Master's thesis

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

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Scenarios for the Decarbonization of Energy Supply for Salmon Aquaculture in Norway

Master's thesis in Industrial Ecology
Supervisor: Johan Berg Pettersen

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Abstract

The Norwegian salmon farming industry is expected to grow in the coming decades. In order to achieve this growth, ecosystem and salmon lice challenges need to be addressed. New farming technologies and methods such as salmon grow-out in land-based recirculating aquaculture systems (RAS), offshore farming, closed containment systems at sea and post-smolt production are developed to alleviate these pressures. With the increased implementation of new technologies and methods, the sectoral pattern in energy consumption and carriers is expected to change and thereby also affecting industry emissions. The salmon farming industry is also required to reduce greenhouse gas emissions to meet the 40% reduction target in 2030 and 80% in 2050.

A 3% annual production growth scenario for the farmed salmon industry from 2020 to 2050 differentiated by production cycle technology has been modelled. The production cycles include the energy requirements from smolt to harvest ready salmon of 4 kg, also taking into account the requirements of the vessels. Four production cycles are differentiated by the farming technology in the grow-out phase: traditional open net pen farming, land-based RAS, offshore farming and closed containment systems in the sea. Based on the production volumes and different scenarios for sectoral energy consumption, the sectoral energy emissions are derived. This includes the greenhouse gas emissions from the combustion of fossil fuels and the production emissions for electricity used in the industry. The emission targets are determined with reference to the 2020 emissions using the current technology level, and the industry targets in 2030 and 2050 are accordingly 259 000 tons CO_2 and 86 400 tons CO_2.

The energy emissions from all scenarios modelled are unable to achieve the 2030 and 2050 emission targets. Further energy efficiency measures and transition to low-carbon energy carriers need to be implemented to achieve a sectoral energy demand sufficiently efficient and decarbonized to meet the emission targets. The results indicate that in the short-run, addressing the emissions from the vessels through increased electrification and application of hydrogen will be an effective measure to meet the targets. In the long-run, considerable measures need to be implemented for all production technologies because of the increase in energy requirements of new technologies and production volume. With the increased electrification and application of hydrogen for the farming operations, the carbon intensity of the electricity mix becomes increasingly relevant and further decarbonization of the electricity mix is needed to ensure the 2050 emission target is achieved.

Sammendrag

Den norske lakseoppdrettsnæringen forventes å vokse de kommende tiårene. For å oppnå denne veksten må økosystem- og lakselusutfordringer løses. Nye oppdrettsteknologier og metoder som matfiskproduksjon i landbaserte resirkulerende akvakultursystemer (RAS), offshore oppdrett, lukkede merdkonsepter til sjøs og produksjon av post-smolt blir utviklet som en løsning på miljøproblemene. Med den økte implementeringen av nye teknologier og metoder, forventes det at mønsteret i næringens energiforbruk-og bærere vil endres og dermed også påvirke industriens utslipp. Oppdrettsnæringen er også pålagt å redusere klimagassutslipp for å oppnå klimamålene, en reduksjon i utslipp på 40 % i 2030 og på 80 % i 2050.

Et scenario for 3% årlig vekst i produksjon av oppdrettslaks fra og med 2020 til og med 2050, differensiert etter teknologien brukt i produksjonssyklus, er modellert som utgangspunkt. Produksjonssyklusene inkluderer energibehovet fra smolt til slakt av laks på 4 kg, dette inkluderer også behovet til fartøyene. Fire produksjonssykluser skilles av oppdrettsteknologien i utvekstfasen: tradisjonelle åpne merder, landbasert RAS, offshore oppdrett og lukkede merdkonsepter i sjøen. Basert på produksjonsvolumene og forskjellige scenarier for næringens energiforbruk kan energiutslippene beregnes. Dette inkluderer klimagassutslipp fra forbrenning av fossile brensler eller produksjonsutslipp for elektrisitet som brukes i industrien. Næringens utslippsmåle bestemmes med henvisning til 2020-utslippene beregnet for antagelser om dagens teknologinivå, og målene i 2030 og 2050 er følgelig 259 000 tonn CO_2 og 86 400 tonn CO_2.

Energiutslippene fra alle modellerte scenarier oppnår ikke utslippsmålene i 2030 og 2050. Ytterligere energieffektiviseringstiltak og overgang til lavustlippsenergibærere må implementeres for å sørge for å oppnå utslippsmålene. Resultatene indikerer at på kort sikt vil tiltaktene rettet mot fartøy gjennom økt elektrifisering og anvendelse av hydrogen være effektivt for å nå målene. På lengre sikt må det iverksettes betydelige tiltak for alle produksjonsteknologier for å motvirke økningen i energibehovet til nye teknologier og i produksjonsvolumet. Med den økte elektrifiseringen og anvendelsen av hydrogen til oppdrettsvirksomheten blir karbonintensiteten i strømforsyningen stadig mer relevant, og ytterligere dekarbonisering av strømleveransen er nødvendig for å sikre at utslippsmålet i 2050 oppnås.

Preface and Acknowledgements

This master's thesis is submitted as part of the two-year MSc Industrial Ecology in the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU). The work was conducted during the autumn semester of 2020, and it relates to the project thesis *Energy Management in Norwegian Salmon Aquaculture* from autumn 2019. The thesis can be seen in relation to projects conducted with the Renewable Energy Cluster (RENERGY) and the previous projects carried out by other students on energy use and management in the aquaculture industry.

I would like to thank my supervisor Johan Berg Pettersen for his insights and motivation when the work seemed overwhelming and overly complex. I have valued our weekly meetings as it has been a rare certainty in this otherwise uncertain semester. I would also like to thank Kari Tyholt at NCE Aquatech Cluster and Marit Sandbakk at ENOVA for providing contacts and useful materials. Lastly, I am grateful for the information and contributions provided by industry contacts.

Trondheim, 28.01.2021

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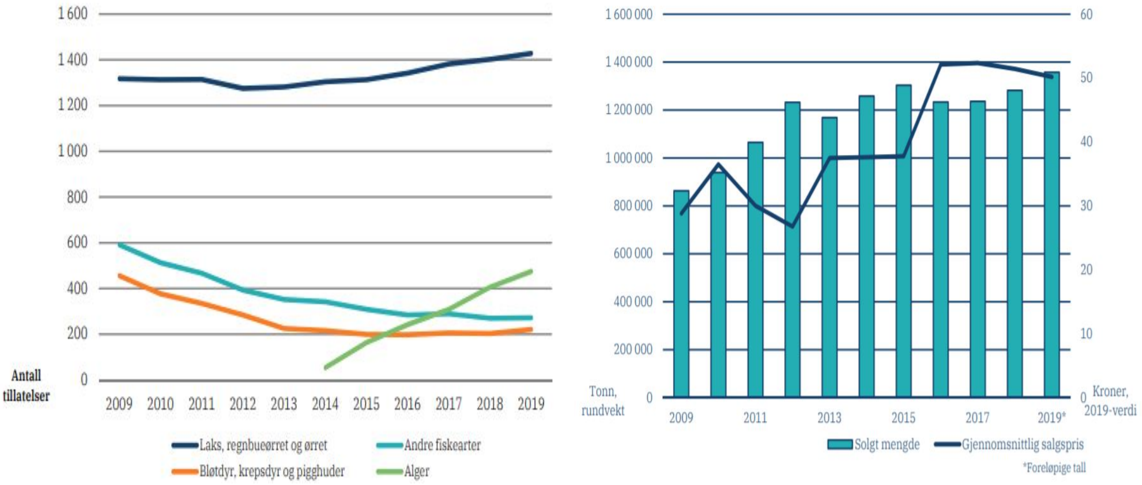
List of Abbreviations

CAGR - Compound annual growth rate
CCS - Closed containment system
GHG - Greenhouse gas
HOG - Head on gutted
LBCC - Land-based closed containment
LCA - Life-cycle assessment
MAB - Maximum allowable biomass
ONP - Open net pen
RAS - Recirculating aquaculture systems
ROV - Remotely operated (underwater) vehicle
SEC - Specific energy consumption

1. Introduction

1.1 Background and Motivation

In 2019, the Norwegian salmon farming industry sold approximately 1,36 million ton salmon (Statistics Norway, 2020a). The future production potential of Norwegian salmon and trout farming was estimated to 5 million tons in 2050 by Olafsen et al. (2012). This was then cautiously considered in the governmental ocean strategy given the concerns about salmon lice, the local environment and climate (Nærings- og fiskeridepartementet and Olje- og energidepartementet, 2017). The 5 million tons growth scenario corresponds to an average compound annual growth rate in production of salmon and trout of just over 4% from 2010 to 2050. Now, ten years later, the growth is stagnating due to the limited number of new farming licenses. These recent developments are displayed in the following Figure 1.1. In Figure 1.1(a), the navy line indicates that the number of farming licenses has been leveled at around 1300-1400 licenses for the past decade. This is also reflected in the salmon sales in Figure 1.1(b) which have been around 1,2 - 1,3 million tons round weight since 2012. At the same time, in the same figure, the average price of salmon has increased from about 30 to 50 NOK per kg indicating considerable demand for the product.



(a) Developments in the number of farming licenses for salmon and trout (navy line) and other species.

(b) Amount of salmon sold and average price.

Figure 1.1: Amount of salmon sold and average price, and developments in the number of salmon and trout licenses from Fiskeridirektoratet (2020d).

The number of new licenses is limited by regulations aiming to protect ecosystems and fish welfare (Nærings- og fiskeridepartementet, 2006). Current production based on existing licenses is also monitored and a traffic light system is in place to ensure ecosystem and fish welfare. The country is divided into 13 production zones and the occurrence of salmon lice in these areas determine the traffic light which sets production limits (Havforskningsinstituttet, 2019), a map of the zones and their current status is included in Appendix A.5. A green light allows for production growth of 6% every other year, a yellow light for steady-state and a red light can result in a production reduction of up to 6% (Havforskningsinstituttet, 2019). Misund and Tveterås (2019) find that even if all the zones are green, the 3% average growth in production per year would be insufficient to reach the 2050 goal of 5 million tons. With the current salmon lice situation and regulations, an average production growth of 1,5% per annum ought to be achievable (Misund and Tveterås, 2019).

The above-mentioned factors limiting production, drive new technology developments to facilitate further production growth. The developments include solutions to move production to areas with no lice, increasing control over the rearing environment or transferring larger fish to sea which are more robust against lice. The following summarises technology trends in Norwegian salmon aquaculture: an increase in the production of post-smolt and the adoption of offshore aquaculture, land-based production in recirculating aquaculture systems (RAS) and closed and semi-closed containment systems at sea (Ernst & Young, 2019; Heen et al., 2017). In recent years considerable investments have been made in these technologies, approximately 8 billion NOK have been or are to be invested under the Directorate of Fisheries development license permit program for the exploration of new farming technologies (Misund and Tveterås, 2019). The introduction of new farming technologies to facilitate industry growth has potential implications for the future energy consumption of the Norwegian salmon farming sector. Hilmarsen et al. (2018) finds that electricity consumption of Norwegian salmon aquaculture in 2017 of 1,3 million tons would require somewhere between 7,8 - 11,7 TWh per year if all production were moved to land-based RAS. The energy requirements would correspond to 5-8 % of Norwegian energy production of 147,2 TWh (Hilmarsen et al., 2018). The increased adoption of new farming technologies therefore has the potential to increase the sectoral energy consumption of Norwegian salmon aquaculture.

Concurrent with the environmental challenges of salmon lice is the increasing concern about greenhouse gas (GHG) emissions from salmon production which drives global warming. In Norway, about half of the salmon farming localities are powered by diesel generators and close to all vessels require fossil fuels (ABB and Bellona, 2018; Winther et al., 2020). The direct annual CO_2 emissions from the Norwegian salmon farming operations, including feed barges and vessels have been estimated to approximately 400 000 tons (ABB and Bellona, 2018). Norway is a signatory of the Paris Agreement and aims to become a low-emission society by 2050 (Klimaloven, 2018). On the way to the 2050 goal, domestic emissions ought to be reduced by 40% in 2030 (Meld.St.41 (2016-2017), 2017). Apart from the feed, the on-site energy requirements are a considerable driver of GHG-emissions in the salmon production life-cycle (Winther et al., 2009). The Norwegian Seafood Federation has in their sustainability strategy for aquaculture 2030 also pointed out the need for efforts on energy efficiency and reduction in fossil fuels in salmon production (Norwegian Seafood Federation, 2014). With the potential increase in energy consumption from the adoption of new farming technologies, increasing energy efficiency and transitioning to low-carbon energy solutions will become increasingly relevant in order to achieve the emissions targets.

Energy consumption has not been a major concern for the salmon farming industry, and little attention has been paid to energy efficiency in the system design (Badiola et al., 2018). Moreover, with the increasing number of farming localities with feed barges connected to shore-side electrical power, emissions are paid less attention and operations are becoming more efficient largely due to efficiency gains from replacing the diesel generator. The replacement of a generator with shore-side electricity has in many cases been beneficial to farming companies because of the lower fuel costs and external funding for such projects (ABB and Bellona, 2018; DNV GL, 2018). ENOVA SF has provided state funding to farming companies wishing to connect the feed barges to shore-side electricity, so far 87 projects have received funding (ENOVA SF, 2019). Currently, about half of the Norwegian farming localities are connected and there are still projects undergoing connection to shore-side electricity (ABB and Bellona, 2018; Kontali et al., 2020). A previous thesis investigated the electrification potential of salmon localities in Trøndelag county, finding that about 80% could be electrified without considerable grid investments (Møller, 2019).

Considering the expected industry growth, rural production location, new energy demanding technologies, and the limitations of the power grid, shore-side electricity might not be economically viable or able to ensure the stable energy supply salmon production requires (THEMA Consulting, 2020). In order to apply shore-side electricity as a mitigation measure in the industry, these issues need to be addressed. Other low-carbon energy solutions such as wind power, solar power or hydrogen ought to be considered as alternative solutions to ensure a reliable energy supply whilst achieving the emission reduction goals. The production expansion and transition to a decarbonized energy supply will also likely result in other environmental impacts such as resource use for infrastructure expansion of the power lines or land use for land-based RAS production. However, the main motivation of this thesis is to provide insights on the development and changes in the energy requirements of Norwegian salmon aquaculture, and the achievement of decarbonized energy supply. How can the sector fulfill their growth ambitions and be part of a low-emission society in 2030 and 2050?

1.2 Problem Formulation

The goal of this thesis is to acquire an understanding of the production potential of new salmon farming technologies, the implications for energy consumption, and the role of Norwegian salmon aquaculture in a low-emission society. The questions this thesis aims to answer are the following:

1. How do new production technologies and methods affect the energy requirements of the industry? Specifically, the production of post-smolt, closed containment aquaculture, salmon grow-out in land-based Recirculating Aquaculture Systems (RAS) and offshore farms.
2. What are the potential energy requirements of the Norwegian salmon farming industry in 2030 and 2050, and how does the energy consumption change?
3. What decarbonization measures for the energy supply and efficiency improvements in salmon farming technologies need to be implemented to allow for industry growth whilst meeting the emission targets?
4. What are potential environmental implications associated with the adoption of new farming technologies and decarbonized energy supply in Norwegian salmon aquaculture?

1.3 Approach

The following approach is adopted to determine the scenarios for the decarbonization of energy supply for salmon aquaculture in Norway and answer the research questions in the above Section 1.2:

1. Provide an overview of new production technologies and identify developments in Norwegian salmon production. Create scenario for growth in salmon production volume towards 2050.
2. Determine the energy requirements for the farming technologies and create sectoral scenarios.
3. Model the sectoral energy consumption and the resulting emissions.
4. Determine emission targets based on base line energy requirements in 2020. energy
5. Analyse the effect of different energy efficiency measures and low-carbon energy solutions on sectoral energy consumption and emissions.
6. Identify energy efficiency measures and low-carbon energy solutions necessary to achieve the sectoral emission targets.
7. Evaluate the potential implications of adopting new farming technologies and low-carbon energy carriers for infrastructure requirements and other environmental concerns.

1.4 Thesis Outline

In the following Section 2, existing studies related to new farming technologies, the energy requirements of the production technologies in the industry and the potential of low-carbon energy solutions are presented. Next, Section 3 includes a system description of the study, and the method used to determine sectoral energy consumption and the associated emissions. The section also includes a description of the data collected and the scenarios for assumed realistic decarbonization of the sectoral energy consumption. Then in Section 4, the results are presented and discussed with reference to existing studies and emission targets. Moreover, a discussion on other challenges and opportunities to the adoption of new farming technologies and low-carbon energy solutions is included. Lastly, the conclusion of the thesis is presented in Section 5. Additional information and calculations are provided in Appendix A.

2. Theory and Literature Review

This section provides information on existing studies related to energy use in salmon aquaculture. Then it moves on to describing the production stages of conventional salmon aquaculture. Following this, new farming technologies and the potential changes in energy consumption are considered. Lastly, the section provides an overview of relevant low-carbon energy technologies for the Norwegian salmon farming industry.

2.1 Existing Literature

The current studies relating to energy consumption in salmon farming are often life-cycle assessments (LCA) based on a single production technology, or a stage in the production cycle. For instance, Badiola et al. (2012, 2017, 2018) has focused on the energy consumption and management in recirculating aquaculture systems (RAS). On the other hand, Pelletier et al. (2009) has conducted LCAs of open net pen salmon production for multiple countries, finding considerable differences in the environmental footprint. Even though the technology is the same, factors such as feed composition, disease, feed conversion ratio and feeding technology might influence the environmental footprint of salmon farming systems (Pelletier et al., 2009).

Determining the environmental impacts of farmed salmon and different farming concepts is a relatively new study field, and the methods are being developed. Bohnes and Laurent (2019) and Bohnes et al. (2019) review existing LCA methodology and findings on various aquaculture systems, and provide recommendations for improvements and how the results might affect policy decisions. In a similar manner, Philis et al. (2019) considers what the methodology of LCAs conducted for salmon aquaculture entail. Henriksson et al. (2012) also provides a review of LCA methodologies in aquaculture systems including a considerable number of species. Lastly, Cao et al. (2013) evaluates LCAs for multiple seafood species and finds that the methods are unable to capture the socio-economic and local ecological impacts of the farming systems.

An extensive carbon footprinting of Norwegian seafood products was carried out in 2009, and later updated in 2020 (Winther et al., 2009, 2020). These studies also included inventories on energy for farmed salmon, and different factors during the production cycle that might influence the energy requirements and footprint of the products. A recent study by Hilmarsen et al. (2018) also looks at the Norwegian salmon farming, but is more concerned with the potential implications of post-smolt production and salmon grow-out in RAS on land use, carbon footprint, and energy and water consumption.

Multiple studies are comparing the environmental impacts of alternative farming methods. Liu et al. (2016) has conducted a comparison of the economic performance and carbon footprint of two different salmon farming systems, land-based closed containment RAS and open net pen production. Ayer and Tyedmers (2009) considered the environmental impacts of the three different salmon production systems; a marine floating bag system, a land-based saltwater flow-through system and a land-based freshwater recirculating system. Studies on the environmental impacts of different systems have also been conducted for trout farming, d'Orbcastel et al. (2009) conducted an LCA of a flow through system and a hypothetical low head recirculating system. Similarly, Samuel-Fitwi et al. (2013) evaluates an extensive system, an intensive system and a recirculating aquaculture system in trout farming. McGrath et al. (2015) has not conducted a comparative study, but has considered a forward-looking farming technology, a floating solid wall aquaculture system for salmon aquaculture in the grow-out phase.

In general, the findings from these papers suggest that, the more closed the production system, the better the performance on local environmental parameters such as eutrophication and water consumption. However, the closed systems score worse in terms of cumulative energy demand, largely from high energy requirements in the grow-out phase. Moreover, the energy mix strongly influences the performance of closed system with regards to global warming potential, closed systems potentially emit more greenhouse gases due to their relatively high energy requirements. The goals of the Paris Agreement need to be addressed within all industries, including salmon farming. The current expectations and hopes about industry growth need to be reconciled with these goals. New technologies addressing environmental concerns and facilitating continued growth may affect the direct energy requirements and consequently the greenhouse gas emissions of the salmon farming industry in Norway.

2.2 The Salmon Farming Production Cycle

The full production cycle of a salmon in Norway usually ranges between 2-3 years (MOWI, 2020). The different production stages are displayed in the following Figure 2.1.

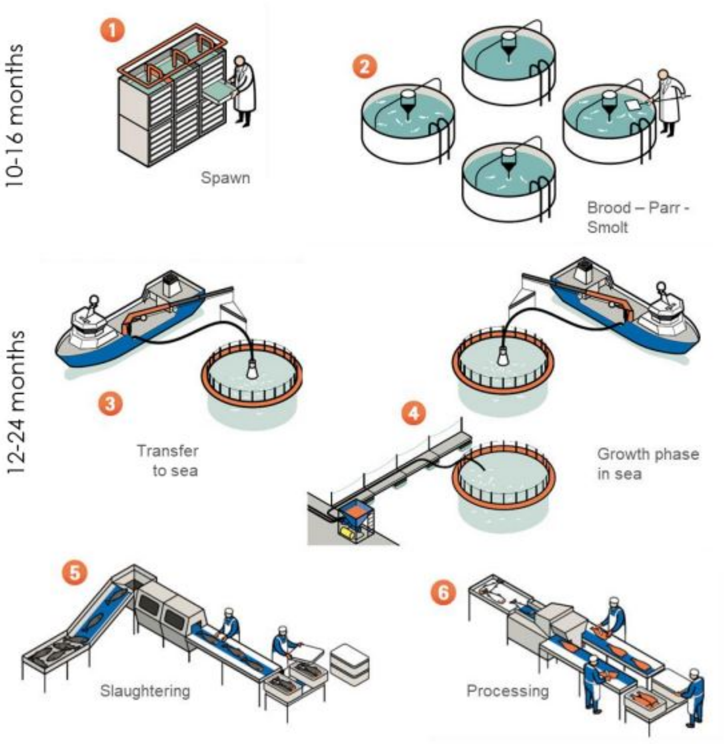


Figure 2.1: Salmon production cycle from (MOWI, 2020).

Firstly, brood fish is used for the fertilization of eggs which is followed by further development into parr and smolt in tanks. The first production stages typically take place in land-based (RAS) facilities or in flow-through systems. In recent years, land-based RAS have become increasingly common, and most new facilities built for smolt production are land-based RAS facilties (Nistad, 2020; Hilmarsen et al., 2018). There is some variation in the classification of salmon between different actors in the industry, for instance MOWI (2020) classifies smolt as fish weighing 100 - 250 grams. Whereas in Hilmarsen et al. (2018) smolts are considered fish between 70 and 200 grams. The current average weight of smolt transferred to sea is 150 g (Hilmarsen et al., 2018). The smolt transferred to sea is placed in open net pens with a further growth phase of usually 12 to 18 months. When the salmon reaches 4 - 5 kg, the fish is transferred from the pens to slaughter and processing facilities before being transported to the market (Liu et al., 2016; MOWI, 2020).

2.2.1 Current Energy Consumption

Smolt production in RAS relies on electricity from the grid. The energy consumption for smolt-sized fish production in land-based RAS is about 2 kWh/kg fish produced according to equipment and facility provider AKVA Group (n.d.). In another master thesis, the energy requirements for 170g smolt was estimated to somewhere between 2,5 and 3,3 kWh/ kg produced based on operational data from 13 RAS facilities in Norway (Nistad, 2020).

Most of the Norwegian salmon grow-out currently takes place in open net pens, Møller (2019) estimates that the mean energy required per kg salmon produced in the grow-out phase in open net pens using fossil energy carriers is 0,47 kWh. This includes energy inputs to the feed barge, work vessel and transport vessel, with the vessels requiring roughly 0,20 kWh/ kg (Møller, 2019). The estimates in Møller (2019) are based on empirical data from the feed barge of 51 localities in Trøndelag county, which is one of the largest salmon aquaculture areas in Norway. Based on the on-site farming inventories from Winther et al. (2009) excluding vessels, energy inputs, largely fossil, can also be estimated to about 0,17 kWh/ kg produced.

Different types of vessels are used to support the salmon production in open net pens. The locality vessel also called transport vessel, and the work vessel are tied to a specific farming locality (DNV GL, 2018). The vessels are used for transport of personnel and smaller operations at the farm (DNV GL, 2018). The well boats and service vessels usually service multiple farming localities (DNV GL, 2018). The well boats are used in the transport of fish and delicing (Winther et al., 2020). The service vessels are used for larger operations such as handling of fish nets and they are owned by independent service companies or larger aquaculture companies (DNV GL, 2018).

In terms of direct sectoral energy consumption, Møller (2018) estimated the direct annual energy demand for Atlantic salmon for the 2017 production volume to 1.15×10^7 GJ at slaughter house. The distribution of direct energy demand is displayed in Figure 2.2.

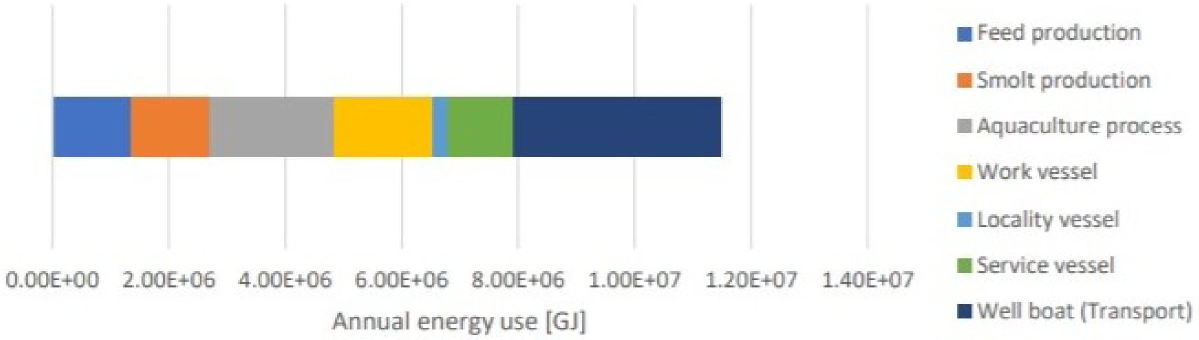


Figure 2.2: Contribution analysis of annual direct energy consumption of the Norwegian salmon industry from Møller (2018).

In Figure 2.2 the well boat accounted for 31% of the direct energy demand, 19% for the aquaculture process in the open net pens and each 12% for the feed production and the smolt production (Møller, 2019). Seeing that domestic net energy consumption amounted to 770,8 PJ in 2019, the total direct energy consumption of 1.15×10^7 GJ corresponds to approximately 1,5% of the domestic electricity consumption (Statistics Norway, 2020b).

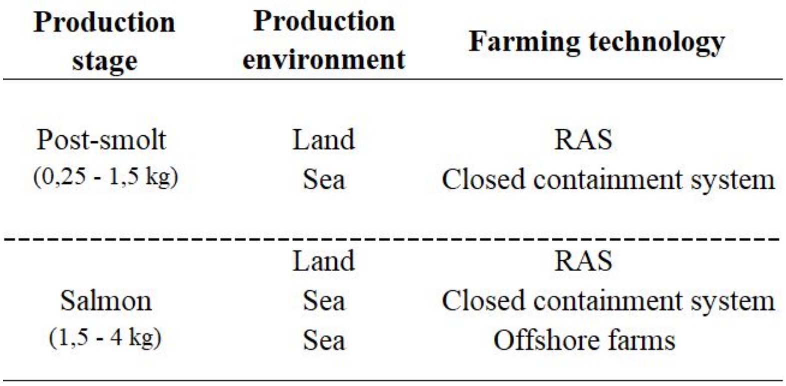
2.2.2 Developments in Production Volume

In order to realize the full potential of Atlantic salmon aquaculture production in the future and protect its position in the market, production technologies need to be improved to prevent escapees, lice, emissions, land occupation and reduce feeding resources (Olafsen et al., 2012). A production volume of 5 million tons salmon per annum would require a compound annual growth rate of 4,31% based on the present production volume. The current growth pattern in the industry is 1,5% on average per year with the current traffic light system, even if all zones were green it would allow for a maximum 3% on average per year (Misund and Tveterås, 2019). With new production technologies such as in sea-based closed containment systems, the industry is hoping for licenses with exemption from the traffic light system to spur industry growth (Berg, 2020). In the Salmon Farming Industry Handbook 2020 by MOWI, the expected compound annual growth rate for 2019-2030 is set to 3% (MOWI, 2020). This is considerably lower than the compound annual growth rate between 2000 - 2019 which was 6% (MOWI, 2020).

In terms of the relative importance of the farming technologies contributing to the overall production volume in the years towards 2050, there is limited information and mostly only general statements about the expected increase in novel technologies. Based on the results from a survey to industry leaders about future production and farming technologies by PwC, open net pen production was still expected to dominate the 2050 production volume, contributing to 53% of the overall volume (Heen et al., 2017).

2.3 New Production Technologies and Methods

New production technologies expected to become increasingly common are offshore farming, closed or semi-closed farming and salmon grow-out in land-based RAS (Olafsen et al., 2012; Misund and Tveterås, 2019). Another trend in the salmon farming industry, is the increased production of post-smolt (Hilmarsen et al., 2018; Ernst & Young, 2019; Misund and Tveterås, 2019). It represents a change in production method, where the smolt is kept longer in land-based or (semi-)closed production systems at sea. This means that time of the salmon's life is spent at sea decreases. An overview of the implementation options of new farming technologies in the production of post-smolt and salmon grow-out is displayed in the following Table 2.1.



Production stage	Production environment	Farming technology
Post-smolt (0,25 - 1,5 kg)	Land	RAS
	Sea	Closed containment system
Salmon (1,5 - 4 kg)	Land	RAS
	Sea	Closed containment system
	Sea	Offshore farms

Table 2.1: Overview of new salmon production technologies and the rearing environment.

As seen in Table 2.1, there are multiple technologies available for the different production stages. RAS technology can be used for the production of post-smolt only, or for the whole production cycle until the salmon is harvest-ready. For post-smolt production, the growth period for smolt production in existing facilities is extended before being transferred for the grow-out phase at sea. Salmon grow-out in land-based RAS means that the whole production cycle of the salmon is moved onshore, taking place in tanks. Water is pumped from a local water source into the tanks/ production system and undergo different treatments before and after contact with the fish (Badiola et al., 2018). The water is then discarded or reused in production, the treatment often involves filtration, disinfection, oxygenation, degassing, waste treatment, and heating or cooling (Badiola et al., 2018).

A more novel post-smolt production technology is the use of closed or semi-closed systems at sea. Here, the smolt is reared in land-based RAS before being transferred to the closed systems (CtrlAQUA, 2019). Closed and semi-closed systems can also be used for the salmon grow-out phase. The closed or semi-closed farming systems are characterised by "an impermeable barrier to isolate the culture environment from surrounding ecosystems." (Ayer and Tyedmers, 2009). The technology combines certain aspects of the land-based RAS and the traditional open net pen farming taking place at sea. The degree to which the structure is closed off from the surrounding environment affects the ability of the system to control the rearing environment, and whether it is considered closed or semi-closed. This type of production technology will from hereon be referred to as closed containment system.

Finally, offshore aquaculture is another novel production technology currently under development. In offshore aquaculture, the grow-out phase of salmon is taking place in more exposed waters than current farming in sheltered waters, and the farms can also be mobile or stationary (Fiskeridirektoratet, 2019). The farms are typically able to hold more fish compared to traditional farms, and their structure is more rigid and sometimes drawing on inspiration from designs from the offshore oil industry (Tveterås et al., 2020).

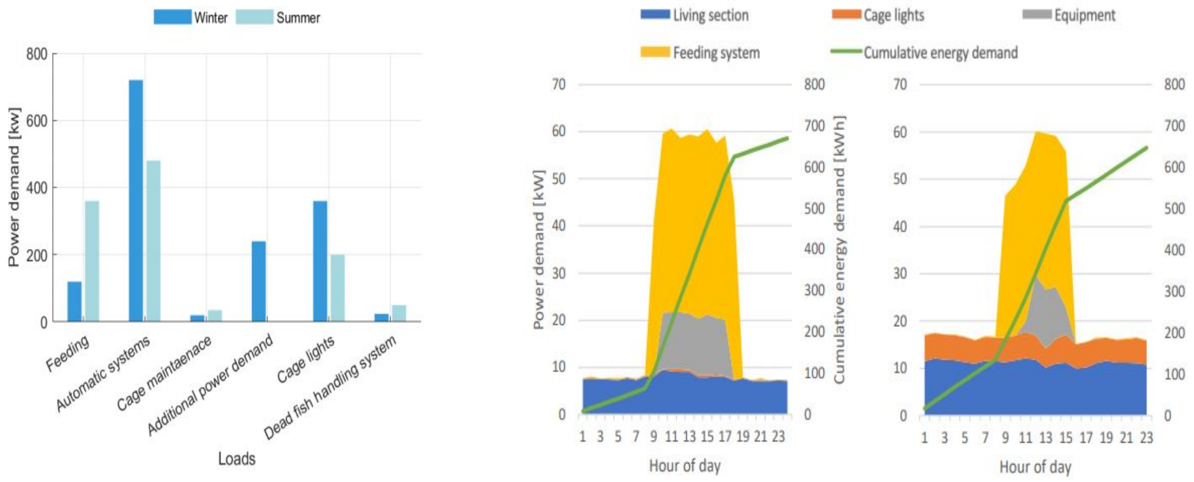
These new production technologies and methods, and the potential change in the energy requirements from implementing these are considered in more detail in the following sections. Starting with offshore aquaculture, then moving onto salmon grow-out in land-based RAS followed by closed containment systems, and lastly the post-smolt production strategy.

2.3.1 Offshore Aquaculture

In recent years a number of companies have invested in large-scale offshore production facilities, for instance SalMar has invested in Ocean Farm, Nordlaks in Havfarm and Norwegian Royal Salmon in Arctic Offshore Farming. Drawing on experience from the offshore oil industry, the farms are to be placed in more exposed waters. There is limited operational experience with the farms. Smolt was first transferred into Ocean Farm 1 during September 2017, and into Havfarm 1 during the summer of 2020. Consequently, the data availability and operational understanding of such farms is limited. Several production cycles will have to be completed in order to get an understanding of the energy requirements throughout the production cycle.

For offshore farming technologies, the power demand varies with the design of the farm (Berg et al., 2020). Since the technology is relatively new, different concepts are currently tested and under development. For instance, Havfarm 1 has a shiplike design whereas the Arctic Offshore Farming design has the appearance of large open net pens with nets that can be submerged 10 meters under water under normal operations (Nordlaks, n.d.; Royal Norway Salmon, n.d.). Nordlaks is also looking to develop offshore farms that do not need to be permanently anchored to one location, but can be moved depending on the season or local environmental factors (Nordlaks, 2017). In this case, it would be reasonable to assume that additional energy is required for transport, navigation and dynamic positioning for stabilization of the farm.

The offshore farms can hold considerably more fish compared to previous designs and appear to have a larger power demand than traditional open net pen farming. For instance, Havfarm 1 is able to hold more than 2,5 times of the maximum allowed biomass compared to regular open net pens (Norwegian Seafood Council, 2017). There is limited information on operational parameters for offshore farms, and challenging to make assumptions for new technologies, but Tveterås et al. (2020) implies that production in offshore farms requires more energy per kg salmon produced compared to production in traditional open net pens. In terms of modeled power demand, Berg et al. (2020) has modelled the potential power demand at three different offshore farms. The daily power demand for an open net pen locality in Trøndelag compared to the power demand modelled for a potential offshore farm are displayed in the following Figure 2.3.



(a) Power demand at an offshore farm on a summer and winter day sorted according to operations from (Berg et al., 2020).

(b) Power demand at a traditional farm with open net pens on a summer and winter day from (Møller, 2019).

Figure 2.3: Overview of power demand at offshore farm and traditional open net pen during the summer and winter.

In Figure 2.3, the power demand for both a summer and a winter day is included, and the power demand appears to be higher during the winter for both production technologies. Though, the feeding system is an exception because the growth conditions are better during the summer and more feed is required. Comparing the power demand of the feeding system in the summer in Figure 2.3, the system of the offshore farm requires almost 400 kW compared to 60 kW of that in open net pens. The average daily power demand for Ocean Farm ranges from 40-160 kW/ day depending on the season (Berg et al., 2020).

As displayed in Figure 2.3 offshore farms have more power demanding automatic systems and equipment. Several farms are designed to be less reliant on vessels for on-site operation, they need to be more self-reliant due their exposed location. Ocean Farm 1 mainly requires boat services in the form of feed boats, transport of personnel and well boats for the transport for smolt to the location and salmon for slaughter and processing (Myrebøe, 2019). Nordlaks' Havfarm is equipped with a ROV and multi-functional service wagon on-site which eliminates the use of vessels commonly needed for on-site operations at traditional farms (Nordlaks, 2016).

In case of lice, there is a need for well boats providing treatment, but by moving the farming locations further away from shore and submerging the nets, one hopes to avoid lice and treatments. This suggests that the energy demand associated with services provided boats are largely transferred to the farming structure itself. The overall power demand at offshore farms is larger compared to traditional farms, but whether this is the case on a kWh/ kg salmon produced is unclear from the literature reviewed. Further operational experience is required to determine and optimize the energy demand of offshore salmon farms.

2.3.2 Salmon Grow-out in Land-based RAS

Land-based RAS allows for full control of the rearing environment throughout the salmon production cycle and ensure optimal growth conditions all year round (Dalsgaard et al., 2013). Hilmarsen et al. (2018) questions the reliability of the existing data on RAS, because there is limited production data from land-based salmon grow-out in RAS, only a few international producers with limited experience. So far, Atlantic Sapphire has an energy input of 6 kWh/ kg HOG for its production in Denmark based on several production cycles with relatively stable growth conditions (Atlantic Sapphire, 2020). In Florida, the first slaughter in autumn 2020 has an energy budget in production of approximately 8 kWh/kg head on gutted (HOG) (Øyehaug, 2020). The difference between production in Denmark and USA can partly be explained by the need for cooling due to higher temperatures (Øyehaug, 2020). According to Badiola et al. (2017), the use of heat pumps to regulate water temperature and ensure optimal growth conditions in land-based RAS is a major driver of energy use. In Hilmarsen et al. (2018), energy inputs of 6-9 kWh/ kg salmon produced are assumed based on expert evaluations. This is considerably higher than for traditional open net farming with energy requirements of 0,25-0,47 kWh/ kg in the grow-out period estimated by Møller (2019). The total control of the rearing environment thereby comes at considerable cost in terms of energy inputs.

The high energy requirements of RAS relate to the pumping and treatment of water. The water is treated before and after contact with the fish, and is recirculated within the system using pumps. The most essential and energy requiring processes are included in Figure 2.4.

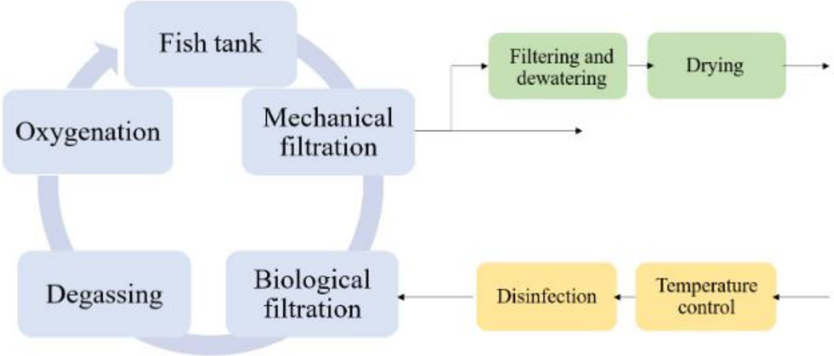


Figure 2.4: Essential water treatment processes in recirculating aquaculture systems including biological filtration from Nistad (2020).

As seen in Figure 2.4, the water pumped into system [yellow processes] undergoes temperature control and is disinfected. The water might have to be heated or cooled depending on the temperature of the water sourced. In terms of the water being recirculated [blue loop], the water needs to be oxygenated before entering the units containing the fish. After exiting the fish tank, the water needs to be filtrated, mechanically and biologically before the degassing takes place. The degassing removes the build up of nitrogen oxide and carbon, before the water is oxygenated and re-enters the fish tank. The green processes in Figure 2.4 represent the waste treatment in the system. Wastes are mechanically removed from the system and dried. The energy use for the waste management depends on the level of filtration and sludge treatment (Nistad, 2020). Different systems design and combination of different components has an effect on the overall energy use and efficiency in RAS (Badiola et al., 2018).

Based on data from several RAS-facilities in Norway, Nistad (2020) finds that the pumping and oxygenation are the most energy demanding, each accounting for about 20% of the total energy consumption of the system. Next, the heat pump in the temperature control requires 10% and the degassing process demands 8% (Nistad, 2020). Combined, various other machinery for vaccination, cleaning and management of dead fish account for another 15% of the overall energy consumption (Nistad, 2020).

2.3.3 Closed Containment Systems

Closed containment systems are in use or planning to be used for the production of post-smolt and salmon grow-out in Norway. These facilities combine certain aspects of land-based RAS and traditional open net pens. The production takes place in the sea and the water is pumped directly into the pens. The water is typically pumped from depths where salmon lice are not located. The production method is considerably more energy demanding compared to traditional open net pens (Ayer and Tyedmers, 2009). The pumping of water and oxygenation are considered the main drivers of this additional energy demand (Sæternes, 2020; Jensen, 2020b). The energy demand will further increase if the pumped oxygen is not portable, but generated on-site. With the increase in the salmon size, the oxygen demand increases and the water volume decreases relative to the biomass in the tank (Thorarensen and Farrell, 2011). Some designs also include systems for waste and dead-fish handling, additional operations which again rely on further energy inputs.

2.3.4 Production of Post-smolt

Post-smolt are larger and more resilient compared to smolt, and are thereby better suited to withstand lice and treatment (Misund and Tveterås, 2019; Hilmarsen et al., 2018; Dalsgaard et al., 2013; MOWI, 2020). Post-smolt are salmon with a weight ranging from 200 - 1000 grams, currently the average weight of post-smolt is 250 grams (Hilmarsen et al., 2018). Another advantage of post-smolt is the shorter growth period at sea which means the farmers are able to make better use of the maximum allowed biomass of their licence and produce more salmon (Misund and Tveterås, 2019; Hilmarsen et al., 2018; Dalsgaard et al., 2013). According to the AkvaGroup CEO, Knut Nesse, about half of Norwegian salmon producers will in the coming decade transfer smolts of 300 g at sea and the other half will transfer smolts weighing between 300 - 900 g (Jensen, 2020a).

As with smolt, post-smolt will typically be produced in land-based RAS. By moving a larger share of the production cycle of salmon on land, it can be expected that the energy consumption of the production cycle increases. The energy required for the growth at sea in open net pens is considerably lower compared to land-based RAS as explained in Section 2.3.2. Current estimates suggest post-smolt of 500 g in land-based RAS require an energy input of 3-5 kWh/ kg produced (Hilmarsen et al., 2018). Moreover, if all post-smolts are produced in land-based RAS and the energy requirements increase from 3 kWh/ kg to 5 kWh/ kg, the overall energy consumption of production would increase threefold from 0,5 TWh to 1,5 TWh (Hilmarsen et al., 2018). For the same sized post-smolt Nistad (2018) estimated the energy consumption to 4,57 kWh/ kg in land-based RAS.

Some aquaculture companies are also looking to produce post-smolt in closed containment systems at sea. This would involve producing smolt on land, then moving them to closed containment systems before moving them into open pens. The aquaculture company, SinkabergHansen, is establishing a new locality with five closed pens (Sæternes, 2020). In order to supply the locality using shoreside electrical power, a high voltage (22 kV) subsea cable to the feed barge is planned, potentially with a 1 kV cable to each pen (Sæternes, 2020). This is considerably higher power demand than what is required for traditional open net pen localities where the subsea cable for the feed barge typically has a voltage of 1 kV (Jebsen, 2019).

2.4 Decarbonization of Energy Supply

Decarbonization of the energy supply refers to a reduction in the carbon intensity of energy. It includes the transition away from high-carbon energy carriers such as coal, oil and natural gas to low-carbon energy technologies which include renewable energy sources such as wind, solar and hydro power, and hydrogen production from low-carbon energy sources (IEA, 2020). These low-carbon energy technologies also include nuclear power and carbon capture, utilisation and storage, but these are considered less relevant for this thesis (IEA, 2020). One of the main goals of decarbonizing the energy supply is to reduce the emission of greenhouse gases driving climate change. Decarbonization of energy supply is frequently associated with decarbonization of electricity supply and increased electrification of various processes (Audoly et al., 2018).

The Norwegian salmon farming industry has traditionally relied upon fossil fuels for electricity production on the farming localities, but in recent years there has been a development towards connecting the feed barges to the mainland electricity grid using subsea cables (Winther et al., 2009). In Norway, the electricity consumption mix consists of 94% renewable energy sources so moving from a fossil based supply to electricity is a shift towards a decarbonized energy supply (Norwegian Water Resources and Energy Directorate, 2020). In cases where a connection to shore-side electricity is not possible, a diesel generator in combination with battery storage can be use to reduce fossil fuel consumption (ABB and Bellona, 2018). Land-based RAS facilities are normally connected to the electricity grid, and so within Norway this technology already has a decarbonized energy supply. When considering new production technologies with different energy efficiencies, the energy carriers are particularly relevant for production emissions. For instance, Liu et al. (2016) find the carbon footprint of a salmon at retailer gate produced in a land-based closed containment recirculating aquaculture system (LBCC-RAS) in the USA with a 90% hydropower electricity mix to be almost comparable to salmon produced in open net pens in Norway transported frozen on ship in terms of kg CO_2/ kg salmon. However, if the energy is sourced from the average US electricity mix, the emissions of the LBCC-RAS are almost double of the salmon from open net pens transported by ship (Liu et al., 2016). This indicates that the energy carrier and not only technology efficiency is highly relevant for the salmon farming industry and its emission reduction potential.

Seeing that shore-side electricity is increasingly common as low-carbon energy source for open net pen farming it will be considered more in-depth in the following section. Subsequently, other existing low-carbon energy solutions and the level of development and implementation for different farming technologies will be investigated.

2.4.1 Shore-side Electricity

Roughly 50% of the Norwegian farming localities are already connected to shore power (ABB and Bellona, 2018). This includes the electrification of the feed barge, but not the boats servicing the farm. The subsea cables to the feed barge commonly have a voltage of 1 kV to reduce the electricity grid losses in the system. As a consequence, a transformer needs to be installed on the feed barge itself. The typical electrical infrastructure for a traditional open net pen farming locality is displayed in Figure 2.5.

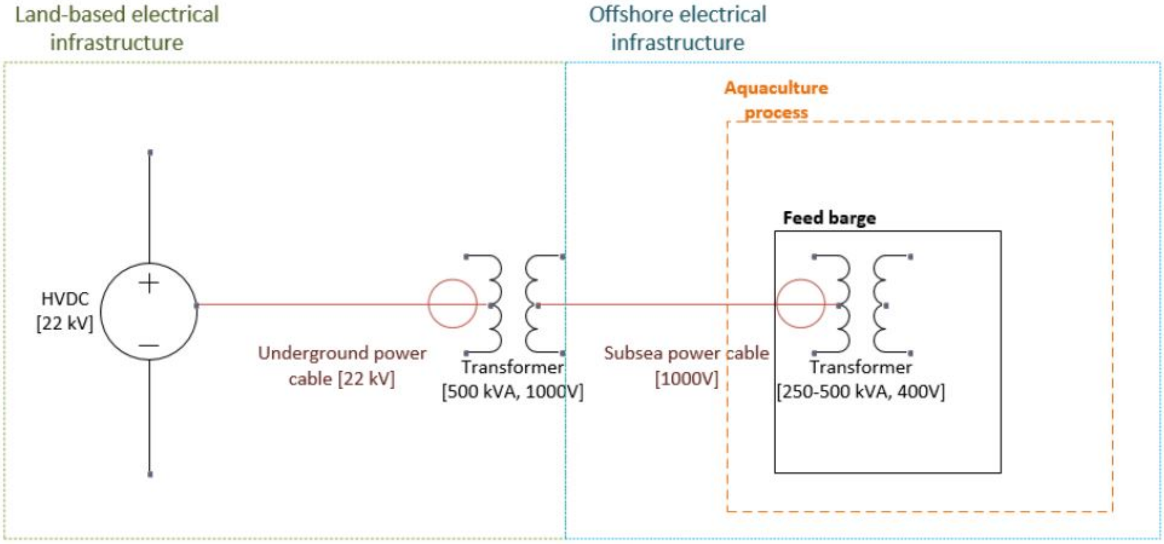


Figure 2.5: Typical electric onshore and offshore infrastructure for a traditional open net pen farming locality from Jebsen (2019).

Møller (2019) considers the electrification potential of salmon farming localities in Trøndelag, Norway. Møller (2019) finds that grid issues can be a limiting factor for electrification, especially the limited capacity in the rural locations of the farming sites. A further finding is that the median energy consumption for localities (including feed barge, work vessel and transport vessel) with fossil generators is 0,47 kWh/ kg salmon produced compared to 0,25 kWh/ kg for localities where the feed barge is connected to shore power (Møller, 2019). The difference in specific energy consumption can be explained by the generator inefficiency when converting fossil fuels into electric power. This suggests that there are energy efficiency gains to be made from moving towards renewable energy solutions.

Berg et al. (2020) looks at the potential for eco-friendly energy supply for offshore farming such as shoreside electrical power, hydrogen generators, fuel cells, solar power, wind power and wave power in addition to battery storage solutions. Finding that the most cost-efficient and eco-friendly power solution is shore power (Berg et al., 2020). However, considering only cost-efficiency, the combined diesel generator and battery solution comes out ahead (Bergheim et al., 2009). The distance to shore may influence the decision to connect to shore power due to increasing cabling costs the further away from shore the farm is located. Nordlaks is planning to connect Havfarm 1 with a 17,5 kV subsea cable to the electric grid with a transformer with a maximum of 3 MW (Nygård, 2020b).

In terms of sea-based closed containment systems, Ayer and Tyedmers (2009) and McGrath et al. (2015) refer to salmon grow-out production systems connected to the electricity grid in Canada. In Norway, SinkabergHansen appears to be the first salmon farming company planning to have a whole farming locality dedicated to post-smolt production in a closed containment system connected to shore-side electricity (Sæternes, 2020).

2.4.2 Alternative Low-carbon Energy Solutions

Solar power, wind power and hydrogen fuel cells are alternative low-carbon energy solutions frequently mentioned as renewable alternatives for the salmon farming industry, but these are largely untested for this purpose (ABB and Bellona, 2018). For the vessels, hydrogen is in the initial phases of testing for maritime sector (Tomasgard et al., 2019). A report on hydrogen production and application in Norway by DNV GL considered the theoretical potential of hydrogen demand for vessels used in the aquaculture industry in 2030 to be 1 200 tons per annum (Killingland and Eliassen, 2020).

In the following Table 2.2, an overview of these technologies, also including battery storage, and their implementation for different farming technologies based on online searches are included.

Energy technology	**(Farming) Technology**	**Comment**	**Reference**
Wind	Open net pens	See battery combinations.	
	Offshore farming	Viewpoint Seafarm - concept of submersible offshore farm with 12 MW wind turbine placed on top under development.	Viewpoint (n.d.)
Solar power	Open net pens	Ocean Sun produces floating PV and have a project for Lerøy Seafood connected open net pens, the potential power of this facility is currently 6,6 kWp.	Ocean Sun (n.d.)
		See battery combinations.	
Hydrogen fuel cell	Work vessel	Plans to develop world's first work vessel, the project was announced September 2020 and is for Midtnorsk Havbruk salmon farming company.	Nygård (2020a)
Battery combinations	Open net pens	Combine energy pack and diesel generator on feed barge. Implemented and increasingly used by several farming companies on localities where connection to shore-side electricity is not considered possible.	ABB and Bellona (2018)
		World's first farming locality with wind and solar power in combination with battery pack and diesel generator in operation by Grieg Seafood, presumably since 2019.	Kyst.no (2019)
	Work vessel	Elfrida, was the world's first electric work vessel and has been in use by SalMar since 2017, multiple full-electric work vessels under development/ construction.	DNV GL (2018)
	Well boat	New vessels built combine diesel or LNG with battery technology. Nordlaks has diesel/battery well boat in use from 2020, and Nova Sea LNG/ battery to be delivered in 2021.	Nordlaks (2019) Aadland (2020)

Table 2.2: Alternative low-carbon energy solutions in the Norwegian salmon farming industry under development.

The energy technologies in Table 2.2 are, if at all adopted, only recently tested for traditional open net pen farming. It might be challenging to develop renewable energy solutions for new farming technologies and concepts which are currently under development themselves. It should also be noted that the small number of projects in Table 2.2 might be due to the inability of the author to find information on existing applications and projects.

A general concern about the application of renewable energy to salmon farms located at sea is the space requirements or the considerable capacity needed to ensure reliable energy supply (Syse, 2016). As a consequence, the final energy technology in Table 2.2, battery combinations, can be viewed as an energy storage solution to help reduce fuel consumption and provide energy security in combination with renewable energy sources. For localities that are unable to connect to shore power, a diesel generator with a battery solution can help optimize the energy generation at the farm. ABB and Bellona (2018) estimated that the diesel consumption could be reduced by 30% if batteries were to be charged during feeding hours when the generators were in use. The generator would then only operate 1/3 of the time, and the operations would run on battery stored power the remaining 2/3 (ABB and Bellona, 2018). Another solution would be for the generators to be operated at a constant optimal load, thereby increasing the efficiency of the generators and reducing emissions (Berg et al., 2020). The generator would produce to battery storage when the energy demand at the farm is low, and the batteries would discharge during peak hours, for instance during feeding. As seen in Figure 2.3b, the power demand of open net pens varies considerably throghout the day.

3. Methodology and Data Collection

The following section includes a description of the scope of the study, and the working method to determine the energy scenarios for the potential decarbonization of the sectoral energy supply. It will also include comments and insights on the type of data and the data collection process in this thesis.

3.1 System Description

The energy requirements for the salmon farming industry referred to in this thesis are the direct energy inputs into the production stages of smolt, post-smolt and salmon grow-out. This includes the energy required for the operationalization of facilities and equipment used in production. Thereby, transport boats and vessels used to service sea-based farms are included, but land-based transport and processing is not considered. The following Figure 3.1 provides an overview of the relevant production activities where the energy consumption is considered.

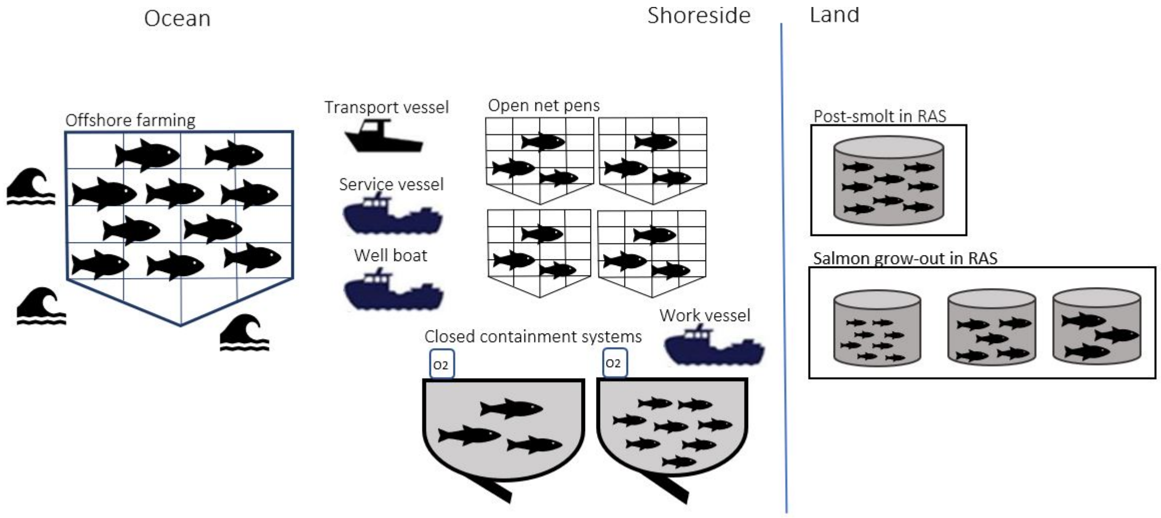


Figure 3.1: Overview of salmon production technologies and activities considered in this study.

3.2 Modelling Decarbonized Sectoral Energy Supply

The work methodology for the modelling of a decarbonized sectoral energy supply of the salmon farming sector in 2050 is displayed in the following Figure 3.2.

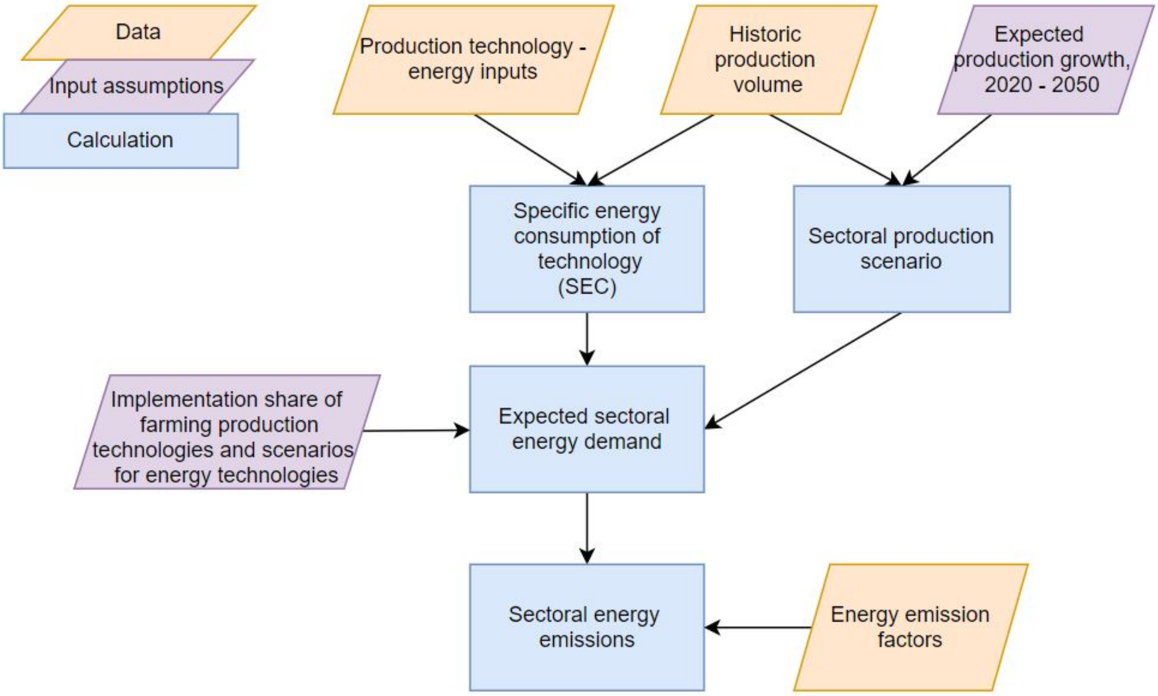


Figure 3.2: Work methodology.

Firstly, the production volume and the application of the different farming production technologies need to be modelled based on historic data and assumptions about future production. From there on, data on energy consumption of the different production technologies need to be collected or derived from existing studies or directly from the salmon farming companies on a kWh/kg produced basis. The sectoral energy consumption can then be derived based on the specific energy consumption of the production technologies and their implementation in the production cycle and scenarios for the application of energy technologies. Following this, the sectoral energy emissions can be estimated based on the CO_2 emissions associated with the application of different energy carriers. Different energy supply options can be evaluated based on their potential for the farming technologies and their suitability to ensure that the industry achieves the 2030 and 2050 GHG emission goals. Figure 3.2 provides an overview of the approach, and specifications on the assumptions, calculations and the data inputs will be described in the following sections.

3.2.1 Determining Future Production - Production Volume

The salmon production volume in 2030 and 2050 is determined using a compound annual growth rate (CAGR). The initial production volume is 1,36 million tons salmon in 2019. The production volume is modelled for a compound annual growth rate of 1,5%, 3% and 4,3%, and the pathways are displayed in the following Figure 3.3.

The final production volume in 2050 is determined as follows:

$$P_n = P_0 \times (1 + CAGR)^n$$

where P_0 is the initial production level,
P_n is the final production level,
n is the number of years.

The compound annual growth rate of 1,5% and 3% are based on the potential growth using the traffic light system, which allows for maximum 6% growth every other year (Havforskningsinstituttet, 2019). The current growth pattern is according to Misund and Tveterås 1,5% per year. The CAGR of 4,3% is derived based on the annual growth necessary to achieve a production volume of 5 million tons in 2050 as described in Olafsen et al. (2012).

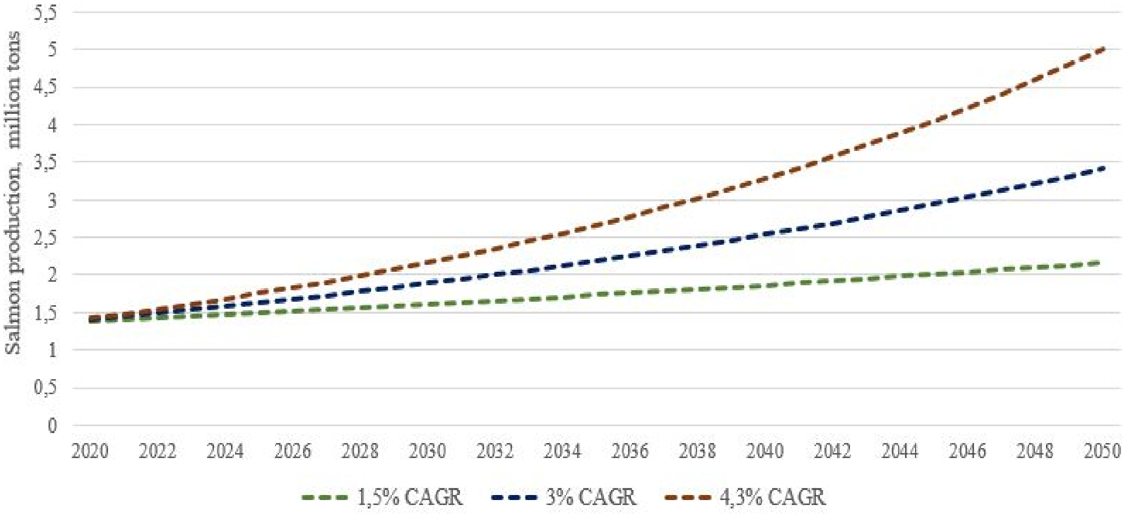


Figure 3.3: Production volume scenarios for Norwegian salmon production from 2020 to 2050.

In Figure 3.3, the 1,5% CAGR would lead to a production volume of 1,61 million tons in 2030 and 2,16 million tons in 2050. For the 3% CAGR, the corresponding values would be 1,89 and 3,41 million tons. The growth trend in the industry over the past decade makes the 5 million tons in 2050 goal appear unrealistic (Misund and Tveterås, 2019; Heen et al., 2017). Based on the growth expectations for the industry in MOWI (2020) and Heen et al. (2017), and the growth potential when overcoming current environmental obstacles with alternative production methods, the 3% CAGR scenario will henceforth be used as the basis for the industry production volume.

3.2.2 Determining Future Production - Production Technologies

Considering the variation in energy demand for different farming technologies, the composition of traditional and new technologies in the 3% CAGR production scenario need to be determined. Based on the new farming methods and technologies as previously described in Section 2.3, the following production cycles are to be considered:

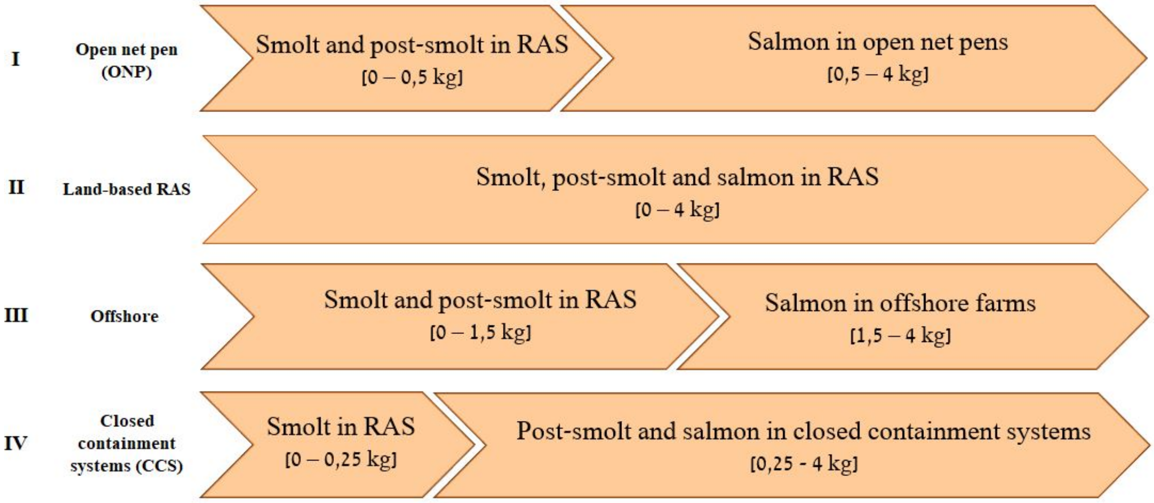


Figure 3.4: Overview of salmon production technologies implemented in the salmon production cycle.

In Figure 3.4, the salmon production cycles include three production stages: smolt, post-smolt and salmon grow-out until a slaughter weight of 4 kg. The first production cycle [I] includes a slight change to the current open net pen farming cycle, here the smolt and post-smolt up to 0,5 kg are produced in land-based RAS before transferred to open net pens at sea. In the second production alternative [II], the whole production cycle takes place on land in RAS facilities. The next production cycle [III] includes production of post-smolt up to 1,5 kg in land-based RAS and the remaining grow-out phase in offshore farms. The post-smolt in this production cycle is assumed to be larger compared to cycle [II], because offshore farms demand larger and more robust fish (Nygård, 2020b). Lastly, in production cycle [IV], smolt is produced in land-based RAS and then transferred to a closed containment system for the remaining production cycle.

Modelling the relative contribution of the farming technologies to the overall 3% CAGR production scenario, investment plans and development licenses from the Norwegian Directorate of Fisheries can be used for estimating the production volume of the new farming technologies in the short-run. For land-based RAS, the Fiskeridirektoratet's map tool based on data from the Norwegian Aquaculture register can provide information on farming companies with licenses for production of salmon grow-out on land. For open net pens, information on farming licenses in use over the past decades is available from Fiskeridirektoratet (2020c). Seeing that considerable information is available on traditional open net pen farming, it will be used together with the 3% CAGR scenario as a reference point for modelling the other technologies. This, combined with the information on novel farming technology projects under development will be reconciled with assumptions about long term development in the Norwegian salmon farming sector. Key assumptions for modelling the four production cycles are included in the following Table 3.1.

Production cycles	**Key assumptions**
Open net pens	• Linear growth in number of licenses in the future based on license growth 2000-2019. Each license amounts to a certain maximum allowed biomass (MAB). • Assume 12 new licenses per year, a decrease compared to the current level due to ecologically limiting factors with increased production. 2 licenses are allocated to Troms and Finnmark and 10 to the remainder of the country. MAB for a license in Troms and Finnmark is 945 tonnes compared to 780 tonnes in the rest of the country. • Assume a utilization factor of MAB of 1,42, based on the differences in licenses in use and annual sales volume. See Appendix A.1 for further details. • Assume that utilization factor will increase as lice decreases and post-smolt, shorter time at sea and more robust, a 15% increase by 2050 an increase in the original utilization factor by 0,5 % every year.
Land-based RAS	• Consider existing commercial licenses for production of salmon grow-out on land with MAB >500 tons including year 2020. • A certain time lag between acquiring a production licenses until production commences and scaled up, further details in Appendix A.2, Table A.1. • Assumed additional annual volume from new licenses for the time period 2021-2024: 30 000 tons, and 2025-2029: 50 000 tons. • The production share of land-based RAS in 2030 and 2050 is summarized in Table 3.2.
Offshore	• Consider concepts referring to offshore or remote farming in the list of development licenses from Norwegian Directorate of Fisheries (2020). • A time lag between acquiring a production licenses until production commences and scaled up, further details in Appendix A.2, Table A.1. • Assumed additional annual volume from new licenses for the time period 2021-2024: 7 500 tons, and 2025-2029: 10 000 tons. • The production share of offshore farming in 2030 and 2050 is summarized in Table 3.2.
Closed containment systems	• A wide range of different concepts, some more closed than others and challenging to identify if concepts are for grow-out versus smaller salmon in list on development licenses from Norwegian Directorate of Fisheries (2020). • Determine volume as the remainder of the 3% CAGR production scenario and the production volume of the other novel technologies. • The production share of closed containment systems in 2030 and 2050 is summarized in Table 3.2.

Table 3.1: Key assumptions for production development of the different production technologies.

For the time period 2030-2050, the production volume of the new technologies are estimated based on subjective judgements on the relative importance of the different production technologies. The production volume of the technologies is determined based on the share of the remainder between the 3% CAGR scenario and the production volume modelled for the traditional open net pens. The relative shares of the new production technologies are displayed in Table 3.2.

Production technologies	**2030**	**2050**
Land-based RAS	65%	35%
Offshore	25%	40%
Closed containment system	10%	25%

Table 3.2: Production technologies as a share of remainder of between the production volume of the 3% CAGR scenario and the volume modelled for open net pens.

Considering the current investment plans and enthusiasm for land-based RAS, the share of land-based RAS is relatively high in 2030. Offshore farming and closed containment systems are deemed less relevant due the to development and testing of new systems for salmon grow-out. According to Norwegian Seafood Federation (2014), closed containment systems for salmon grow-out are not profitable, and CtrlAQUA (2019) suggests that none of the facilities are yet in use for commercial production. The relative importance of land-based RAS is considered to be lower in 2050 because it requires considerable investments and area (Hilmarsen et al., 2018). Moreover, since the production is less dependent on the local environment, it might be more tactical to locate such facilities closer to the markets (Hilmarsen et al., 2018; Norwegian Seafood Federation, 2014). In the long run, it is expected that offshore farming and closed containment system technology becomes increasingly mature and competitive, thus to a greater extent applied. Offshore aquaculture is judged to be more relevant because of its ability to hold large volumes of fish and make use of available areas in more exposed waters with advantageous rearing conditions. Closed containment systems are with further technological development also expected to become increasingly relevant, because they will contribute to alleviate environmental pressures along the coastline. Yet there are some reservations with regards to the considerable energy requirements and space availability for the salmon in closed systems in the grow-out phase (CtrlAQUA, 2019).

3.2.3 Sectoral Energy Consumption

To determine the sectoral energy consumption, the specific energy consumption (SEC) for the different production technologies at different stages of the production cycle needs to be determined. The production cycles considered are those previously described in Figure 3.4 and includes the activities referred to in the system description.

The specific energy consumption of the salmon farming production technologies provides a basis for comparing the energy efficiency of the technologies, and a basis for extrapolating the sectoral energy consumption for future production. The specific energy consumption is a cumulative measure and is a ratio of the energy inputs to the production of biomass:

$$SEC = \frac{Cumulative \quad energy \quad input}{Biomass \quad growth}$$

The following information on specific energy consumption for the farming technologies and vessels is collected and derived from existing studies, relying on Norwegian data and studies when possible.

Open Net Pens

- Salmon grow-out: from smolt to grow-out requires 0,25 kWh/ kg if the feed barge is connected to shore power and 0,47 kWh/ kg if the feed barge relies on a diesel generator, from Møller (2019). These values also include the energy consumption of fossil based vessels, making up approximately 0,2 kWh/kg produced for both electrified and non-electrified feed barges.
- Vessels: Based on the contribution analysis in Figure 16 in Møller (2019), of the total energy requirements of 0,2 kWh/kg, roughly 0,195 kWh/kg produced can be attributed to the work vessel and 0,005 kWh/kg to the transport vessel.

Land-based RAS

- Smolt: 2 kWh/ kg smolt produced, from AKVA Group (n.d.).
- Post-smolt [0,5 kg]: demands 3-5 kWh/ kg produced according to Hilmarsen et al. (2018).
- Post-smolt [1,5 kg]: requires energy use of 4,6-7,6 kWh/ kg produced according to Nistad (2020).
- Salmon grow-out: requires 6-9 kWh/ kg based on Hilmarsen et al. (2018). This coincides with the energy production requirements from Atlantic Sapphire ranging from 6 kWh/kg in Denmark to an expected 8 kWh/ kg in the USA (Atlantic Sapphire, 2020; Øyehaug, 2020).

Offshore

- The specific energy consumption of offshore farming is estimated based on data on hourly power demand in 2019 for SalMar's Ocean Farm 1 and information on biomass growth in a report on their production experience with the farm in SalMar (2019). The report was made available after the first production cycle in the farm had been completed, and the second cycle had commenced.
- From SalMar (2019), the smolt weight was 230 g when roughly over 1 million fish were transferred to Ocean Farm 1 for production cycle 1 and 2. Since this thesis considers an offshore production cycle with a transfer weight of 1,5 kg, the specific energy consumption is calculated for the weeks in the production cycle where the average weight of the salmon increased from 1,435 kg to 4,106 kg, this takes approximately 6 months. Taking into account the 7% total mortality from the first cycle, a 5% loss in fish is assumed here.
- Seeing that the energy data is only available in 2019 and the production cycle started late August 2019, an average electricity demand of the first months after the transfer to the offshore farm is assumed for the remaining production time, though this might lead to the underestimation of the specific energy consumption since energy consumption is lower when the fish is smaller. The average monthly electricity demand for September - December 2019 was estimated to: 80 415 kWh.
- Following this, the specific energy consumption of salmon grow-out (1,5 - 4kg) in offshore farms can be estimated to: *0,16 kWh/kg*, not taking into account energy use from boat operations. It is assumed that this value reflects the net energy consumption, and that the gross energy consumption would be *0,47 kWh/kg*, taking into account the generator inefficiency.
- Vessels: Based on information from SalMar (2019) and Nordlaks (n.d.), it is assumed

that the farms mainly require services from transport boats, service boats for feed and well boats for fish transport. Even though the fish is larger when transferred to sea, it is assumed that the energy requirements for the boats will be the same because offshore farms are located further away from the shore. The specific energy consumption of the boats will be the same as described for the open net pens.
- A more detailed description of the calculation is available in Appendix A.3.

Closed Containment Systems

- Specific energy consumption of two different closed containment systems can be derived based on the life cycle inventory in the articles Ayer and Tyedmers (2009) and McGrath et al. (2015). Both production systems are mainly powered by shore-side electricity, but closed containment systems may also rely on on-site electricity production from diesel generators. Therefore, the energy requirements of the systems have also been derived for the case of a diesel generator with an assumed conversion efficiency of 35%.
- Estimated SEC for salmon grow-out in a marine floating bag system from Ayer and Tyedmers (2009):
  - The system includes production units where the salmon is separated from the surrounding ecosystem in heavy gauge plastic bags. Seawater is pumped into the bags and the water leaves the bags into the ecosystem untreated. The water in the bags is oxygenated, but there is no oxygen production on-site.
  - From the life-cycle inventory, operational inputs of electricity and diesel is provided on a per ton fish produced basis. Based on data on total production volume, smolt inputs and mortality combined with own assumptions, the cumulative biomass and electricity use can be derived.
  - The SEC of salmon grow-out is estimated to *1,82 kWh/ kg.* For the production case, where the system is completely powered by a diesel generator, the energy requirements are *4,95 kWh/kg.*
- Estimated SEC for Chinook salmon grow-out in a solid wall aquaculture system (SWAS) from McGrath et al. (2015):
  - The solid wall aquaculture system is flow-through system located which requires the pumping of water into the structure where oxygen is added. Other additional processes includes partial waste capture and treatment on land, which also requires the waste to be pumped ashore. Due to a storm, the production cycle had to be terminated prematurely, but McGrath et al. modelled an intended production cycle (IP) which will be used to determine the specific energy consumption.
  - From the supplemental information of the paper, the life-cycle inventory (Table S1) including system characteristics, inputs and outputs. The total on-site energy use of diesel and electricity from the local grid for the grow-out period from the initial smolt weight of 35g to harvest weight of 4 kg in the IP is estimated to 808 649 kWh.
  - The specific energy consumption of salmon grow-out in the SWAS was estimated to *4,77 kWh/kg*, and for a fossil based system it would be *13,45 kWh/kg.*
- Vessels: It is assumed that the boat requirements are the same for open net pens and closed containment systems in the sea.

Vessels

The energy consumption of the vessels in the farming operations are based on the requirements of vessels servicing open net pen localities. The energy requirements of vessels servicing the novel production technologies are based on assumptions and findings from relevant literature. The specific energy consumption of the vessels are included in Table 3.3.

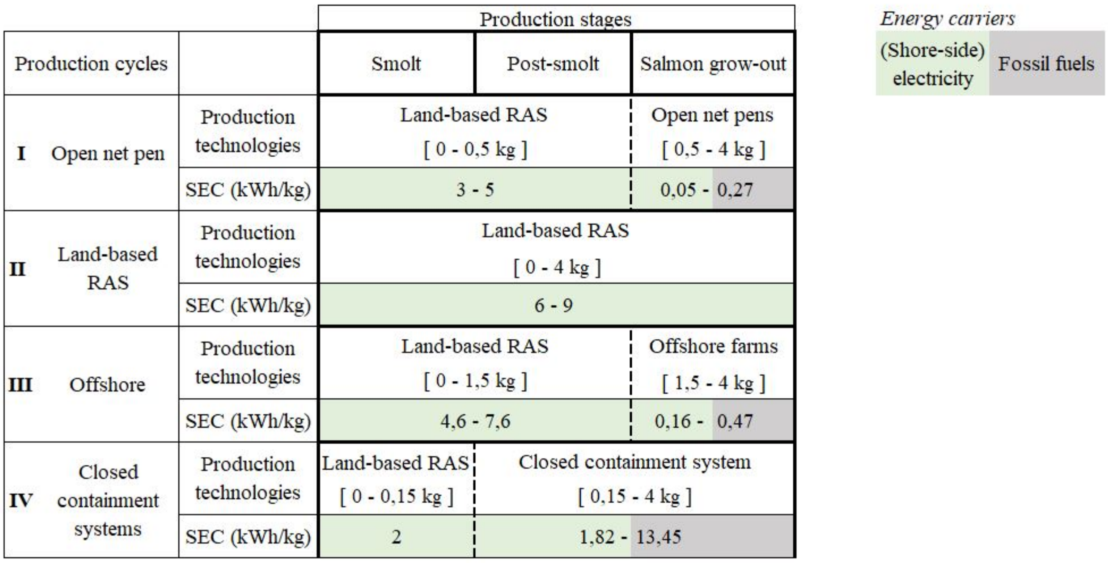
			Production cycles				**Reference**
	Energy carrier	**SEC (kWh/kg)**	ONP	Land-based RAS	Offshore	CCS	
Work vessel	Diesel	0,195	x	-	-	x	Møller (2019)
Service vessel	Diesel	0,242	x	-	x	x	Møller (2018)
Well boat*	Diesel	0,75	x	-	x	x	Møller (2018)
Transport vessel	Gasoline	0,005	x	-	x	x	Møller (2019)
Total (kWh/kg)			1,19	-	0,92	1,12	

Table 3.3: Specific energy consumption of vessels for production cycles.

* For well boats, the energy consumption is assumed to be 10% lower for offshore and closed containment systems. This assumption is based on a reduction in delicing operations with these new technologies. According to Møller (2018), 7% of the time and energy of a well boat is spent on delousing and grading operation at the cages.

For the potential electrification of boats used in aquaculture, a decrease in the energy requirements from diesel electric boats by 67% is assumed for work vessels in DNV GL (2018), and that same assumption is applied to all boats in this thesis. For boats using hydrogen, a 50% decrease in the energy requirements are assumed in Chryssakis et al. (2015) and Killingland and Eliassen (2020), and this assumption will also be applied in here.

The estimates of the specific energy consumption of the different farming production technologies and current energy carriers available are summarized in Table 3.4.



		Production stages		
Production cycles		Smolt	Post-smolt	Salmon grow-out
I Open net pen	Production technologies	Land-based RAS [0 - 0,5 kg]		Open net pens [0,5 - 4 kg]
	SEC (kWh/kg)	3 - 5		0,05 - 0,27
II Land-based RAS	Production technologies	Land-based RAS [0 - 4 kg]		
	SEC (kWh/kg)	6 - 9		
III Offshore	Production technologies	Land-based RAS [0 - 1,5 kg]		Offshore farms [1,5 - 4 kg]
	SEC (kWh/kg)	4,6 - 7,6		0,16 - 0,47
IV Closed containment systems	Production technologies	Land-based RAS [0 - 0,15 kg]	Closed containment system [0,15 - 4 kg]	
	SEC (kWh/kg)	2	1,82 - 13,45	

Energy carriers

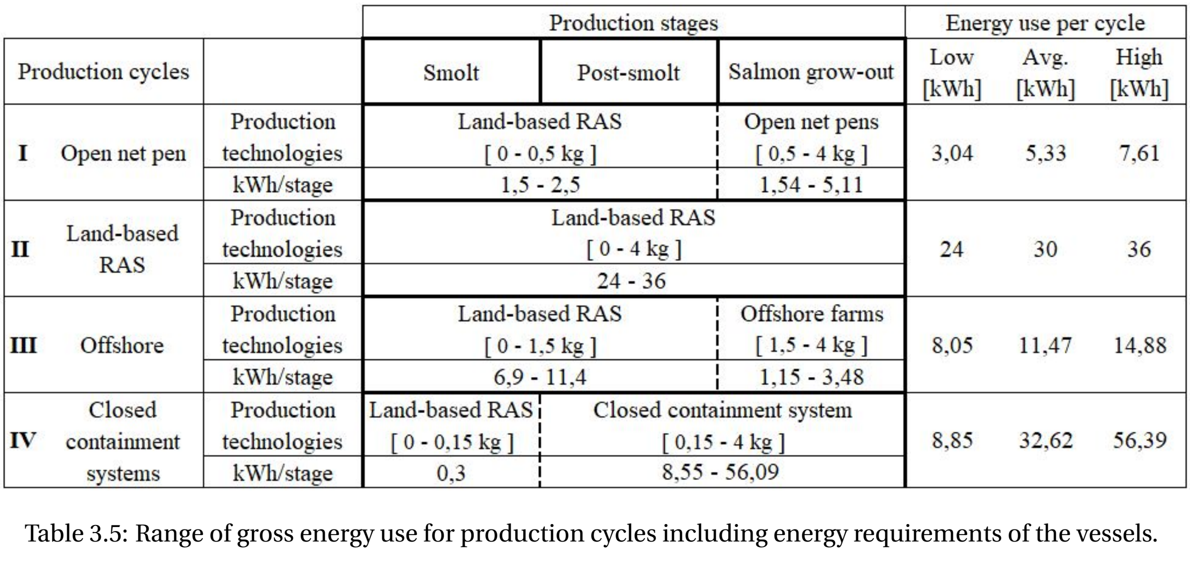
(Shore-side) electricity	Fossil fuels

Table 3.4: Specific energy consumption (SEC) for production technologies at different stages in the salmon production cycle, energy requirements from vessels have not been included here. The shaded colors indicate the common energy carriers used in the different production stages.

In Table 3.4, the SEC is of land-based RAS and closed containment systems considerably higher compared to the more open and less controlled rearing environment in open net pens and offshore farms. For the closed containment systems, the large interval in energy consumption may be explained by the different system design and the limited availability of studies and data. Moreover, the variation is exacerbated by the additional inefficiency of fossil energy technology. The difference in energy consumption of land-based RAS for different production stages reflects the variation in requirements of the salmon at different stages in the production cycle, for instance feeding. It could also be partly explained by the differences in design and operational management.

In terms of the energy carriers used for the different production technologies, electricity is the common power source for land-based RAS. Open net pens are also increasingly connected to the electricity grid, but due to capacity limitations in the grid and viability of electrification projects, diesel generators are still an important power source. For offshore farming, both fossil and electric solutions are under development. Nordlaks' Havfarm is powered by shore-side electricity, whereas other systems such as Ocean Farm 1 relies on diesel generators. For closed containment systems, the articles by Ayer and Tyedmers and McGrath et al. present systems connected to the electricity grid. SinkabergHansen is a Norwegian farming company currently planning a closed containment system locality with shore-side electricity for post-smolt production, but as with open net pen production some systems can be expected to have a fossil energy supply.

Taking into account the growth of the fish taking place within different rearing environments at different stages in the production cycle, the absolute energy requirements of the four production cycles can be determined based on the specific energy consumption factors in Table 3.4. It also takes into account the energy requirements of the vessels, and the variation in production and energy technology efficiency, the values for energy consumption per cycle is included in the following Table 3.5. When energy use per cycle is low, energy efficient farming technologies and efficient energy carriers are applied.



			Production stages			Energy use per cycle		
Production cycles			Smolt	Post-smolt	Salmon grow-out	Low [kWh]	Avg. [kWh]	High [kWh]
I	Open net pen	Production technologies	Land-based RAS [0 - 0,5 kg]		Open net pens [0,5 - 4 kg]	3,04	5,33	7,61
		kWh/stage	1,5 - 2,5		1,54 - 5,11			
II	Land-based RAS	Production technologies	Land-based RAS [0 - 4 kg]			24	30	36
		kWh/stage	24 - 36					
III	Offshore	Production technologies	Land-based RAS [0 - 1,5 kg]		Offshore farms [1,5 - 4 kg]	8,05	11,47	14,88
		kWh/stage	6,9 - 11,4		1,15 - 3,48			
IV	Closed containment systems	Production technologies	Land-based RAS [0 - 0,15 kg]	Closed containment system [0,15 - 4 kg]		8,85	32,62	56,39
		kWh/stage	0,3	8,55 - 56,09				

Table 3.5: Range of gross energy use for production cycles including energy requirements of the vessels.

In Table 3.5, the range in energy use per production cycle of a 4 kg salmon varies considerably from low to high for all four production cycles. For the open net pen production cycle, the low value assumes energy-efficient post-smolt production in land-based RAS followed by production in open net pens where the feed barge is connected to shore-side electricity and all vessels are electric. When the post-smolt production is inefficient and production at sea is powered by fossil fuels only, the energy use per cycle more than doubles. A similar pattern is observable for the offshore farming production cycle.

Production in the land-based RAS production cycle has a high energy demand overall, but the relative variation between low and high energy use is smaller compared to the other production cycles. This might be because production in land-based RAS is only powered by electricity, and the variation in energy use is only caused by differences in energy efficiency of the farming technology and not efficiency differences between energy technologies. For closed containment systems, the uncertainty associated with the production is reflected in the large range in energy use per production cycle from 8,85 kWh to 56,39 kWh. The values are based on data from only two production systems with different systems design. As mentioned, the variations in energy use are further increased by the different efficiency of the energy carriers. Of all the production cycles in Table 3.5, the combination of land-based post-smolt production and salmon grow-out in open net pens connected to shore-side electricity appears to be the most energy efficient production method.

In order to determine the sectoral energy consumption, the specific energy consumption of the production of the production stages are multiplied by their relative contribution to the overall production volume.

$$Sectoral\ energy\ consumption = \sum_i (P_i, t \times SEC_i \times \frac{1}{\eta_j})$$

where
P_i, t is the production volume of salmon from a specific production cycle *i* in year *t* in *kg*,
SEC_i is the specific energy consumption of production technology *i* in *kWh/kg*,
η_j is an efficiency factor taking into account the efficiency of the production or energy technology.

3.2.4 Energy Scenarios

Energy scenarios can be useful to demonstrate potential implications of variation in technological efficiency in salmon production and the application of different energy carriers. The growth in production volume and distribution of farming technologies remains the same for all energy scenarios. Production of smolt, post-smolt and salmon grow-out in land-based RAS are in all scenarios powered by electricity, as illustrated in Table 3.4. The energy technology for the vessels used in the grow-out phase of the production cycles are considered separately from the energy sourcing for the farming technologies. Three energy scenarios are modelled based on the available literature and best judgement of potential development in the industry.

The base line scenario reflects the current state of production and will also be used for determining emissions targets in 2030 and 2050. The second scenario aims to address the potential energy reduction from decarbonization of the energy supply, achieving efficiency gains by partly changing the energy source to electricity. The final scenario should reflect an assumed best-case scenario for the industry with higher energy efficiency in production and a higher share low-carbon energy supply.

Scenario 1 - Base Line

The gross energy consumption of today's production cycles are assumed to be constant towards 2050. Technological efficiency of the farming technologies is assumed to be the average energy use of the technologies. For instance, for closed containment systems connected to share-side electricity, the energy use in the grow-out phase for the two studies available is 1,82 kWh/ kg and 4,77 kWh/ kg, and so the average value of 3.3 kWh/ kg is assumed in the calculations. The distribution of the energy carriers for the farming technologies in the base line scenario are assumed to be:

- Open net pens: 50% fossil, 50% electric (ABB and Bellona, 2018; Kontali et al., 2020).
- Land-based RAS: 100% electric (Hilmarsen et al., 2018).
- Offshore: 90% fossil, 10% electric.
- Closed containment system: 80% fossil, 20% electric.
- Vessels: 100% fossil (Kontali et al., 2020).

Scenario 2 - Electrification

Assumptions about the potential connection of (shore-side) electricity as an energy source for the different production cycles and vessels. The non-electrified localities or facilities are assumed to be powered by fossil fuels. The share of electrified localities representing the current or short-term potential are reflected in the 2020/ 2030 value and the 2050 value reflects a long-term hypothetical.

Production Technology	2020/2030 [% electric]	2050 [% electric]
Open net pens	80%	80%
Land-based RAS	100%	100%
Offshore	20%	30%
Closed containment system	30%	60%
Vessels	10%	30%

Table 3.6: Assumed electrification rates of farming technologies in 2030 and 2050 in Scenario 2 - Electrification.

For open net pens, the electrification potential is set to 80% because this is the share of localities which can be connected to shore-side electricity without triggering substantial grid investments (Møller, 2019; DNV GL, 2018). It is assumed to be the same for 2030 and 2050 due to the growth in the industry which will require grid upgrades to maintain the electrification share of farmed localities. For offshore farming, the electrification potential is considered limited due to the remote location of the farms. This is reflected in the modest increase in the electrification share between 2020/2030 and 2050. For closed containment systems, the electrification share is higher because of the shore-side location and assumptions about transferable experience from connecting open net pen localities to shore-side electricity. However, the electrification rate is still considered smaller than for open net pens due to the significantly higher energy requirements.

Scenario 3 - Electrification and Efficiency

This scenario builds on the electrification scenario and the electrification rates are assumed to be the same in both scenarios. In addition, assumptions are made about efficiency of the farming and energy technologies. When electrification is not possible, a hybrid battery-diesel solution is assumed for all cases which reduces diesel requirements by 1/3 (ABB and Bellona, 2018). The efficiency gains from the farming technologies summarized:

Production Technology	Efficiency Improvements Farming Technology	Reference
Open net pens	14 %	(Jebsen, 2019)
Land-based RAS	20%	(Nistad, 2020)
Offshore	30%	Best guess
Closed containment system	30%	Best guess

Table 3.7: Energy efficiency improvements of farming technologies in Scenario 3 - Electrification and Efficiency.

For offshore farming and closed containment systems, no sources on potential energy efficiency gains were found in the literature. Seeing that these are novel technologies currently being tested and developed, energy efficiency improvements are likely and here a 30% improvement is assumed.

For the *vessels*, the energy sourcing now includes the application of hydrogen replacing fossil fuels. The following distribution is assumed:

- *2030* - Electricity: 10%, Hydrogen: 10%, Fossil: 80%.
- *2050* - Electricity: 30%, Hydrogen: 30%, Fossil: 40%.

3.3 Greenhouse Gas Emissions

The environmental impact associated with the different energy technologies are estimated based on emissions to air. For fossil energy carriers the combustion emissions are considered and for electricity the production emissions. For a decarbonized energy supply the emissions to air will be low, which is important with regards to climate agreements. The emission targets will be calculated based on the sectoral energy emissions of the base line scenario in 2020.

$$Total\,emissions = EMF_i \times Input\,energy\,carrier\ [kWh]$$

where EMF_i is the emission factor of different energy carriers in $kgCO_2eq./kwh$.

The emission factors for the energy carriers are listed in Table 3.8.

Energy carrier	**kg CO_2-eq./kWh**	**Scope**	**Reference**
Marine gas oil/ Diesel	0,256	Combustion emissions	Norwegian Environment Agency et al. (2017)
Gasoline	0,257	Combustion emissions	Norwegian Environment Agency et al. (2017)
Electricity	0,017	Production emissions, Norwegian electricity consumption mix 2019	Norwegian Water Resources and Energy Directorate (2020)
Electricity	0,007	Production emissions, Norwegian electricity production mix	Ecoinvent Database (Ecoinvent, a)

Table 3.8: CO_2 emission intensities of energy carriers.

For hydrogen, the greenhouse gas emissions are assumed to originate from the electricity production as inputs to the electrolysis process (Horne and Hole, 2019). It is assumed to be generated from renewable energy sources to take advantage of the emission reduction potential, the electricity production is here assumed to be the Norwegian electricity production mix as displayed in Table 3.8. Taking into account the efficiency of the electrolysis process of 66%, the emissions from the electricity production mix for the use of 1 kWh on-site would be 0,0106 kg CO_2 (Chryssakis et al., 2015; Horne and Hole, 2019).

Lastly, further environmental implications of novel salmon farming technologies and decarbonizing energy supply as described by research question number 4, will be evaluated by drawing on findings from literature such as life-cycle assessments and feasibility studies.

4. Results and Discussion

This section includes the results modelled for the sectoral energy consumption and the associated greenhouse gas emissions with reference to the estimated emission reduction targets. Firstly, the implementation and relative contribution of the four production cycles to the production volume towards 2050 will be considered. Then the sectoral energy consumption based on the assumptions for the three energy scenarios in the methodology section are presented, and factors driving the energy use will be identified. Then moving on to how the sectoral energy consumption translates into sectoral greenhouse gas emissions. Subsequently, the emissions will be evaluated with reference to the 2030 and 2050 emission targets. Lastly, a discussion on the potential opportunities and challenges of farming and energy technologies towards a decarbonized sectoral energy supply for Norwegian salmon aquaculture is included.

4.1 Salmon Production Scenario and Technologies

The 3,0% compound annual growth production scenario with the composition of different production technologies are displayed in Figure 4.1 below.

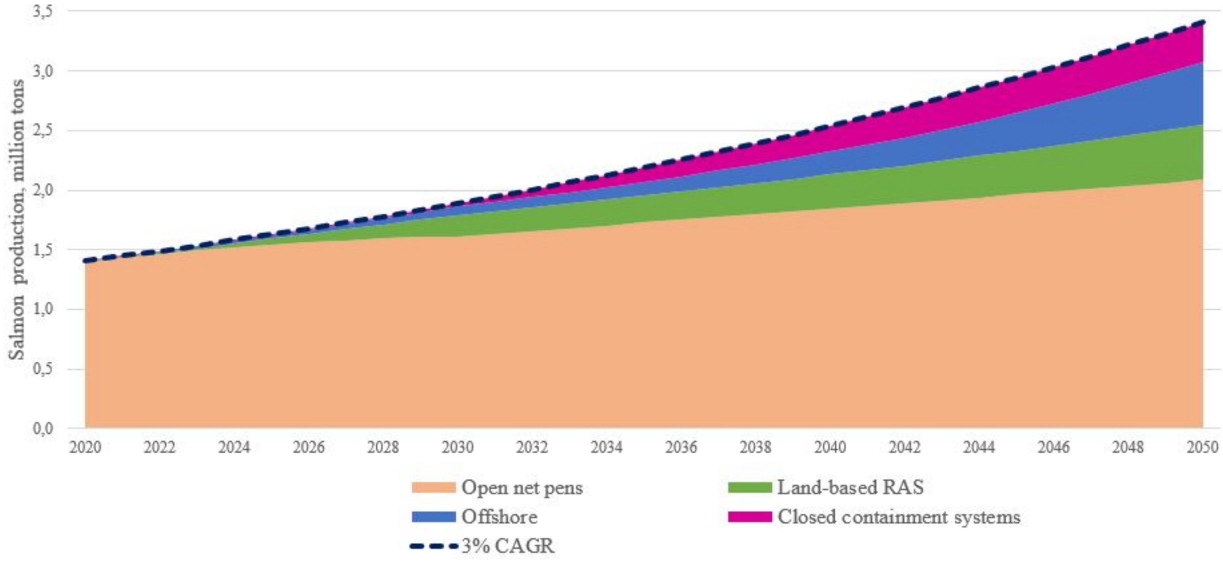


Figure 4.1: 3% compound annual growth production scenario with the breakdown of production technologies.

The production of salmon grow-out in open net pens continues to be the dominant production technology in 2030 and 2050, though it is increasingly complemented by newer production technologies. Initially, land-based RAS is the most favourable new production technology. With the ongoing projects for salmon grow-out in land-based RAS in Norway, the production volume in 2030 ought to be 650 000 tons salmon (Sundnes, 2020). In Figure 4.1, the production volume of salmon in land-based RAS is 180 000 tons which is considerably lower, however it has been pointed out that some of the projects appear overly optimistic and will not be realised (Sundnes, 2020).

Towards 2050, the production contribution of the different technologies becomes increasingly similar. A summary of the production shares in the of production technologies are included in the following Table 4.1.

Production technologies (salmon grow-out)	**Production share 2030**	**Production share 2050**
Open net pens	85,0%	61,2%
Land-based RAS	9,5%	13,5%
Offshore	3,6%	15,5%
Closed containment system	1,5%	9,7%
Total production volume (million tons)	1.89	3.41

Table 4.1: Production share of technologies in 2030 and 2050 for the 3% CAGR scenario.

In terms of growth in production volume between 2030 and 2050, the production volume of open net pens increases by 29% and 159% for land-based RAS. For offshore farming and closed containment systems, the growth is considerably higher because of the slow adoption of the technology modelled, the growth from 2030 to 2050 is 671% and 1104%, respectively.

With the uncertainty associated with the implementation of farming technologies and industry development so far ahead, it is challenging to project the production volume for different technologies. There are few studies available considering this topic, but in a 2017 seafood analysis by PwC, the potential implementation share of new technologies in 2050 was derived based on surveys from industry leaders (Heen et al., 2017). The estimates by the industry leaders are summarized in Figure 4.2.

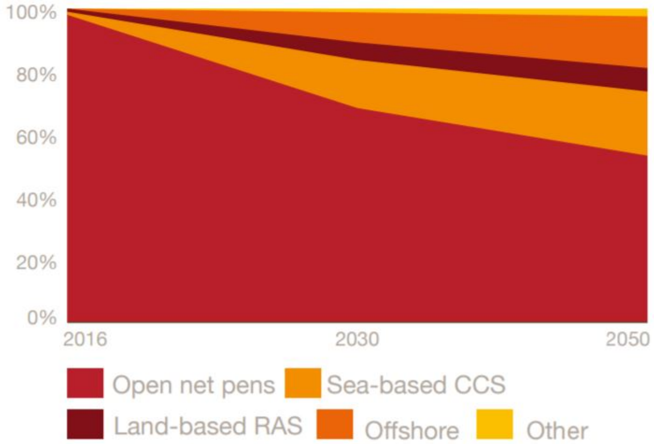


Figure 4.2: Implementation of different technologies in Norwegian salmon aquaculture in 2030 and 2050, based on surveys from industry leaders from Heen et al. (2017).

Comparing the 2050 results from Heen et al. (2017) with the estimates in this thesis, industry leaders believe that open net pens will make up 53% of the production volume versus 61,2% in this model. Industry leaders are more hesitant towards land-based RAS, expecting a production volume of 8%, less than the 13,5% estimated in this study (Heen et al., 2017). However, just in the past one to two years since the Heen et al. (2017) report was published, the number of salmon grow-out in land-based RAS projects have doubled (Sundnes, 2020). This provides an indication of the fast pace by which the industry is moving, however it is uncertain how many of these projects will be realised which makes it challenging to predict future production. Moreover, the profitability of salmon grow-out in land-based RAS in Norway has been questioned because the products are in competition with salmon produced in open net pens which is more cost-effective (Sæternes, 2020; Øyehaug, 2020). For offshore farming, the potential production share of 17% in the PwC seafood report is similar to this study with 15,5%, but expectations for closed containment system is considerably different with 21% and 9,7%, respectively (Heen et al., 2017).

The expectations about the implementation of new farming technologies by industry leaders as indicated by Figure 4.2 provides a slightly different production narrative than the thesis. However, overall it identifies similar trends for Norwegian salmon aquaculture. Open net pens will continue to be the dominant production technology in 2030 and 2050. Other relevant production methods identified are land-based RAS, closed containment systems and offshore farming. The expectations about offshore farming and land-based RAS are in the long-run quite similar, but industry leaders have a greater confidence in the adoption of closed containment systems compared to this study.

4.2 Sectoral Energy Consumption

This section presents the results on sectoral energy consumption and includes a discussion on the contribution of different farming technologies to sectoral energy consumption. Firstly, the base line scenario is discussed, highlighting the contribution potential of the new farming technologies, the share of fossil energy consumption and development in sectoral energy consumption over time. Following this, changes in energy consumption with regards to the implementation of electrification and efficiency measures in Scenarios 2 and 3 are deliberated. Research question number 1 and 2 will thereby be addressed in this Section 4.2.

4.2.1 Base Line Scenario

The following Figure 4.3 reflects the developments in sectoral energy consumption towards 2050 given the current level of farming and energy technologies in industry. It provides an indication of how the new production technologies and methods affect the energy consumption of the Norwegian salmon aquaculture in the coming decades without changes in the energy carriers.

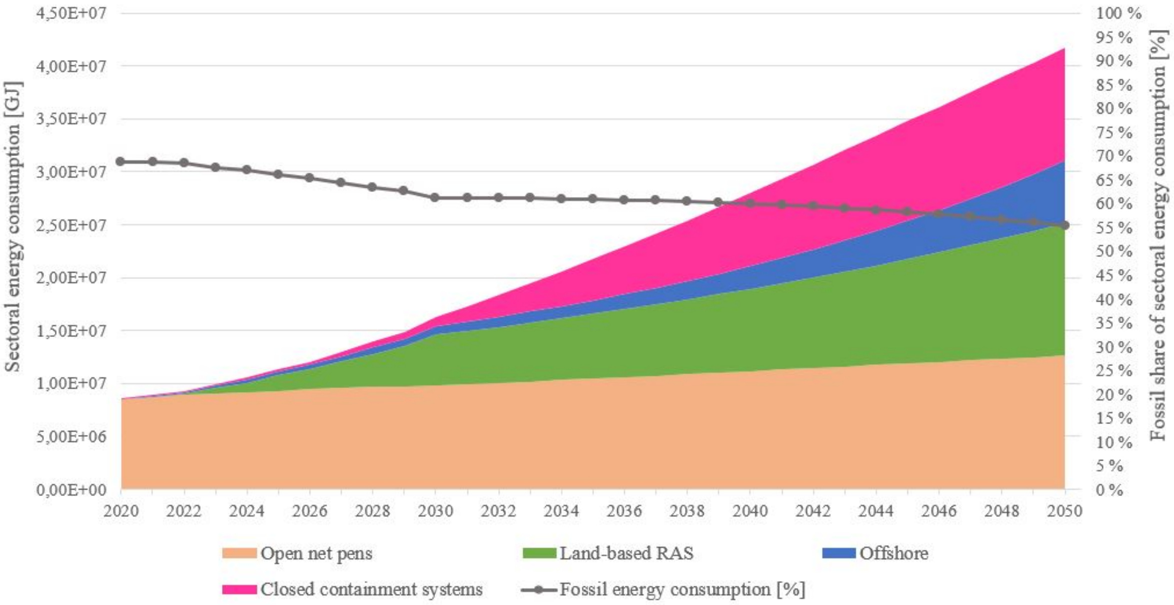


Figure 4.3: Sectoral energy consumption modelled for the base line scenario from 2020 to 2050.

In the base line scenario, the sectoral energy consumption in 2020 is estimated to 8.60×10^6 GJ, corresponding to 3,6% of the energy consumption of Norwegian households in 2019 (Statistics Norway, 2020c). The sectoral energy consumption increases to 4.17×10^7 GJ in 2050. This is an increase in energy consumption of 385% between 2020 and 2050 compared to an increase in production volume of 143%. It suggests that if current technology and energy efficiency is continued, the sectoral energy consumption will increase disproportionately. The energy consumption increases at a higher rate towards 2050 as the novel and more energy demanding production technologies make up a greater share of the production volume. If all salmon were to be produced in the open net pen production cycle, the energy consumption in 2030 would be 30% lower compared to the energy required in 2030 for the base line scenario and 50% lower in 2050.

Based on the distribution of the sectoral energy consumption in Figure 4.3, the high energy requirements of land-based RAS and closed containment systems appear to be driving the sectoral energy consumption. The share of production volume in land-based RAS in 2050 is 13,6%, but the contribution to sectoral energy consumption is considerably higher with 30%. For closed containment systems, the salmon production share is 9,7%, and share of overall sectoral energy consumption is 25,3%. The open farming systems, open net pens and offshore farms are less energy intensive. In 2050, open net pens are responsible for 61,2% of the production volume, but only contribute to 30,3% of sectoral energy consumption, for offshore farming the corresponding values are 15,5% of the production volume and 14,3% of energy consumption.

In terms of energy carriers, the share of fossil energy consumption in 2020 is 69%, and open net pen production makes up 99,5% of the production volume. Even though half of the open net pen farming localities are assumed to be connected to shore-side electricity and the smolt and post-smolt production takes place in land-based RAS, the fossil energy consumption by the vessels and remaining localities dominates. Towards 2030, the share of fossil energy consumption decreases with the increased production in land-based RAS relying on decarbonized electricity. From 2030 to 2050, the sectoral share of fossil energy consumption continues to decrease, but at a slower rate due to the increased production in closed containment systems which is energy-intensive and assumed to largely be powered by fossil fuels. The relative share of fossil energy in the closed containment system production cycle when the locality is powered by diesel generators is 99% compared to 25% when it is connected to shore-side electricity. On the other hand, the difference in the share of fossil energy consumption in the offshore production cycle between farms running on diesel and shore power is lower with 28% and 19%, respectively. The fossil share is relatively low for both because the salmon is reared in land-based RAS until it reaches 1,5 kg and is only then transferred to the offshore farm. Even with considerable variations in the fossil share of energy consumption in the production cycles, the fossil energy carriers continue to dominate the sectoral energy consumption and is in 2050 estimated to 55%.

The average production efficiency of the farming technologies were assumed in the base line scenario. The variation in farming technology efficiency is in the model mainly relevant for the land-based RAS and closed containment system which is modelled based on two studies. For offshore farming and open net pens, the variation in energy requirements in the grow-out phase stem from the application of different energy technologies. If the base line scenario were modelled under the assumption that the farming technologies were highly energy efficient, the sectoral energy requirements would be 8% lower in 2020 and 21% lower in 2050. The growing discrepancy in sectoral energy consumption can be explained by the increased implementation of production cycles with farming technologies that have a greater variation in technological efficiency. For instance, for the closed containment system production cycle the difference in energy use per cycle is 40% between the cases when the most and least efficient production technologies are applied. Whereas the difference for the open net pen production cycle is only 7%, and this variation mainly stems from the different energy efficiencies in smolt and post-smolt production in land-based RAS. Now, considering the potential difference between the sectoral energy consumption if the least efficient and most efficient farming technologies were implemented for all production cycles. The sectoral energy consumption would be 17% higher in 2020 and 53% in 2050. These efficiency differences in the production technologies are relevant when determining the sectoral energy consumption and potential emissions, but are not considered in the thesis beyond the discussion here. The average efficiencies of the farming technologies are assumed as a reasonable starting point for modelling and further efficiency improvements have been incorporated in Scenario 3 - Electrification and Efficiency as described in this Section 3.2.4.

4.2.2 Scenario Comparison - Electrification and Efficiency

The replacement of fossil fuels with low carbon energy carriers and the implementation of energy efficiency measures result in reductions in energy consumption. The sectoral energy consumption encompassing some of these changes are included in Scenario 2 - electrification and Scenario 3 - electrification and efficiency in the following Figure 4.4. The base line scenario is also included as a reference point to illustrate the effect of the measures on the sectoral energy consumption. The scenarios provide insights into what the potential energy requirements of Norwegian salmon aquaculture in 2030 and 2050 might be depending on the farming and energy technology.

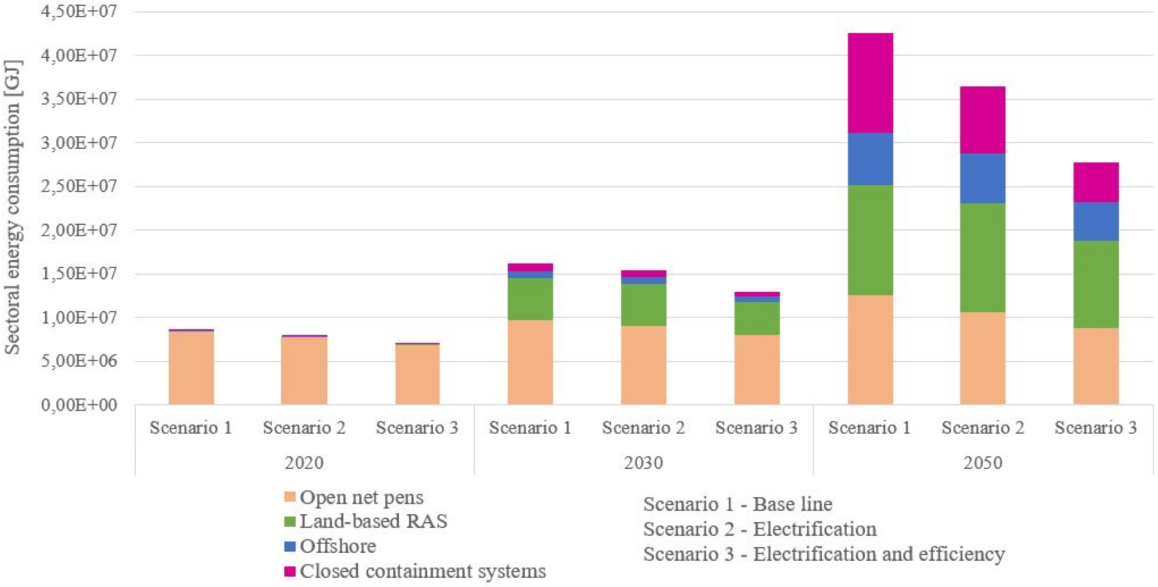


Figure 4.4: Overview of the estimated sectoral energy consumption [GJ] of the salmon farming industry for Scenarios 1-3 for the years 2020, 2030 and 2050.

In all scenarios, the contribution of new farming technologies to sectoral energy consumption appears to be negligible in 2020. This is due to their marginal implementation, their combined contribution to the overall production volume is only 0,5% at this point in time. The 2020 decrease in energy consumption from the base line scenario to the electrification scenario is 8% and to the electrification and efficiency scenario the reduction is 18%. The difference in energy consumption between the scenarios grows towards 2050 with the increased implementation of new and more energy demanding farming technologies, and the effects of the measures in the scenarios become increasingly apparent.

In 2030, the land-based RAS production cycle becomes a noticeable driver of sectoral energy consumption in all scenarios, accounting for roughly 30% of the energy consumption in all scenarios. This is due to its high specific energy consumption and relative high implementation share compared to the other new production technologies. In Scenario 1 and 2 the absolute sectoral energy consumption for land-based RAS is the same because the production technology is already assumed to be fueled by electricity. However, in Scenario 3 land-based RAS energy consumption is 20% lower due to the assumptions about technological energy efficiency gains. According to Nistad (2020), these efficiency gains can be achieved through the implementation of measures such as energy management, reducing the pressure of the pumps recirculating the water in the facility and also frequency controls for the pumps. In 2030, the energy consumption of the open net pen production cycle is 18% lower in Scenario 3 compared to Scenario 2 - electrification. This is due to increased energy efficiency from installing batteries on feed barges still powered by diesel generators, and from increased energy efficiency to changes in power consumption at the feed barge. For open net pens, energy efficiency measures have been identified from energy management projects funded by ENOVA as described in Jebsen (2019). Efficiency gains of roughly 14% of total energy consumption at a feed barge can be made from implementing measures such as energy monitoring systems, installing pressure gauges for the feeding system and photodetectors for light management (Jebsen, 2019). Greater efficiency gains are potentially achievable, but it largely depends on the existing state and management of the system at the feed barge.

For the closed containment systems production cycle, the energy consumption in 2030 is almost halved with the adoption of shore-side electricity and energy efficiency measures, from 8.78×10^5 GJ in the base line scenario to 4.52×10^5 GJ in Scenario 3. This can partly be explained by the high uncertainty associated with the energy use of this technology. The contribution of closed containment system and offshore farming to the overall sectoral energy consumption in 2030 remains low, no more than 10% combined.

In 2050, the sectoral energy consumption is significantly higher for all scenarios and more evenly distributed between the production cycles. The sectoral energy consumption of Scenario 3 is 2.77×10^7 GJ, this is more than three times higher than the 2020 energy consumption modelled in the base line scenario. Considering this substantial gap in sectoral energy consumption, achieving energy emission reductions of at least 80% to reach the emission target might be challenging. Nevertheless, this would be a considerable improvement from the base line scenario in 2050, in which the energy consumption would be almost fivefold relative to the 2020 base line values. In terms of energy distribution between the production cycles, the open net pen cycle is the greatest contributor to sectoral energy consumption in the base line scenario with 30,3%, followed by land-based RAS with 30%. For Scenarios 2 and 3, land-based RAS is the greatest contributor to the energy consumption accounting for 34% and 36% of the overall result in the respective scenarios. The large share of energy required for land-based RAS is disproportionate to the production volume from the production cycle. For all scenarios in 2050, land-based RAS accounts for 30% - 35% of sectoral energy consumption, but is only responsible for 14% of the total production volume. On the contrary, production taking place in the open net pen cycle accounts for 61% of the volume, but sectoral energy consumption is around 30% in all scenarios.

The electrification and efficiency scenario is the scenario where the production cycles show the greatest similarity in terms of distribution between production volume and energy consumption. The offshore farming cycle is in 2050 estimated to produce 16% of the overall volume, and is responsible for 16% of the sectoral energy consumption. For the closed containment system cycle, the contribution to salmon production volume is believed to be 10% and energy contribution 16%. Compared to the energy requirements of the closed containment system in the base line scenario in 2050, the energy requirements are halved in the electrification and efficiency scenario. This development is not apparent for the other production cycles, but the same variation in specific energy consumption is not apparent in the other cycles either.

4.3 Sectoral Greenhouse Gas Emissions

This section presents the results on sectoral energy emissions stemming from the sectoral energy requirements modelled for Norwegian aquaculture. It also includes a discussion on the effects of the measures implemented in the three energy scenarios on sectoral emissions and the necessary measures needed to achieve the emission targets. Thereby, this section aims to answer research question number 3 of the thesis.

4.3.1 Emission Targets

The greenhouse gas emissions estimated are either from the direct combustion of fossil fuels or the emissions from the electricity production. The base year 1990 which is used to determine emission targets for 2030 and 2050 in climate accords was difficult to find or determine for the salmon farming industry. Moreover, the Norwegian salmon farming industry has undergone major changes in terms of production volume and technological improvements over the past 30 years. The following climate targets used as a reference in this thesis is based on the emissions from the base line scenario for 2020. It allows for a comparison of the current state and the need for change moving forward towards 2030 and 2050. In the following Figure 4.5, the sectoral CO_2 emissions from the base line scenario for year 2020 and the subsequent emission targets for 2030 and 2050 are included. For 2050 there are two targets, the 80% reduction target and the more ambitious 95% reduction target.

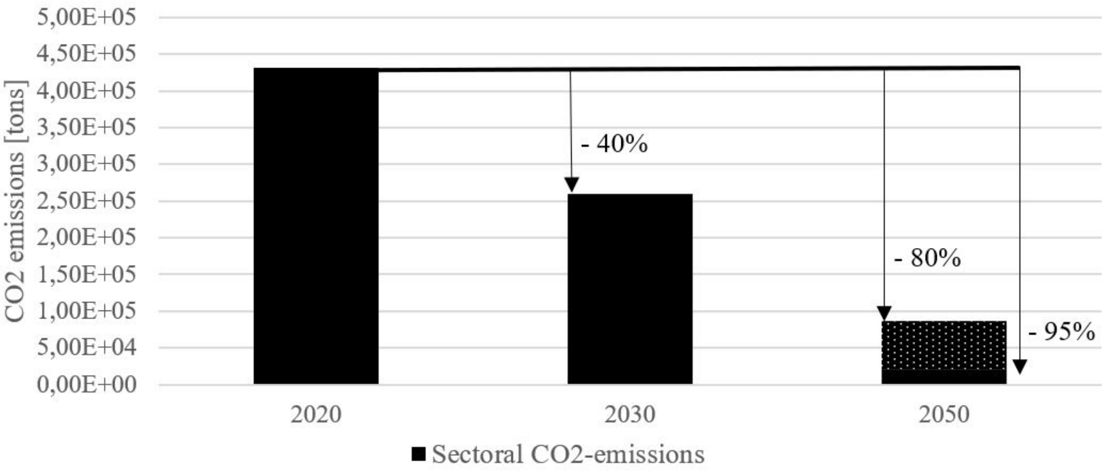


Figure 4.5: Emission targets for 2030 and 2050 based on emissions in the base line scenario in 2020.

In Figure 4.5, the 2020 base line emissions are estimated to 427 ktons CO_2 which corresponds to 0,85 % of current national emissions of 50,3 million tons CO_2-eq. (Miljødirektoratet, 2020). The emission estimate in 2020 is similar to the sectoral CO_2 emissions of 396 ktons estimated in ABB and Bellona (2018). Though, it should be noted that the study by ABB and Bellona only considered combustion emissions in the salmon grow-out phase in open net pens, whereas this study included the energy consumption associated with smolt and post-smolt production. Moreover, this study does not assume that the use of grid electricity is associated with zero CO_2 emissions.

In 2030, the sectoral CO_2 emissions would have to be lower than 259 ktons in order to meet the 40% reduction target determined based on the 2020 emissions in the base line scenario. For 2050, the CO_2 emissions would have to be below 86,4 ktons to meet the 80% target, and 21,6 ktons for the ambitious 95% emission reduction target.

The CO_2 emissions from the energy carriers in the production of salmon to slaughter weight of 4 kg is in the base line scenario for 2020 estimated to 0,302 kg CO_2 per kg salmon produced. In 2050, with a higher production volume and different distribution in production technologies, the carbon footprint would increase to 0,414 kg CO_2 per kg. With the current technology available, the increased application of salmon grow-out in RAS and closed containment systems largely increases the energy consumption, but due to the low emissions from electricity production, land-based RAS is not a considerable driver for energy emissions. Closed containment systems are a considerable contributor to the carbon footprint of the energy consumption because it in the base line scenario is assumed to mainly be powered by fossil fuels.

The carbon footprint of the open net pen production cycle in the base line scenario is 0,30 kg CO_2 per kg salmon produced. In Liu et al. (2016), the CO_2-emission associated with "grow out and smolt (fuel and electricity)" are estimated to 0,16 kg CO_2-eq./kg salmon produced. Differences in the modelling that may cause this gap is the production of regular sized smolt in the Liu et al. study, and it is also unclear how the vessels' energy use are accounted for. This is highly relevant, because the vessels account for at least 60% of the energy requirements in the open net pen production cycle modelled here in this thesis. Moreover, the salmon grow-out in the open net pens in Liu et al. (2016) rely on fossil fuels, compared to 50% in the base line scenario of this study. Based on this, it might appear that the results in the base line scenario overestimate the energy emissions of salmon production.

Møller (2019) estimated the carbon footprint of the onsite energy use for farming localities in Trøndelag to be 0,086 kg CO_2 emissions/ kg salmon produced. This was under the assumption that 50% of the farming localities in use are connected to shore-side electricity and that the transport and work vessels' energy use and emissions are locality specific. For this thesis, the carbon footprint of the grow-out phase in open net pens including work vessel and transport vessel would be 0,084 kg CO_2 emissions/ kg salmon produced in the 2020 base line scenario. This result is quite comparable to that derived by Møller, though it is not unexpected considering the data for open net pens and vessels is based on Møller's previous work.

4.3.2 Scenario Comparison - Electrification and Efficiency

The electrification scenario and the electrification and efficiency scenario present hypotheticals that ought be achievable with existing technology and reasonable assumptions about expected technological development. The following Figure 4.6 and ensuing discussion addresses how decarbonization and efficiency measures contribute to the reduction of sectoral energy emissions.

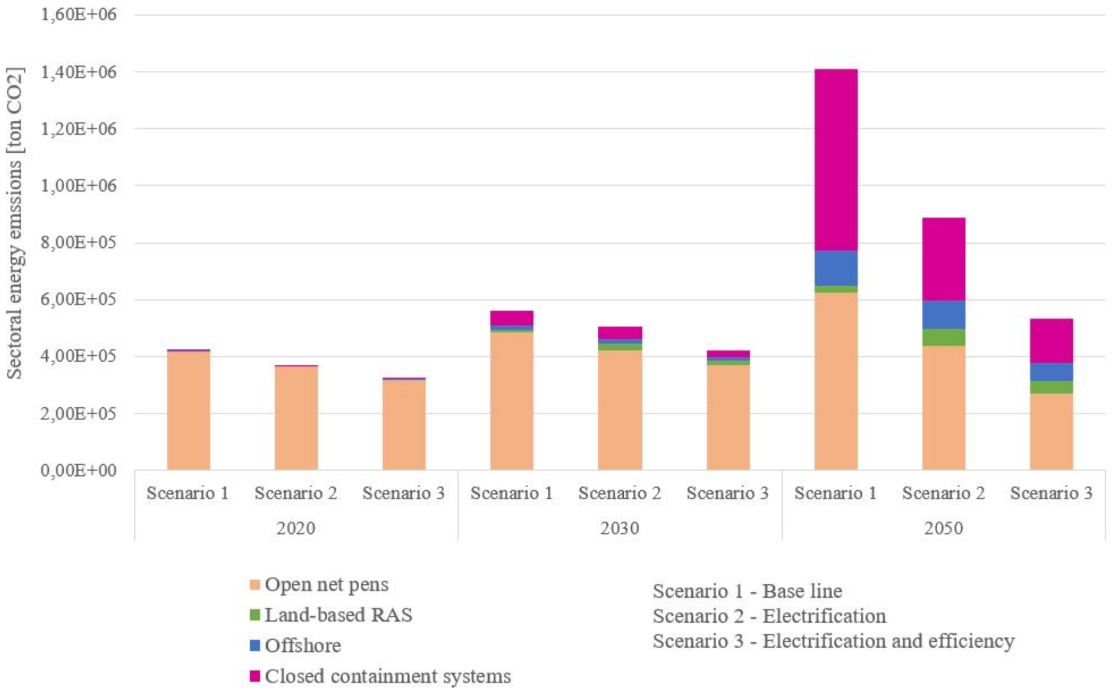


Figure 4.6: CO_2 emissions from sectoral energy consumption for all energy scenarios.

As seen in Figure 4.6, the emission targets are not reached with the assumed electrification and efficiency changes made in Scenario 3. The CO_2 emissions for Scenario 3 in 2030 is equal to the base line emissions in 2020 used to determine the emission targets, and the 2050 Scenario 3 emissions are visibly higher. The Scenario 3 - electrification and efficiency emissions for 2030 are more than 1,6 times higher than the 40% emission target. For 2050, the emissions in the same scenario are more than sixfold of the less ambitious 80% reduction target.

In 2020, the open net pen production cycle is responsible for 99% of sectoral energy emissions. In 2030, it is responsible for between 83% - 87% of the emissions depending on the energy scenario. This is due the high production volume of the open net pen production cycle and the considerable application of fossil fuels for the vessels. In 2030 and 2050, a relatively large share of the sectoral energy emissions can be traced back to the closed containment system production cycle, this is relative to the contribution towards the overall production volume. In 2030 and 2050, the production volume from closed containment systems is 1,5% and 9,7%, but the contribution to the sectoral energy emissions is considerably higher with 6% - 9% in 2030, and 29% - 45% in 2050 depending on the scenario. Comparing the sectoral energy consumption with the sectoral energy emissions, it is in 2050 apparent that the high energy requirements of land-based RAS does not translate into considerable greenhouse gas emissions. This can be explained by the decarbonized electricity supply from the Norwegian electricity consumption mix.

In 2050, the difference between the energy emissions of the production cycles in the base line scenario and electrification and efficiency scenario is quite large. The emissions from the open net pen production cycle is reduced by 57% with the increased implementation of hybrid battery diesel generator solutions, and increased energy efficiency in open net pen and land-based RAS production technologies. For the closed containment systems in 2050, the reduction potential between the scenarios is even greater because of the large range in the specific energy consumption, resulting in a difference of 75% between the base line scenario and the electrification and efficiency scenario.

Seeing that the emission targets are not met based on the assumptions in electrification and efficiency scenario, further improvements in energy efficiency and measures to decarbonize energy supply to meet the targets are considered in the following section.

4.3.3 Achieving the Emission Targets

As seen in Figure 4.6, the emissions in the electrification scenario and the electrification and efficiency scenario are too high in 2030 or 2050 to achieve the emission targets. Hypothetically, if all salmon farming operations were to be powered by electricity, the sectoral energy emissions would be 53,5 ktons CO_2 in 2030 and 136 ktons in 2050. This corresponds to an emission reduction of 87% in 2030 and a 68% reduction in 2050 from the base line 2020 emissions scenario used to determine the emission targets. Thereby the 2030 emissions could be achieved, but not the 2050 target. Full electrification of all operations may not be realistic, and other measures need to be considered.

2030 Emission Target

In 2030, the open net pen production cycle accounts for 62% of the sectoral energy consumption and 87% of the CO_2 emissions. The vessels are in the 2030 electrification and efficiency scenario mostly powered by fossil fuels and a significant driver of CO_2 emissions, particularly in the open net pen production cycle where the specific energy consumption of the feed barge is relatively low. Potential emission reduction measures for 2030 are displayed in the following Figure 4.7.

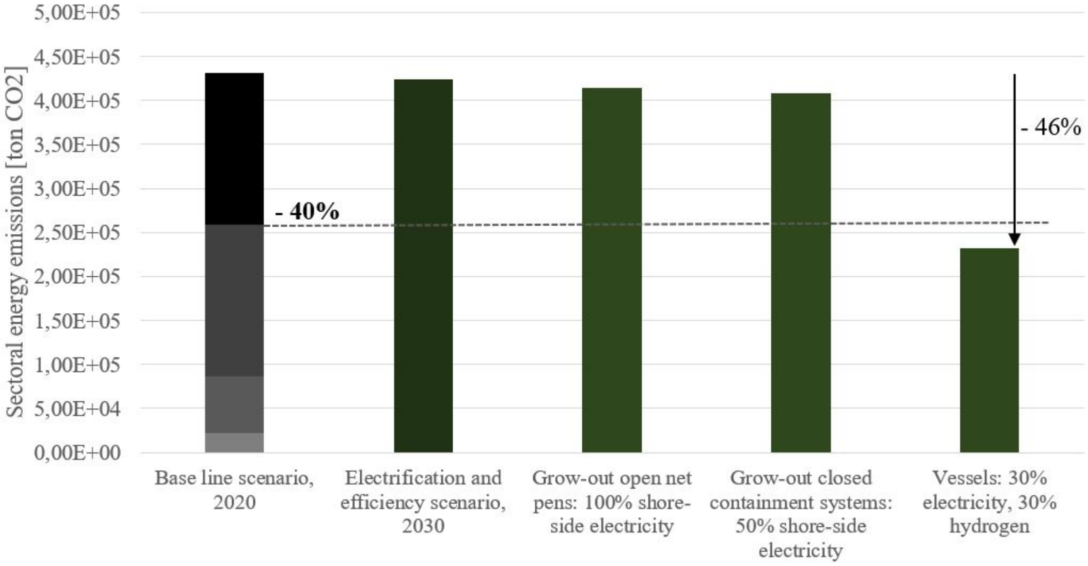


Figure 4.7: Potential measures to reduce CO_2 emissions to achieve the 2030 emission target. Starting point for implementation of the reduction measures is the electrification and efficiency scenario in 2030.

Implementing the three measures in Figure 4.7, the overall reduction corresponds to a 46% decrease compared to the 2020 base line scenario emissions. The increase in the electrification rate of salmon grow-out in open net pens from 80% to 100% and from 30% to 50% for closed containment systems have a relatively small effect on the sectoral energy emissions. Increasing the share of hydrogen and electric vessels each from 10% to 30% has a substantially higher effect on emissions. The measure has an annual emission reduction potential of 176 ktons CO_2. Implementing the measure would in itself be sufficient to reduce emissions below the 2030 target, the CO_2 emissions would then amount to 249 ktons.

2050 Emission Target

In 2050, the new production technologies are to a greater extent applied, increasing the energy consumption per kg salmon produced. In addition, the salmon production volume is considerably larger and needs to be compensated for by further improving energy efficiency or applying low-carbon energy carriers. Figure 4.8 below has included potential measures for all production technologies and the carbon intensity of the electricity in order to ensure that the 2050 emission target is met.

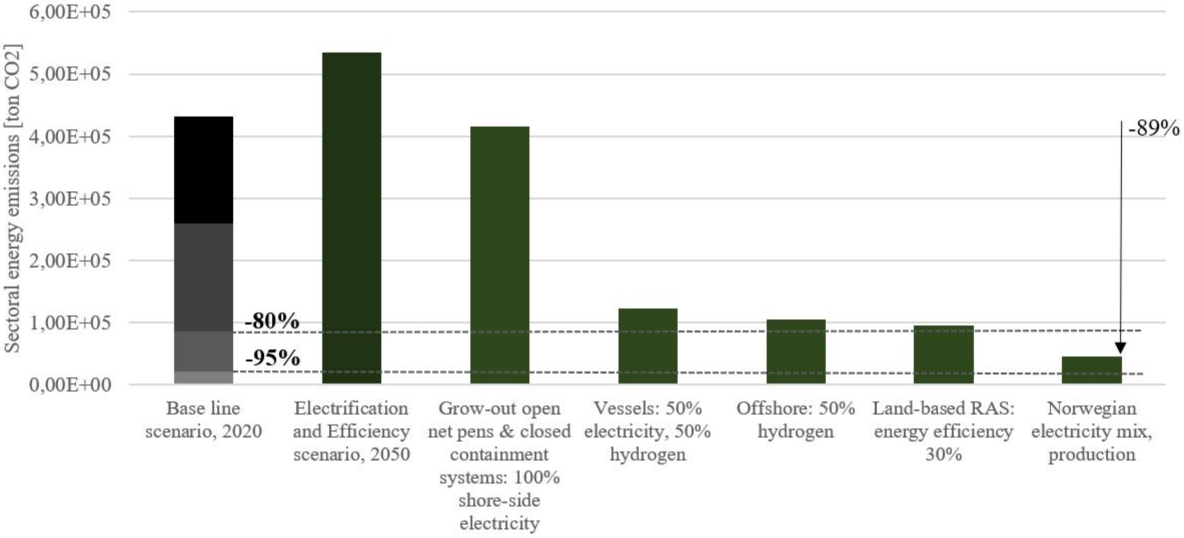


Figure 4.8: Potential measures to reduce CO_2 emissions to achieve the 2050 emission target. Starting point for reduction is the electrification and efficiency scenario in 2050.

The starting point for implementation of further measures is the electrification and efficiency scenario for 2050. The overall emission reduction potential of the measures displayed in Figure 4.8 would correspond to a decrease of 89% in the 2020 base line scenario, thereby achieving the 80% emission reduction potential. Again, the vessels appear to have the greatest emission reduction potential. Here, half of the vessels are assumed to be fuelled by electricity and the other half by hydrogen compared to 30% each in the electrification and efficiency scenario for 2050. This measure results in an emission reduction of 296 ktons CO_2 emissions, thereby more than halving the sectoral emissions.

In terms of farming technologies, the adoption hydrogen as an energy carrier is also considered a potential emission reduction measure for offshore farming. Because of more remote locations, it is assumed that electrification is a limited option and that hydrogen might be a better alternative. The emission reduction measure by decarbonizing the energy supply is that 50% of the production volume will be powered by hydrogen in stead of fossil fuels. The reduction potential overall is quite small, likely because the offshore grow-out phase is shorter and quite energy efficient compared to the other production technologies. The measure where all open net pens and closed containment systems are connected shore-side electricity yields the second-most emission reductions, 118 ktons CO_2 emissions corresponding to a 22% reduction. This is largely due to the increased efficiency from the conversion to shore-side electricity for closed containment systems which have a large range of specific energy consumption in the model. For land-based RAS, an additional increase in the energy efficiency of production can be expected, according to Nistad (2020) further reduction is possible through biomass optimization which increases the salmon output for each unit of energy inputs. A 30% improvement in specific energy consumption to 5,25 kWh/ kg falls within the achievable range of optimized energy consumption between 4,6 - 5,3 kWh/ kg salmon produced as presented in Nistad (2020).

The final (rightmost) measure in Figure 4.8 is the change in the carbon intensity of the electricity from the Norwegian consumption mix in 2019 of 17g CO_2/ kWh to the Norwegian production mix of 7g CO_2/ kWh. This change results in a 10% reduction in sectoral emissions, ensuring the industry adherence to the 80% reduction target. With the increased production of post-smolt in land-based RAS for offshore farming and open net pens, and the need to connect open net pens and closed containment systems to shore-side electricity, the carbon intensity of the electricity supply becomes increasingly relevant. Seeing that the Norwegian electricity production mix has a lower carbon intensity than the consumption mix, further integration of the European electricity market may increase energy emissions in the salmon farming industry. Figure 4.9 illustrates the effect of different electricity sourcing on emissions. The starting point for the consideration of the electricity mix in the figure is Scenario 3 - electrification and efficiency including the potential measures for achieving the emission target in 2050 as previously described in this Section 4.3.3.

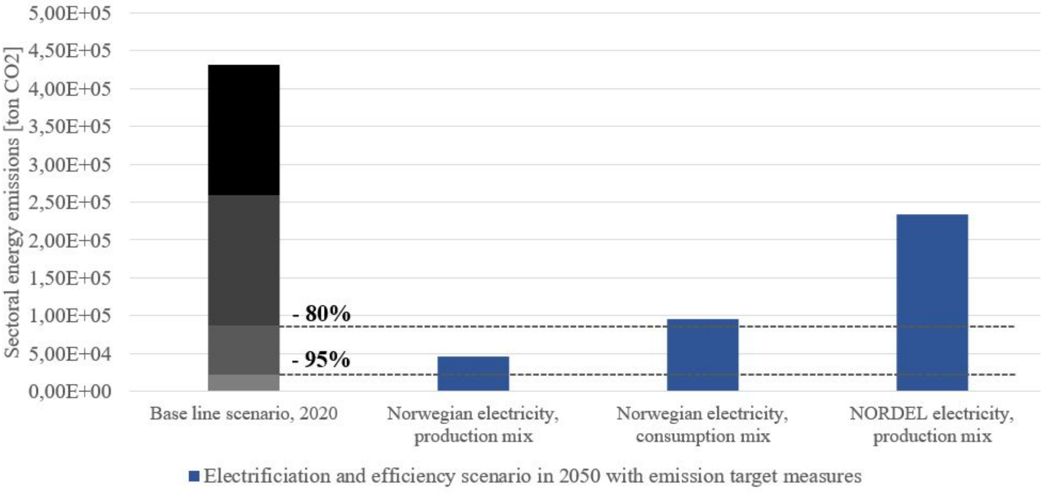


Figure 4.9: The effects of different electricity sourcing on the sectoral energy emissions and achieving the 2050 emission target.

In Figure 4.9, with the current Norwegian electricity production mix, the sectoral emissions would result in an emission reduction of 89% and thereby achieve the emission reduction target. The use of current Norwegian electricity consumption mix would result in a shortfall of the 2050 target by 9300 tons CO_2. The Nordic (NORDEL) electricity mix of 45 g CO_2/ kWh results in sectoral emissions considerably above the 2050 emission targets (Ecoinvent, b). The CENTREL European electricity mix of 824 g/ kWh is not included in the figure, but would result in emissions 9 times greater than the 2020 base line scenario emissions (Ecoinvent, c). This suggests that in order for electrification to be a successful strategy towards sectoral emission reductions, the electricity mix needs to be highly decarbonized. Local, on-site generation solutions with solar or wind power hybrid systems currently being tested can be a solution to partly cover power demand and reduce the overall carbon intensity of the electricity mix consumed. At this point, the implementation potential is still very uncertain in terms of technological and economic aspects and how it may develop in the long-run.

To summarize, for the Norwegian salmon aquaculture industry to reduce GHG emissions and achieve the 2030 and 2050 target, different measures are effective based on the distribution of production technologies and energy carriers applied. In the short-run it will be more important to target the vessels since open net pens with fossil powered vessels is the dominant production technology. The vessels are still highly relevant in 2050 because they are also needed for production in novel technologies such as offshore farming and closed containment systems which will be increasingly important. In 2050, the production volume is almost 2,5 times larger than in 2020, thus the reduction measures also need to be more ambitious and target all production technologies in the sector. It is also apparent that hydrogen or other low-carbon energy carriers need to be part of the solution in the long-run. Local renewable energy production may also help reduce the emissions as the sector becomes increasingly electrified and the strain on the electricity grid grows. The farming companies striving to reduce environmental impacts in their production might also gain an advantage when allowances for production volume is determined (Meld.St.16 (2014-2015), 2014). If this would be the case, there would be a financial incentive to reduce emissions in farming operations to increase the production volume. Such factors potentially influencing production and decarbonization decisions in the salmon farming sector will be discussed next.

4.4 Evaluation of Challenges and Opportunities to Decarbonize the Energy Supply in Salmon Farming

The ensuing sections provide an evaluation of the application potential of the farming and energy technologies in Norwegian salmon aquaculture to achieve the emission targets through a decarbonized energy supply. It will also consider other relevant factors for implementation such as investment costs, infrastructure requirements or other environmental impacts, for instance land-use required by land-based RAS facilities or for the expansion of transmission lines necessary for further electrification. Thereby, the farming and energy technologies will be considered from a more holistic point of view. Moreover, environmental aspects beyond greenhouse gas emissions from electricity generation or fossil fuel combustion are discussed, and by that addressing research question number 4 of this thesis.

4.4.1 Salmon Farming Production Technologies

Open Net Pens

The production development in open net pens has taken place over several decades and the specific energy consumption as displayed in Figure 3.4 is quite low. However, in the base line scenario 66% - 72% of the energy requirements still stem from fossil energy carriers depending on whether the feed barge is connected to shore-side electricity or not. Targeting the energy carriers is therefore an efficient measure to reduce the emissions from this production technology. With the increased connection to shore-side electricity, operations carried out by the vessels at the locality could be powered by electricity from the locality, thereby reducing the fuel consumption of the vessels. ABB and Bellona (2018) has assumed that the transport boat and work vessel can fully run on electricity with a connection on-site at the barge, a charging station on shore and batteries. This is not accounted for in this thesis because the vessels' energy source is considered separately from the feed barge, but would serve as measures to achieve a reduction in fuel consumption of the vessels.

In the base line scenario, when the feed barge is connected to shore-side electricity, the vessels are responsible for all fossil energy consumption in the production cycle and 66% of the overall energy consumption. Correspondingly, the vessels are responsible for 59% of the overall consumption when the feed-barge is powered by a diesel generator. In some cases natural gas is pointed as a transition fuel from marine fuels, but it is not considered because it does not fall within the categorization of low carbon energy carriers used here. Apart from challenges in technology and infrastructure development, there are also organizational challenges to reducing fossil fuel consumption and emissions. According to interview responses reported in Winther et al. (2020), salmon farming companies pay for the fuel consumption of service vessels and well boats. Service vessels and well boats are not tied to a specific locality, but service multiple farming localities. The possibility of service and well boat companies to pass on fuel costs reduces the incentive to optimize their operations according to fuel use and thereby reducing greenhouse gas emissions (Winther et al., 2020).

Land-based RAS

With regards to the novel technologies, salmon grow-out in land-based RAS is the most energy demanding production technology, but the energy consumption does not translate into carbon emissions with a low-carbon electricity mix. Advantages of the production technology compared to the other technologies is the potential placement near transport hubs or in areas where the capacity of the electricity is not strained (Hilmarsen et al., 2018). For instance, the placement of a grow-out facility for land-based RAS by Fredrikstad Seafoods in Fredrikstad by Oslofjorden, away from remote open net pen farming localities along the west and northern coast. Most new land-based RAS facilties for smolt production and salmon grow-out are or will be located close to the coast and existing industry infrastructure (Hilmarsen et al., 2018; Sundnes, 2020). For smolt and post-smolt production delivering to open net pens along the coast, locating the facilities close to the next production stage makes sense logistically. The same reasoning applies to the location close to slaughter and processing plants. Therefore, when planning new facilities it is reasonable locate it close to the existing infrastructure. If the location were to be moved further away from the coast, the transport pattern would change and increase energy consumption and emissions from road infrastructure (Hilmarsen et al., 2018).

Apart from the above mentioned emission advantage and flexible location advantage, the production is quite capital intensive and successful commercial production is challenging (Liu et al., 2016; Dalsgaard et al., 2013; Ernst & Young, 2019; Dalsgaard et al., 2013; Øyehaug, 2020). Firstly. the economic aspects, Liu et al. (2016) considers the economic performance of a land-based RAS facility in the US and an open net pen system in Norway each producing 3 300 tons of salmon. The paper finds the capital costs of the land-based RAS to be 80% larger than for open net pen farming (Liu et al., 2016). For open net pen systems in Norway, the costs of the salmon licenses make up approximately 80% of the total capital costs, a corresponding cost is not applicable for the RAS system in the US (Liu et al., 2016). The main capital expenditure of the land-based RAS is the RAS-system itself which makes up half of the total capital costs (Liu et al., 2016). In terms of operating costs, the difference between the two systems was estimated to be considerably lower with only 10% (Liu et al., 2016).

Secondly the production aspects, some of the land-based RAS facilities planned or built for salmon grow-out might only be used for the production of smolt and post-smolt (Sundnes, 2020). For salmon over 1,5 kg there have been difficulties ensuring sufficient fish welfare and achieving wanted biomass growth due to challenges with stocking density, water quality and feeding (Hilmarsen et al., 2018). This provides a challenge for the success of commercial application of salmon grow-out in land-based RAS (Øyehaug, 2020). These challenges can in time be overcome with increased operational experience and improved facility design (Øyehaug, 2020; Hilmarsen et al., 2018). With the integration of the whole production cycle in land-based RAS facilities, the salmon producers might have a greater incentive to ensure energy efficient operations compared to when producing smolt or post-smolt to other companies for grow-out (Øyehaug, 2020). Though with relatively low electricity prices this might not be a priority.

Lastly, other environmental aspects of increased production in land-based RAS is the land-use and water demand. Hilmarsen et al. (2018) finds that if the Norwegian 2017 salmon production volume of 1 300 000 tons is produced in land-based RAS facilities of 5 000 tons each, the gross land use would be 11,7 km^2. This corresponds to 2,6% of the area of Oslo or 1638 football fields. The land-based RAS production volume in 2050 modelled in this thesis is 463 501 tons salmon. This corresponds to roughly a third of the production volume in 2017. Similarly, the freshwater consumption modelled for the 2017 production volume in land-based RAS would be 343 million m^3/year which corresponds to half the water volumes distributed in Norwegian municipal water supply (Hilmarsen et al., 2018). These estimates suggest that even though energy-intensive production in land-based RAS has a low carbon-footprint with a decarbonized electricity supply, the production method drives water use and land-use changes. Moreover, the infrastructure material requirements are high compared to open net pens, the facilities require substantial amounts of concrete, steel and glass fibre (Liu et al., 2016). The carbon footprint of "Construction of facility and equipment" of a land-based closed containment RAS is 0,39 kg CO_2-eq./ kg salmon compared to 0,02 kg CO_2-eq./ kg salmon in open net pens. Thereby, infrastructure emissions of land-based RAS production are almost 40 times larger per salmon produced. However, the systems perspectives of such emissions are not taken into account by this thesis which only considers the direct energy inputs to salmon production.

Closed Containment Systems

Salmon production in closed containment systems is also highly energy demanding, but the emissions are significantly higher than in land-based RAS because of the application of fossil energy carriers. The energy demand varies with the design of the system and the level of control over the rearing environment. The large range in specific energy consumption reflects the uncertainty in the data, but also illustrates the need for low-carbon energy carriers to reduce the emissions from this production technology. Compared to open net pen production, the control over the environment tends to result in improved performance on local ecological parameters, but may drive global warming and acidification through increased fossil energy consumption (Ayer and Tyedmers, 2009).

In the study by Ayer and Tyedmers (2009), a marine floating bag system, i.e. closed containment system performs significantly better in the impact category marine toxicity potential. This is because the anti-fouling paints used on open net pens are avoided for the marine floating bag which can be lifted and sprayed clean (Ayer and Tyedmers, 2009). Moreover, the study finds that 80% of the eutrophication potential of open net pens can be attributed to wastes in the grow-out phase (Ayer and Tyedmers, 2009). This suggests that if excess feed and faecal matter containing nutrients is collected from the closed containment system, the impacts on surrounding waters will likely decrease. Overall, a change towards increased closed containment production appears to be a trade-off between local ecosystems and climate issues when the energy carriers are fossil. Unlike land-based RAS facilities, the location of the closed containment systems have to be close to the shore, with potential challenges for electrification due to the high power demand of the systems.

In terms of data uncertainty, the values for the closed containment systems are from facilities with little operational experience, and in McGrath et al. (2015), the life cycle assessment relied upon data from a partly modelled production cycle because production was ended prematurely due to a storm damaging the structure. From this, some uncertainty in the estimates from the intended production cycle can be expected, but it is one of few studies with relevant data available. The energy consumption of production in these facilities can be expected to decrease with more operational experience (McGrath et al., 2015). Regarding costs, the production of salmon in closed containment systems is costlier than in open net pen production (Nodland, 2017). The costs can be expected to decrease with the commercialization of the technology, and the reduction in delicing operations may also compensate for the additional investment costs (Sæternes, 2020; Nodland, 2017).

Offshore Aquaculture

For offshore farms, the experience from the first production cycle in Ocean Farm 1 suggests improved growth conditions and no need for delicing (SalMar, 2019). With the improved conditions, one would expect the specific energy consumption in kWh/ kg salmon produced to be reduced due to greater volumes produced with the same energy inputs. Moreover, with the experience from Ocean Farm 1, SalMar follows up with a larger and more technologically advanced Smart Fish Farm with a greater production potential with a MAB of 19 000 tons (Kyst.no, 2021). There is hardly any data or information available in terms of operational costs, Tveterås et al. (2020) suggests offshore farms are potentially more energy demanding than traditional open net pens which coincides with the results from the modelling in this thesis.

The current investment costs of the offshore farms are larger than for traditional open net pens, Nordlaks has invested roughly 1 billion NOK in Havfarm 1 and 21 licenses are to be shared between Havfarm 1 and 2, SalMar invested 720 million NOK in Ocean Farm 1 with 8 licenses, and the new Smart Fish Farm has an investment cost of 1,5 billion NOK (Tveterås et al., 2020). According to Tveterås et al. (2020), the profitability of production in offshore farming is sensitive to the cost of farming licenses. With the same license costs as currently for open net pens, offshore farming does not appear to be profitable (Tveterås et al., 2020). However, reduced mortality and improved fish welfare increases the competitiveness of offshore farms compared to open net pen farming (Tveterås et al., 2020).

Lastly, in terms of the energy supply, the applied for location of the Smart Fish Farm is on the border of one of the areas explored by the authorities for offshore farming 30 - 70 nautical miles (55,6 - 129,6 km) from the sea baseline (Kyst.no, 2021). The large distance to shore considered for the placement of offshore farms potentially provides issues for the electrification and low-carbon energy supply of the farms. Berg et al. (2020) finds that shore-power is the most cost-efficient low-carbon energy solution for the three offshore farming concepts. The maximum distance to a transmission line modelled in Berg et al. (2020) is 25 km, and the levelized cost of energy are then slightly higher compared to a hybrid diesel battery solution. However, locating farms further offshore increases the infrastructure costs and risk of disruption beyond a profitable level (Berg et al., 2020). Moreover, even with the offshore farm connected to shore-side electricity, it would also be necessary to have back-up generators to ensure the energy supply and this would require additional investments in a fossil infrastructure (Berg et al., 2020).

4.4.2 Low-Carbon Energy Technologies

The decarbonized energy supply solutions considered most relevant is low-carbon electricity and hydrogen, and will be discussed in further detail in the following section. Other renewable technologies are only briefly mentioned because of limited information on relevant projects and uncertainty about their application.

Electricity

As mentioned, roughly 20% of the current open net pen farming locations are unable to connect to shore-side electricity without triggering further investments in the electricity grid (DNV GL, 2018; Møller, 2019). In cases where the electricity grid needs to be upgraded, the salmon farmer has to fund upgrades in the grid because they are user financed (THEMA Consulting, 2020). The grid costs, in addition to transformers and subsea cabling thereby become an impediment in the transition towards shore-side electricity and a decarbonized energy supply. Based on experience from electrification projects funded by ENOVA, 40-90% of the total costs can be allocated to the subsea cable (DNV GL, 2018). Based on information from the same projects, Jebsen (2019) finds that the investment costs per locality mostly ranges from 1,5 - 4 million NOK. In cases where the costs are higher or too high, a solution could also be to share cable and infrastructure costs with other farming locations or other interested parties, but this would require cooperation and coordination (Møller, 2019; Berg et al., 2020; Tveterås et al., 2020).

The regional distribution of electrified farming localities can be derived from Kontali et al. (2020), where the energy sourcing of 80% of the Norwegian farming localities have been identified. A map of the production zones is included in Appendix A.5.

Production zone [PO]	Electrification share [%] - all localities	Electrification share [%] - identified localities
South [PO 1-4]	48%	67%
Middle [PO 5-7]	46%	50%
North [PO 8-13]	43%	53%

Table 4.2: Regional distribution of farming localities connected to shore-side electricity in Norway from (Kontali et al., 2020).

The regional distribution of farming localities connected to shore-side electricity appears to be relatively even. For the South, Middle and North region the electrified localities make up 43 - 48% of all localities. The energy carriers have been accounted for 70-90% of all the localities in each region (Kontali et al., 2020). However, it should be noted that the number of farming localities and geographic range between the regions differ, so even with a similar electrification share the total load on the grid will vary. For instance, 258 salmon farming localities are located in the Middle region and 411 in the North region, but the North region is also the largest. Lastly, the size of the fish farm also affects the electrification potential, larger farms have higher load requirements and require more costly transformers, but the potential savings from reduced fuel consumption is also greater (DNV GL, 2018).

Of those farming localities currently in use, 65% are either connected to shore-side electricity or hybrid solution with diesel generator and battery (Kontali et al., 2020). With the need for increased electrification of open net pen and closed containment system localities, information on energy sourcing of existing farming locations and grid conditions is highly relevant with the expansion of production volume. Møller (2019) finds that simultaneous electrification of the remaining fossil farming localities in Trøndelag compared to individual electrification has a lower electrification potential without triggering further grid investments. Furthermore, the additional costs of a longer subsea cable connected to transmission lines with greater capacity might be an economic alternative to grid investments for nearby transmission lines (Møller, 2019). Additionally, it might also be relevant for grid operators to be informed about regional expansion plans in production in order to make upgrades in the grid to be able to support the electrification. Even for land-based RAS production, the location might still be relevant because electricity access is better within the fjords, though the access to seawater and receiving waters for waste water improves closer to the coastline (Sundnes, 2020). Nevertheless, if the placement of closed containment systems and land-based RAS is less dependent on environmental factors such as lice, the geographic pattern in energy consumption of Norwegian salmon aquaculture might change.

As indicated by the results in Section 4.3.3 the sectoral CO_2 emissions is sensitive to the carbon intensity of the electricity mix. With an increased integration of the European electricity market, one might expect the carbon footprint of the electricity and consequently Norwegian salmon farming industry to increase. This might have implications for the successful achievement of the 2030 emission reduction target. However, it might be less relevant for the achievement of the 2050 emission target because the European energy sector is also to undergo considerable decarbonization to ensure a transition towards a low emission society. This study has a limited view of the greenhouse gas emissions and other environmental impacts of electrification. It only accounts for the generation emissions and does not take into account grid losses, the emissions or environmental impacts embodied in the infrastructure.

Other environmental considerations of electrification are the land-use and habitat fragmentation from expanding power lines. Norwegian transmission lines have an average right-of-way of 38 m, which corresponds to a total land-use of 417 km^2 (Jorge and Hertwich, 2013). The infrastructure requirements such as masts and conductors are also highly material demanding, they require steel and aluminium and wiring requires copper contributing to metal depletion impacts (Jorge et al., 2012). In Hilmarsen et al. (2018), the carbon footprint of electricity is 114 g CO_2/ kWh including transformers and distribution. Taking into account that the embodied emissions in electricity are considerably higher than the production emissions considered in the thesis, the emission targets would not be met with the additional efficiency and decarbonization measures described in section 4.3.3. In view of this, improving energy efficiency in salmon farming is an important measure to reduce indirect emissions and ecosystem impacts caused by expanding grids to meet the increasing power demand.

Hydrogen

Nearly all hydrogen production today is based on a fossil fuels (Tomasgard et al., 2019). To reap the emissions benefits for hydrogen as an energy carrier, it should be produced from electrolysis using renewable energy technologies or steam reforming using natural gas combined with carbon capture and storage (Horne and Hole, 2019). In Norway, electrolysis is considered a production method with a more widespread application potential due to the substantial infrastructure requirements of natural gas production and carbon capture and storage technology (DNV GL, 2019). For hydrogen to be a competitive energy carrier, large-scale production and distribution is required (Tomasgard et al., 2019). A hydrogen station requires a utilization rate of 75% in order to be profitable (Tomasgard et al., 2019). The need for governmental incentive schemes and coordinated planning to support the infrastructure and distribution has been highlighted as a criteria for the successful adoption of hydrogen as a fuel (Tomasgard et al., 2019; DNV GL, 2019). The location of hydrogen stations is highly relevant for the farming companies in terms of the distance and time vessels will spend on fuelling (Bjørdal, 2020). The organisation of the hydrogen infrastructure and the associated fuel costs will likely be a contributing factor in determining whether hydrogen is a viable solution (Bjørdal, 2020). Lastly, if hydrogen is to be produced from electrolysis with electricity based on renewable energy on a large scale, grid expansions would be required (DNV GL, 2019). Some of the potential environmental effects of the expansion of electricity infrastructure has been described in the previous section.

In terms of industry synergies, in areas along the west coast of Norway with considerable salmon farming activity, there are also ferries and high-speed crafts for passenger transport planned to be powered by hydrogen, thereby providing a potential overlap in hydrogen infrastructure. Another industry synergy to be considered is the use of excess oxygen from the electrolysis process as an input to land-based RAS facilities and closed containment systems (DNV GL, 2019). Hydrogen application to maritime vessels and aquaculture industry still remains largely immature as an energy technology, and its application will likely be quite limited for at least another decade (Tomasgard et al., 2019). This is also supported by the modelling in Berg et al. (2020), where the fuel cell hybrid solution is too costly and immature as an energy solution for the three offshore farming concepts considered.

Other Low-carbon Energy Solutions

On-site electricity generation from wind turbines is mentioned as a solution for open net pen farming localities unable to connect to shore-side electricity, but is considered to be in the test phase (DNV GL, 2018). Syse (2016) finds that a cost-optimal hybrid system consisting of on-site renewable solar and wind power combined with batteries and diesel generators produce enough energy to cover 34% of the energy demand with renewable electricity. The operational experience from an open net pen farm that has implemented a hybrid energy system based on the Syse study indicates that the renewable energy generated covers energy demand 16 hours per day (Kyst.no, 2019). In Syse's thesis, increasing the renewable on-site generation to cover 100% of the energy consumption would result in high excess capacity, 41,4% of the electricity generated would be wasted (Syse, 2016). Similarly for an offshore farm using floating or onshore wind power combined with diesel generators and batteries, Berg et al. (2020) simulate that roughly 90% of the electricity produced to cost-efficiently ensure the power demand will be wasted. This suggests that for wind power systems, investment in excess capacity is necessary to ensure a secure energy supply. For all the energy solutions presented in Berg et al. (2020), the levelized costs of energy from onshore and offshore wind is the highest.

For solar power, the lack of space for panels on the farms, open net pens or offshore, is a limiting factor (Syse, 2016; Berg et al., 2020). The floating solar panels by Ocean Sun can be located next to open net pens and provide electricity, but is currently only tested and able to cover a limited share of power demand (Hosteland, 2017). Another issue is that the weather conditions in Norway are not ideal for solar power generation, and the floating solar power has a higher potential for energy generation closer to the equator (Valmot, 2020). In Berg et al. (2020), the energy generated from 15,5 kW panels is insufficient to load the batteries on the offshore farms, it only contributes a marginal share of the total power demand. In Syse's 100% on-site renewable energy generation case, the energy from solar power is greatest in the summer months, and the combination with higher wind generation during the winter months provides a more reliable renewable energy supply throughout the year.

In terms of other environmental consequences associated with the adoption of low-carbon energy sources, wind and solar power have higher impacts on metal depletion compared to fossil energy systems (Gibon et al., 2017). The production of PV modules and wind turbines requires metals such as copper and iron (Hertwich et al., 2016). The technologies also have a larger impact on land-use due to occupation of land when generating electricity (Hertwich et al., 2016). It should be noted that for onshore wind generation, the resistance to wind parks along the coast in Norway has been growing (Stephansen, 2020). The turbines affect wild-life such as birds and bats, and service roads contribute to further fragmentation of habitats (Gibon et al., 2017; Hertwich et al., 2016). Such a resistance might prove a challenge to further decarbonization of the energy supply from wind power and local supply possibility for salmon aquaculture.

The life-cycle emissions for wind power ranges between 10 - 20 g CO_2 eq./ kWh and for PV between 20-75 g CO_2 eq./ kWh, and are substantially lower compared to fossil energy sources (Gibon et al., 2017). If the life-cycle emissions were used for the modelling of electricity emissions, the measures implemented would not be sufficient to meet the targets. Moreover, the batteries needed to address the intermittency of solar and wind power production are also not accounted for. The production tends to be energy-intensive and resource demanding, requiring materials such as lithium, zinc, nickel and cobalt (Hertwich et al., 2016). According to Hertwich et al. (2016), the life-cycle GHG emissions of the batteries are even higher than the renewable energies for which it is used as storage.

To summarize, current simulations and operational tests suggests that other low-carbon renewable energy solutions are considerably space demanding and not yet able to provide the necessary energy supply. The costs of renewable generation is also higher compared to alternatives for electrification or hybrid battery diesel system, but its partial implementation has greenhouse gas emission reduction benefits locally. However, the reduced emissions from the implementation of renewable energy has potential environmental effects which might affect the transition to a decarbonized energy.

4.5 Limitations of the Study

The major limitations of this study relate to the lack of data and uncertainty in the data used in the model. Moreover, the assumptions made for future production volume and technological development in the salmon farming industry as far as 2050 are based on the author's intuition working with the material and is difficult to support with credible sources because limited material is available. Sometimes, it has been challenging to separate between reasonable and reflective analysis, and wishful thinking for the development of the sector in the years to come. Some of the main limitations are discussed in further detail:

- For several of the production technologies there are considerable variations in the specific energy consumption. For instance, for salmon grow-out in land-based RAS an efficient production cycle will require an energy input of 24 kWh compared to 36 kWh in a less efficient cycle. For closed containment systems, the difference in energy consumption per cycles is even greater with a low gross energy consumption of 8,55 kWh ranging up to 56,09 kWh as illustrated in Table 3.5. The high uncertainty in energy consumption may stem from differences in design and operation patterns.
- The large range in energy consumption for closed containment systems may also stem from inaccuracies related to that values were derived from data/ studies with a different goal than this thesis. The studies by McGrath et al. (2015) and Ayer and Tyedmers (2009) are life-cycle assessments, and the lack of details on energy consumption and biomass growth was supplemented by the author's assumptions. Similarly, the specific energy consumption for offshore farming is derived by combining biomass growth trajectories of two production cycles and extrapolation of existing energy consumption data.
- For the novel production technologies and vessels, the small sample size of studies may result in energy consumption values that do not reflect the industry standard. When making assumptions based on these values for the whole industry, the results might be skewed.
- Data on energy consumption for the vessels is difficult to verify from multiple sources. Furthermore, the model does not take into account that the adoption rate of electric and hydrogen technology for the vessels might be different. One might expect the vessels tied to one specific locality such as the transport or work vessel to have a higher electrification rate due their size and shorter travelling distance compared to service vessels employed at multiple localities. Depending on the location of the farming localities, one might also expect adoption rates to vary, for instance vessels tied to remote offshore farming localities might take longer to transition from fossil fuels. These considerations are not accounted for in the model, partly because of the further complexity it adds to model, which seeks to address overall industry trends. Furthermore, because of lacking information on the specific operation and energy consumption patterns of the vessels.
- The production and energy scenarios show little regard for cost perspectives and land use. The sectoral energy consumption and emissions are calculated based on production volume with limited consideration of the implications for the necessary infrastructure to support the production volume. This is highly relevant for the realization of the production volume using the different production technologies.

4.6 Outlook and Further Work

The results indicate that the emission target for 2030 can be reached by partly transitioning to low-carbon energy carriers for the vessels and increasing the electrification share of open net pen and closed containment system production. Moreover, considerable efforts need to be made to achieve the 2050 target. Some suggestions for further research and measures supporting the strategy and transition towards a decarbonized energy supply for the salmon farming sector are described here:

- In order to further understand the potential of low carbon energy solutions in the salmon farming industry, the data on energy requirements of the new farming technologies needs to be reliable. Considerable improvements can also be made for existing technologies, the data on energy requirements for the different vessels is still limited. Existing studies refer to reports based on assumptions or single studies. The industry structure with sub-contractors and vessels servicing multiple locations provide a challenge for the data collection. Nevertheless, increasing the number of data samples is necessary to model the energy requirements and to make informed decisions.
- With new farming technologies and technological development there is considerable secrecy around production plans (Sundnes, 2020). As a consequence, it is challenging to estimate future production and energy consumption. Whilst understanding the need for salmon farming companies to protect their business proposition, the secrecy may provide a barrier to external research and analysis that may provide useful insights and context to the salmon farming industry and society.
- The potential implementation of new energy solutions such as solar and wind power need to be further tested and evaluated, and other energy sources such as hydrogen as well. Further examination and studies on hydrogen and how the infrastructure might be implemented and potential industry synergies would also be useful. The results indicate that with the growth aspirations for the industry, hydrogen needs to be included if the emission targets are to be fulfilled.
- With the adoption of new energy demanding farming technologies to reduce salmon lice and escapees, and increased decarbonization of the energy supply, there is potentially a trade-off between ecosystem and climate impacts. The new farming technologies are more energy intensive and further decarbonization of the energy supply is needed to reduce the sectoral emissions. However, the increased application of decarbonized electricity requires expansion in grid infrastructure and other low-carbon energy solutions are resource demanding. This thesis has a limited its scope to the direct energy emissions, and thus not accounted for these implications in the model. The potential trade-off between climate and environment ought to be further examined to fully understand the environmental impacts and costs of the changes in the Norwegian salmon farming industry moving forward.

5. Conclusion

To ensure an energy supply sufficiently decarbonized to meet the emission targets in the salmon farming industry, considerable energy efficiency measures and transition to low-carbon energy carriers need to be carried out. The thesis finds that with a 3% annual growth in the production volume and implementation of new salmon farming technologies to target salmon lice and escapees, the sectoral energy requirements will increase which also translates into increased GHG emissions. The new farming technologies considered in the thesis are: land-based RAS, offshore farming and closed containment systems, and they are more energy intensive than traditional open net pen production. Assuming that the specific energy consumption of the farming technologies and current distribution of energy carriers remains constant, the sectoral energy consumption will be 8.6×10^6 GJ in 2020, 1.63×10^7 GJ in 2030 and 4.17×10^7 GJ in 2050. The sectoral energy consumption will thereby increase almost fivefold from 2020 to 2050. Moreover, the energy consumption grows at a faster rate between 2030 and 2050 due to the increased implementation of novel farming technologies.

Between 2020 and 2050, the sectoral energy consumption translates into a 3,5 time increase in the greenhouse gas emissions. However, the emissions per unit of energy consumed decreases towards 2030 due to the increased production in land-based RAS powered by a decarbonized electricity supply. Towards 2050, the emissions per unit of energy consumed in the salmon farming sector stagnates due to the due to the increased implementation of farming technologies such as closed containment systems and offshore farming which due to their technical requirements and location are assumed to largely rely on fossil energy carriers. Even with the implementation of the efficiency and decarbonization measures in the electrification and efficiency scenario, the emissions are substantially higher than the 2030 emission target of 259 000 tons CO_2 emissions and the 80% reduction target in 2050 of 86 400 tons CO_2.

Towards 2030, measures targeting the electrification and hydrogen application for vessels is an efficient method to achieve the emission target. This is because open pen production is responsible for 85% of the production volume and the vessels are a considerable energy consumer in the production cycle and largely rely on fossil fuels. In the long-run towards 2050, it will be more challenging to achieve the 80-95% emission reduction target because of increased implementation of energy intensive technologies, and growing production volume. To achieve the 80% emission reduction target, the increased adoption of shore-side electricity, hydrogen and efficiency gains are required across the sector. With the increased reliance on electricity for production and vessel operations, a decarbonized electricity supply is necessary to meet the emission targets. Alternatives to shore-side electricity need to be developed to ensure a sufficient and decarbonized energy supply for offshore farms placed in remote locations, for production growth in open net pens and for closed containment systems with a high power demand in rural areas with limited grid capacity.

Moving ahead, the results indicate that hydrogen needs to be part of the low-carbon energy solution for the industry. Yet, the energy technology is still quite immature for the industry application and the infrastructure remains largely undeveloped. Moreover, with the increased connection to shore-side electricity, the capacity of the electricity grid will likely have to be expanded. Alternatively, local renewable energy technologies such as solar and wind power can provide additional power and reduce the carbon intensity of the electricity mix, but the application potential of this technology in the salmon farming industry is also still largely uncertain. Lastly, environmental implications beyond the greenhouse gas emissions associated with fossil fuel combustion and electricity ought to be paid attention to. Increased habitat degradation and resource depletion are potential consequences of the adoption of low-carbon energy solutions and expanding power grids for electrification. Similarly, land-based RAS production has many times the impacts on land and freshwater use and infrastructure requirements compared to open net pens.

Overall, moving from traditional open net pen production to novel farming technologies to avoid salmon lice challenges drives energy consumption. In turn, the efforts to decarbonize the energy supply in the sector to meet the targets of the Paris Agreement has negative ecosystem impacts. Thereby, Norwegian salmon aquaculture appears to be moving in a direction where the emission reduction objective potentially comes at a considerable cost to the environment.

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12_09.pdf.

A. Appendix

A.1 Estimated MAB Utilization Factor for Traditional Farming

To determine the production volume of traditional open net pens, existing data on farming licenses for grow-out production of Atlantic salmon, Rainbow trout and Trout in use and salmon sales in Norway was considered. The data on sales volume are from Statistics Norway (2020a), and the data on licenses in use is from Fiskeridirektoratet (2020c). Farmed salmon makes up 93-95% of the aquaculture sales (in tons) in Norway, and the licenses from Directorate of Fisheries are therefore assumed to be dedicated Atlantic salmon production only (Statistics Norway, 2020a).

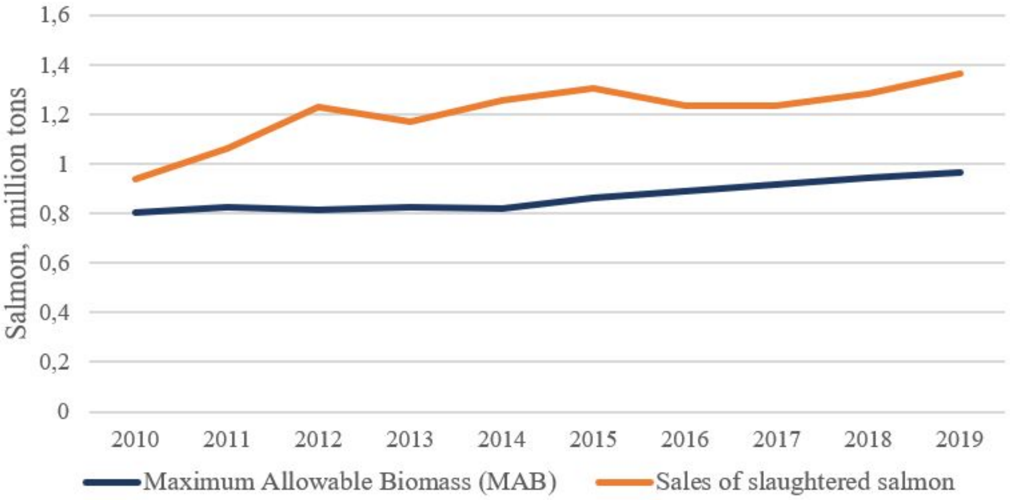


Figure A.1: Development of maximum allowable biomass for salmon grow-out licenses in use and sales of slaughtered salmon from 2010-2019.

On average, the MAB is approximately 70% of the annual salmon sales. This indicates that the utilization rate of the MAB is 1,43. Salmon of different sizes are kept in the pens at the same time, and transferred for slaughter at different times. It is assumed that the utilization rates will increase with the move towards production of post-smolt and as the industry overcomes issues such as lice.

The MAB utilization rate is in the model assumed to increase by 15% from the current level. For simplicity, the utilization rate is set to increase by an additional 0,5% every year, from 1,43 to 1,65.

A.2 Assumptions about Production Volume of Land-based RAS and Offshore Farming

Assumptions about the time lag between acquiring the farming licenses until production is realised is included in Table A.1. According to Øyehaug (2020), production of salmon in land-based RAS should be achievable in 5 years if the location for the facility has been determined. The assumptions are applied to the newer technologies to make production estimates towards 2030. The production shares of MAB aim to account for the need to test and gain operational experience.

Years after license	**Land-based RAS (Share of MAB)**	**Offshore (Share of MAB)**
3 years	-	20%
5 years	30%	50%
7 years	50%	70%
10 years	70%	100%
13 years	100%	-

Table A.1: Utilization of MAB (%) for land-based RAS and offshore farming assumed for estimating production volume towards 2030.

The following Table A.2 displays the assumed annual production volume from new licenses. It is partly derived based on information about current development licenses for new farming technologies from (Norwegian Directorate of Fisheries, 2020).

Time period	**Land-based RAS (New volume tons)**	**Offshore (New volume tons)**
2021-2024	30 000	7 500
2025-2029	50 000	10 000

Table A.2: New annual MAB (tons) for land-based RAS and offshore farming assumed for estimating production volume towards 2030.

A.3 Energy requirements of Salmon Production in Offshore Aquaculture

The daily energy consumption of a fish farm, Ocean Farm 1 by SalMar, has been derived based on the hourly power demand provied for 2019. A few outliers (around 10) were removed and replaced by the average energy consumption of the remaining days, this is particularly apparent from 10th to 15th of December in the following Figure A.2. The first production cycle in Ocean Farm 1 ended on the 20th of January in 2019 and a new cycle began the following autumn, 22nd of August.

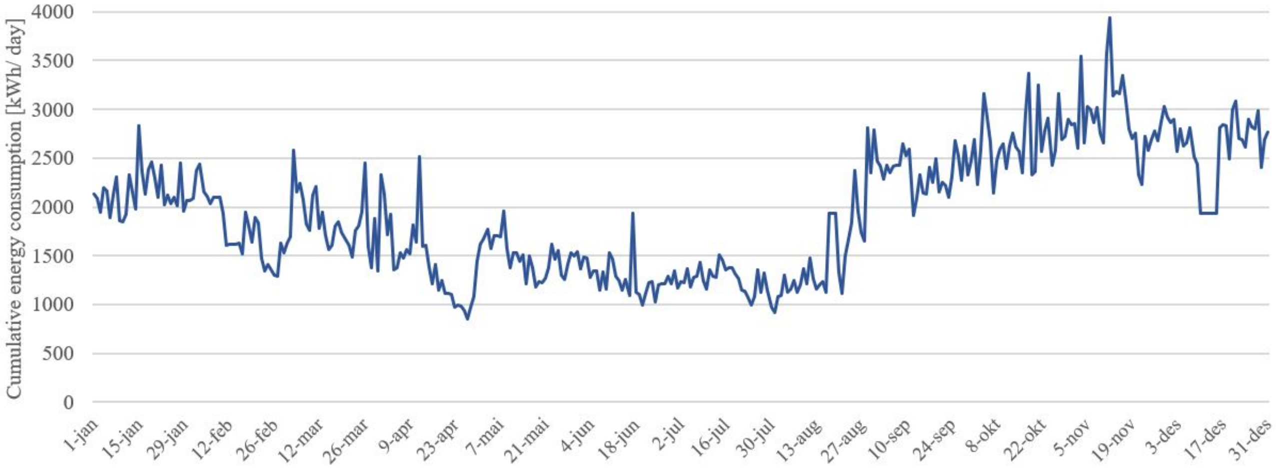


Figure A.2: Daily energy consumption of Ocean Farm 1 offshore fish farm in 2019.

In terms of biomass growth, the following two graphs in Figure A.3 represent changes in biomass over time in Ocean Farm 1. The left figure displays biomass growth in the first production cycle, and the right, the second cycle. The smolt transfer consisted of 1 038 439 individuals sized 233g and 1 156 240 fish sized 230g, respectively. Combining the information from these two figures, an approximation of the production cycle in the offshore farm can be derived.

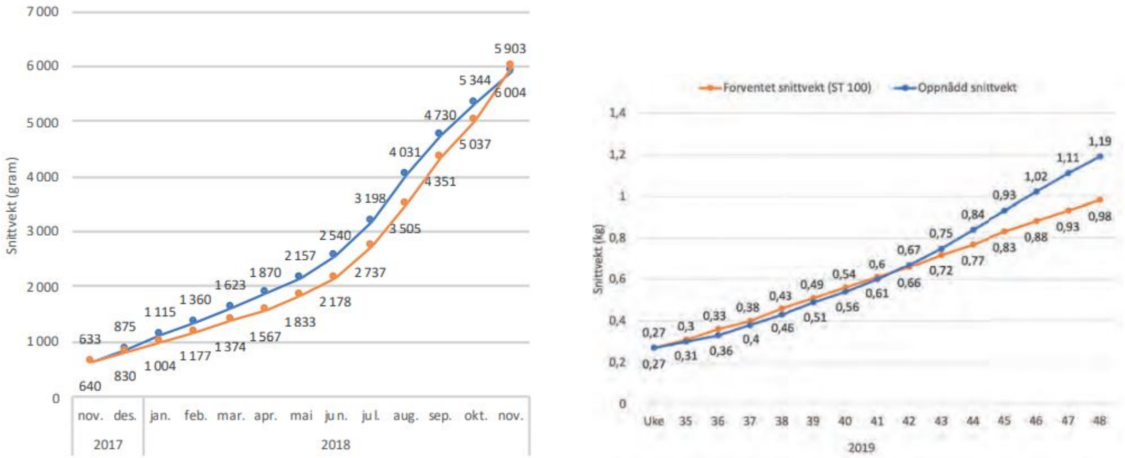


Figure A.3: Average weight of salmon in Ocean Farm 1 over time for the first production cycle (left) and the second production cycle (right), from SalMar (2019).

In Figure A.3, the blue line indicates the average weight of a salmon in Ocean Farm 1, and the orange line reflects the expected weight based on average fish growth within SalMar for the past 5 years (SalMar, 2019).

Estimating the specific energy consumption for salmon grow-out in offshore farms with a start weight of 1,5 kg corresponding to week 19 in the production cycle in the farm with an initial smolt size of 230 g. Assumptions in Table A.3 are based on information gathered from production cycle 1 and 2 in Ocean Farm 1 included in SalMar (2019) and data provided by SalMar.

Assumptions	**Value**	**Unit**
Number of smolt transferred	1 156 240	nr.
Total mortality	5	%
Start weight	1,435	kg
Final weight	4,106	kg
Monthly average energy consumption (Sept.- Dec.2019)	80 415	kWh

Table A.3: Assumptions and data for modelling specific energy consumption in offshore fish farms.

The specific energy consumption in kWh/kg for 1,5-4 kg salmon in offshore farms, excl. boats is derived:

Biomass accumulated/ fish	2,671 kg
Total biomass accumulated	2 933 901 kg
Cumulative energy consumption	482 493 kWh
Specific energy consumption	**0,16 kWh/kg**

Table A.4: Key parameters for estimating specific energy consumption for salmon grow-out offshore farms.

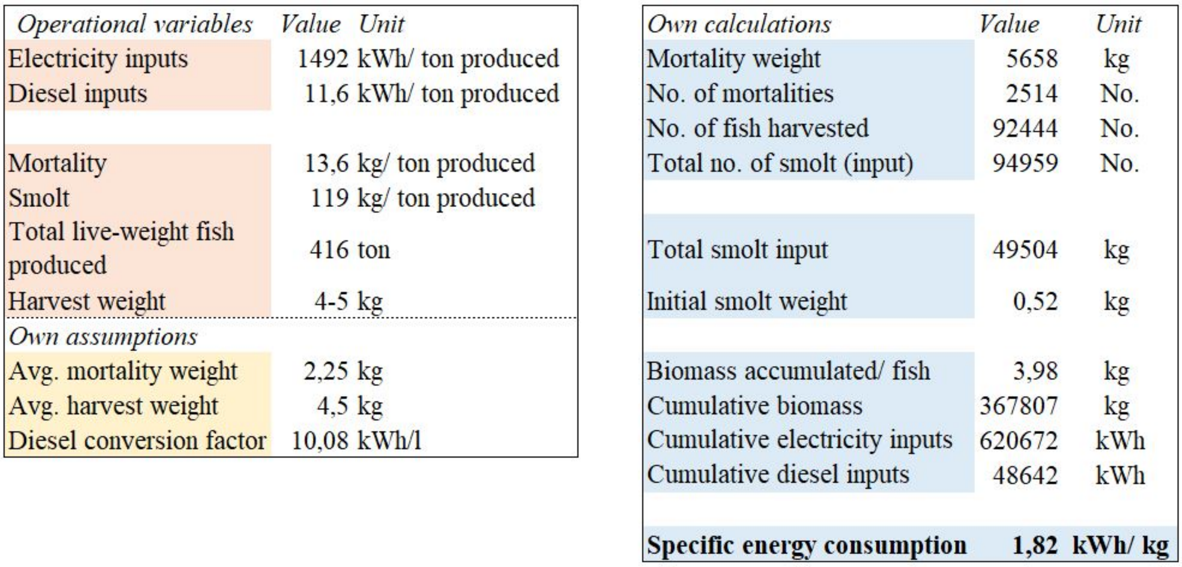
The specific energy consumption of *0,16 kWh/kg* based on the power demand data is here assumed to reflect the net energy consumption. Taking into account a generator efficiency of 35%, the energy consumption of a farm using a diesel generator would be *0,47 kWh/kg*.

These calculations of specific energy consumption are based on the author's own assumptions and have not been confirmed by SalMar.

A.4 Energy Requirements of Closed Containment Systems

Based on Ayer and Tyedmers (2009): A marine floating bag system consisting of a 6 impermeable heavy gauge plastic bags housed in a steel frame. The inputs of the energy carriers are for 1 ton live weight Atlantic Salmon produced in British Columbia, Canada. The energy is for the grow-out phase, and does not consider energy requirements for smolt production. Additionally, energy used in potential boat operations does not appear to be included.

The calculation of the specific energy consumption for the marine floating bag system is based on the operational variables from the life cycle inventory, Table 2 in Ayer and Tyedmers (2009), and is included in the following Table A.5:



Operational variables	*Value*	*Unit*
Electricity inputs	1492	kWh/ ton produced
Diesel inputs	11,6	kWh/ ton produced
Mortality	13,6	kg/ ton produced
Smolt	119	kg/ ton produced
Total live-weight fish produced	416	ton
Harvest weight	4-5	kg
Own assumptions		
Avg. mortality weight	2,25	kg
Avg. harvest weight	4,5	kg
Diesel conversion factor	10,08	kWh/l

Own calculations	*Value*	*Unit*
Mortality weight	5658	kg
No. of mortalities	2514	No.
No. of fish harvested	92444	No.
Total no. of smolt (input)	94959	No.
Total smolt input	49504	kg
Initial smolt weight	0,52	kg
Biomass accumulated/ fish	3,98	kg
Cumulative biomass	367807	kg
Cumulative electricity inputs	620672	kWh
Cumulative diesel inputs	48642	kWh
Specific energy consumption	**1,82**	**kWh/ kg**

Table A.5: Operational variables for salmon production and calculations of SEC for a marine floating bag system, from Ayer and Tyedmers (2009).

In Table A.5, the diesel use has been converted to kWh using a conversion factor of 10,08 kWh/ l from Miljødirektoratet (n.d.). The energy inputs in the operational phase are mostly based on electricity, and not fossil fuels. If we consider the challenge of connecting to shore-side electric power, the closed pens would be operated using fossil generators. The efficiency of a diesel generator can be assumed to be 35%.

Consequently, the potential cumulative energy requirements of a marine floating bag system using a diesel generator can be estimated: $620672\ kWh \times \frac{1}{0{,}35} = 1773348,6\ kWh$.
Including existing diesel requirements from the operational phase, the total energy requirements of a fossil system would be: $\frac{1821990{,}6\ kWh}{367806{,}9\ kg} = \mathbf{4{,}95}$ **kWh/kg**.

Based on McGrath et al. (2015): A solid wall aquaculture system (SWAS) where Chinook salmon is separated from the surrounding environment using a solid structure tank. The flow-through system includes pumps for pumping water, oxygen provision and a solution for partial waste capture.

From the supplemental information in Table S1 in McGrath et al. (2015), the following data can be used to determine specific energy consumption of the intended production cycle in salmon grow-out in the solid wall aquaculture system. As we can see in Table A.6, electricity is the main on-site power source.

System Characteristics/ Inputs	**Value**	**Unit**
Salmon harvested	42 752	No.
Total weight harvest	171 011	kg
Harvest weight per fish (derived)	$\frac{171011\ kg}{42752\ No.} = 4,00$	kg
Total on-site electricity use	80 415	kWh
Total on-site diesel use	1 595	l

Table A.6: System characteristics of Chinook salmon production in solid wall aquaculture system selected for determining specific energy consumption, from Table S1 in supplemental information in McGrath et al. (2015).

Determining the specific energy consumption kWh/kg for salmon grow-out (0,035 - 4 kg) in a solid wall aquaculture system, excl. boats - see Table A.7.

Biomass accumulated/ fish	3,965 kg
Total biomass accumulated	169 515 kg
Cumulative energy consumption (el + diesel)	808 649 kWh
Specific energy consumption	**4,77 kWh/kg**

Table A.7: Key parameters for estimating specific energy consumption for salmon grow-out in the SWAS, closed containment system.

Now considering the potential cumulative energy requirements of the solid wall aquaculture system using a diesel generator in place of shore-side electrical power. Following the same steps used to determine the energy requirements for a marine floating bag system with completely fossil on-site energy use:

Specific energy consumption of a fossil solid wall aquaculture system: **13,45 kWh/kg**

A.5 Production Zones

Figure A.4: Map of production zones for salmon aquaculture, with color shading according to environmental state from Fiskeridirektoratet (2020b).

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Science and Technology