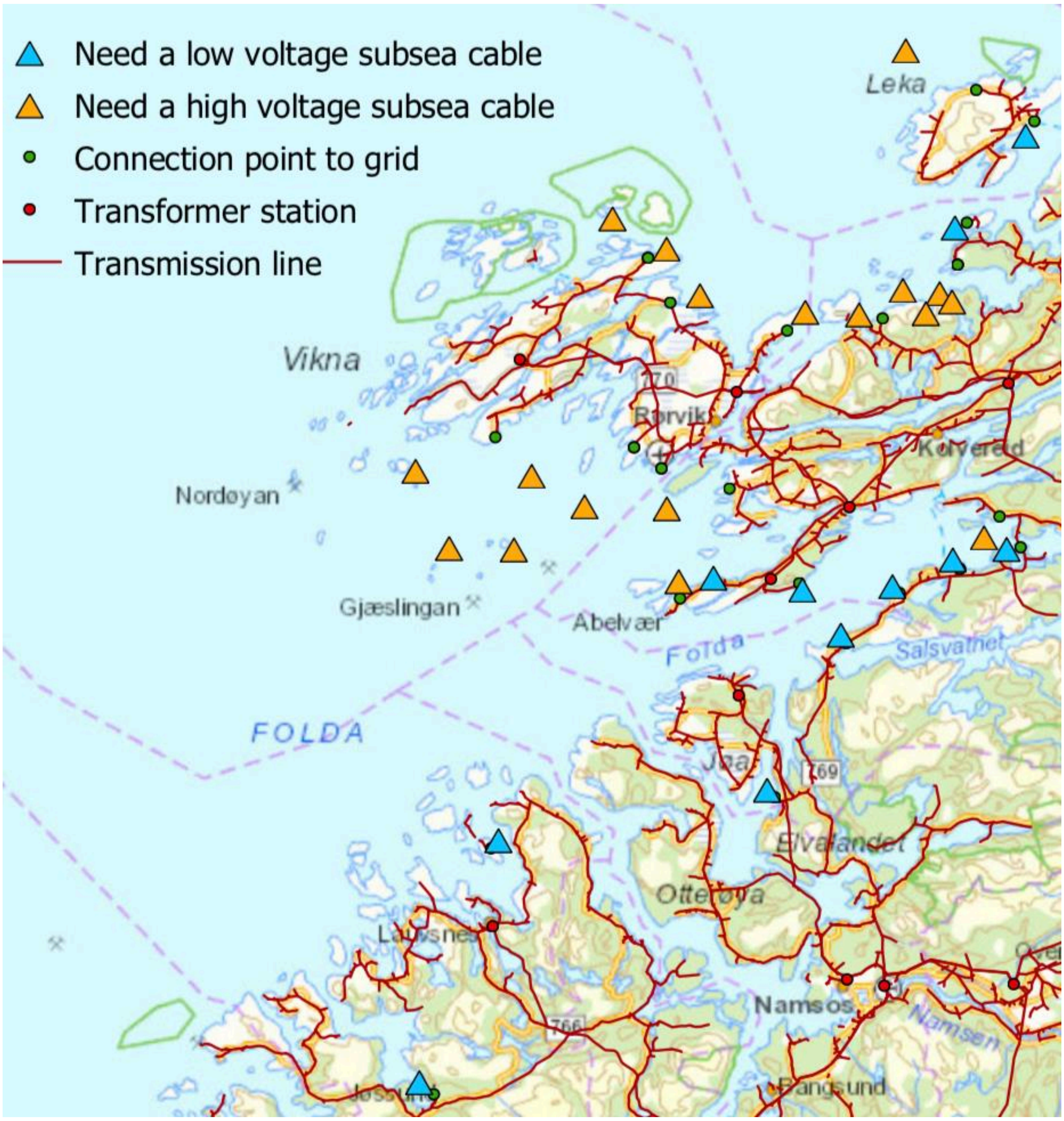


Figure B 5: Visualisation of the voltage level needed in the event of electrification for the non-electrified localities in northern Trøndelag. The results are shown for the efficiency scenario as all localities need a high voltage connection for the base case.

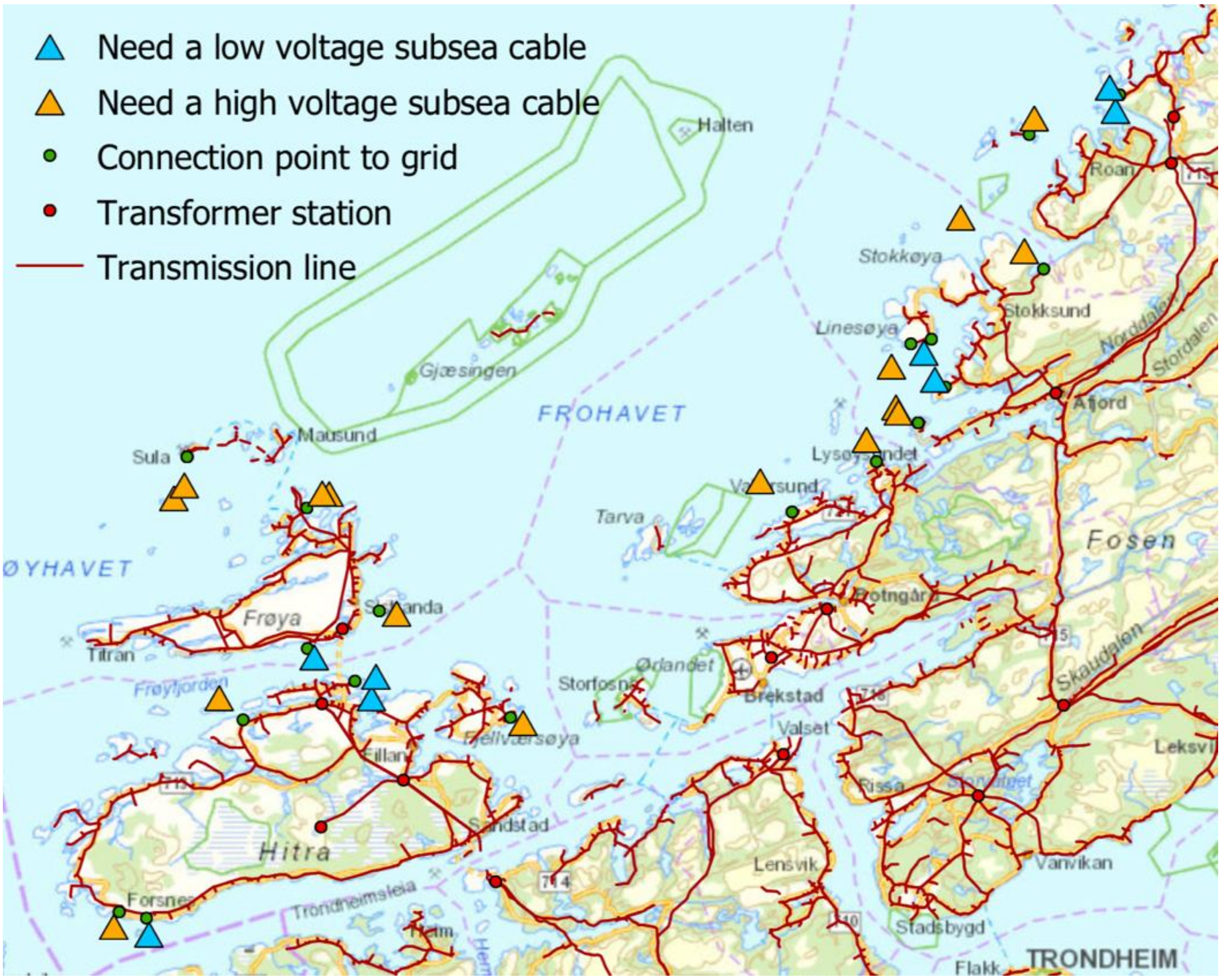


Figure B 6: Visualisation of the voltage level needed in the event of electrification for the non-electrified localities in southern Trøndelag. The results are shown for the efficiency scenario as all localities need a high voltage connection for the base case.

NTNU
Norwegian University of
Science and Technology