Andrea Arntzen Nistad

Current and Future Energy Use for Atlantic Salmon Farming in Recirculating Aquaculture Systems in Norway

Master's thesis in Energy and Environmental Engineering
Supervisor: Johan Berg Pettersen
January 2020

Master's thesis

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Preface

This thesis was carried out during the autumn semester 2019 and concludes my Master of Science in Energy and Environmental Engineering at the Norwegian University of Science and Technology (NTNU). The thesis is a continuation of the project thesis work performed in autumn 2018.

The outcome of this thesis has been dependent upon data on energy use from Recirculating Aquaculture System (RAS) facilities. I would like to thank all the companies sharing data on energy use and the operation of their facility. Special thanks to Øyvind Haraldseid, Ivan Alstad and Robert Husby that took the time to invite me to their facilities. Moreover, I would like to thank Kari Attramadal, Øyvind Prestvik, Øyvind Hilmarsen, Kennet Glomseth, Tore Evjen and Asbjørn Husby crucial insight into biological and technical issues in RAS. Finally, I would like to thank my supervisor Johan Berg Pettersen for continuous guidance, valuable feedback, and motivation during the work with this thesis.

Trondheim, January 2020

Andrea A. Nistad

Andrea Arntzen Nistad

Abstract

In recent years, the land-based production phase is extended in the Norwegian salmon farming industry. This is a consequence of problems with sea lice and pathogens in conventional production in open-net pens, as well as a wish to optimise production. The land-based production now mainly takes place in Recirculating Aquaculture Systems (RAS), which allow for control of the rearing environment, low water demand and reduction in nutrient discharge. However, high energy use is identified as a major drawback. Few previous studies have focused on energy use and efficiency in RAS, which is of increasing importance for the Norwegian salmon farming industry. This study evaluates the current and future energy use for the production of Atlantic salmon, smolt and post-smolt in RAS facilities in Norway. The current energy use for smolt and post-smolt production is analysed based on data collected from Norwegian RAS facilities, while an energy model is developed to evaluate future energy use for large post-smolt production and salmon grow-out in RAS.

The data collected show that energy use is highly variable across RAS facilities. The on-site energy use for production of 1 kilo live-weight smolt ranges from 5.1 to 12.8 kWh, with a mean of 8.8 kWh. The current average energy use is about twice as high as previous estimates, as well as estimates by the proposed model. This study demonstrates that the implementation of available energy efficiency measures, can in average reduce energy use by 30%. Additionally, if biomass production is optimised, the energy use can be lowered to 4-5 kWh/kg, which is the level of previous estimates.

The simulated on-site energy demand for production of 1 kilo live-weight post-smolt of 1 kg is 3.4 to 5.4 kWh. Energy use for salmon grow-out to market-size in RAS is estimated to be between 6 and 10 kWh per kilo live-weight. The analysis of scenarios for future biomass production in RAS indicates a considerable total energy demand in future. These projections assume that the RAS facilities are energy efficiently operated and designed. However, the data on energy use in Norwegian RAS facilities show that this is currently not the case. Hence, an increased focus on energy efficiency is needed for RAS facilities in Norway to avoid a situation where high energy use, power grid capacity and associated costs become a barrier for future growth in land-based aquaculture.

Sammendrag

Den landbaserte produksjonsfasen er utvidet i den norske lakseoppdrettsnæringen de siste årene, hovedsakelig som en konsekvens av problemer med lus og sykdom i tradisjonell produksjon i merder. I tillegg, er ønsket om å optimalisere biomasseproduksjon og utnyttelsen av lisenser en viktig driver. Landbasert produksjon skjer ofte i Recirculating Aquaculture Systems (RAS), som gir mulighet for kontroll av oppdrettsmiljøet, lavere vannbehov og reduksjon i utslipp av næringssalter. Imidlertidig krever slike systemer et høyt energiforbruk. Få tidligere studier har fokusert på energibruk og energieffektivitet i RAS, noe som er av økende betydning for den norske lakseoppdrettsnæringen. Denne studien evaluerer energibehovet for produksjon av Atlantisk laks, smolt og post-smolt i RAS anlegg i Norge i dag og fremover. Basert på innsamlet data fra norske RAS anlegg er dagens energibehov kartlagt, mens energibehovet for fremtidig produksjon av post-smolt og laks i RAS er evaluert ved hjelp av en energimodell utviklet i denne studien.

Innsamlet data for energiforbruk viser at energibruken er høyst variabel i dagens RAS anlegg i Norge. Det direkte energibehovet for produksjon av 1 kilo smolt varierer fra 5.1 til 12.8 kWh, med en gjennomsnittsverdi på 8.8 kWh. Dagens energiforbruk er omtrentlig det dobbelte av tidligere estimater, samt estimater basert på energimodellen utviklet. Denne studien viser at energibruken kan reduseres med 30% hvis allerede tilgjenglige energieffektiviseringstiltak implementeres. Hvis biomasseproduksjonen i tillegg optimaliseres kan energibruken reduseres til 4-5 kWh/kg, som er på nivå med tidligere estimater.

Det simulerte energibehovet for produksjon av 1 kilo post-smolt med en vekt på 1 kg er 3.4 til 5.4 kWh, mens energibehovet for produksjon av 1 kilo slakteklar laks er estimert til 6 til 10 kWh. Analyser av ulike scenarier for fremtidig produksjon i RAS viser at det fremtidige totale energibehovet vil være betydelig. Det fremtidige energibehovet beregnet forutsetter at RAS anleggene er designet og drives optimalt med tanke på energieffektivitet. Basert på innsamlet data, kan det derimot konkluderes med at dette ikke er tilfelle i dag. Det er dermed behov for et økt fokus på energieffektivisering i RAS anlegg i Norge, slik at et høyt energibehov, begrenset kapasitet i kraftnettet og tilhørende kostnader ikke blir en barriere for fremtidig vekst i landbasert oppdrett.

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Abbreviations

AP	Acidification Potential
COP	Coefficient Of Performance
DM	Dry matter
DMx%	Dry matter concentration of x%
DO	Dissolved oxygen
EP	Europication Potential
FCR	Feed Conversion Rate
GHG	Greenhouse gas emissions
GWP	Global Warming Potential
HRT	Hydraulic retention time
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Lice Cycle Inventory
LHO	Low Head Oxygenation
MAB	Maximum Allowed Biomass
MBBR	Moving Bed Biofilm Reactor
SEC	Specific energy consumption
TAN	Total ammonium nitrogen
TSS	Total suspended solids
VFD	Variable Frequency Drive

Definitions

Post-smolt	Post-smolt refers to the first stage after the salmon have undergone smoltification. The size range of post-smolt is not clearly defined, but in this thesis post-smolt is refered to as salmon with a weight of about 200-250 g to 1.5 kg.
Salmon	By salmon it is referred to Atlantic salmon (*Salmo Salar*), which is the salmon produced in Norway. This thesis refers to salmon as the general species. Besides, it is referred to salmon, in contrast to smolt and post-smolt, when the weight is higher than 1.5 kg.
Smolt	Smolt refers to salmon juveniles that have undergone smoltification and have adapted to life in seawater. This thesis refers to smolt as salmon with a weight between 70-80 g and 200-250 g.

1 Introduction

1.1 Background and motivation

The aquaculture industry is today growing faster than any other food production sector globally (FAO, 2018; Jones et al., 2015; Troell et al., 2014). The growth is anticipated to continue as wild fish stocks reach or exceed their sustainable limits (Troell et al., 2014). In Norway, the aquaculture industry is the second largest exporting industry today and is foreseen to grow substantially also in future (Nærings og Fiskeridepartementet, 2015). To realise the anticipated growth in aquaculture production, an improvement in the sustainability of the sector is necessary (Jones et al., 2015; Nærings og Fiskeridepartementet, 2015). Today the main sustainability concerns include the production of feed ingredients, escapes, discharge of wastes and water pollution (Martins et al., 2010; Badiola et al., 2017; Ayer and Tyedmers, 2009).

These sustainability issues are also present in the Norwegian salmon farming industry. Besides, sea lice and pathogens are considerable challenges faced in today's traditional open net-pen production systems (Rosten et al., 2011; Taranger et al., 2015). This causes high economic costs for the producers, and the cost of preventing and controlling sea lice is estimated to account for 12% of the total production cost (Iversen et al., 2017). As a consequence of sea lice and diseases, many producers extend the land-based production phase to reduce the retention time in sea. Earlier, only salmon smolt were produced in land-based systems. Recently, however, the production of larger smolt (post-smolt) or market-sized salmon in land-based systems is challenging the traditional production in open net-pens (Dalsgaard et al., 2013). This can reduce mortality due to sea lice and diseases, and thereby yield economic and fish health benefits as losses and the number of lice treatment operations are reduced (Nofima, 2014; Hilmarsen et al., 2018; Dalsgaard et al., 2013). Moreover, it allows for more intensive use of the Maximum Allowed Biomass (MAB)[1] given in the concessions (Iversen et al., 2018).

Two main technologies are used in land-based aquaculture: flow-through systems (FTS) and recirculating aquaculture systems (RAS). The extension of the land-based production phase has resulted in substantial investments in larger system volumes. Consequently, freshwater resources have become a limiting factor (Kristensen et al., 2009; Dalsgaard et al., 2013), and RAS has turned into the preferred technology as 90-99% of the water can be reused (Hjeltnes et al., 2012; Hilmarsen et al., 2018). As a high degree of water is recycled, RAS are closed systems where continuous water treatment is necessary to create the desired rearing environment. The basic water treatment processes required are mechanical and biological filtration, CO_2 removal, pH control and oxygenation. Additionally, inlet water is disinfected and heated, and effluent water is filtered (Bregnballe, 2015; Espinal and Matulić, 2019).

Past environmental assessments of RAS technology have highlighted the low eutrophication potential and water demand, while stating that the energy use is high compared to other aquaculture production systems (Philis et al., 2019; Badiola et al., 2017, 2018; Ayer and Tyedmers, 2009; d'Orbcastel et al., 2009a,b; Samuel-Fitwi et al., 2013; Liu et al., 2016). As the Norwegian aquaculture industry is changing towards an extension of the land-based production phase, a shift in environmental impacts may occur. Present concerns in open net-pen systems such as sea lice, diseases, escapes and nutrient emissions may decrease, while energy use and related emissions increase.

The Norwegian salmon farming industry has set a goal of increasing production to five million tonnes in

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[1] The Maximum Allowed Biomass determines the maximum number of fish allowed in the open net-pen at any given time, and is defined in the license granted by the Ministry authority.

2050 (Sjømat Norge, 2016; Nærings og Fiskeridepartementet, 2015). At the same time, the industry has defined a set of environmental sustainability goals (Sjømat Norge, 2016). These goals include reducing sea lice, fish escapes, nutrient emissions and the use of fossil fuels, and increasing energy efficiency in the industry. An extension of the land-based production phase in RAS can both increase production and contribute to realising the environmental sustainability goals. However, to meet the goal of increasing energy efficiency in the industry, the energy use in the land-based production phase is of key importance. This is especially the case if large volumes of post-smolt or market-sized salmon are produced in RAS (Hilmarsen et al., 2018).

To assess the implications for energy use in the Norwegian salmon farming industry due to increased production in land-based systems, a better understanding of energy use in RAS is needed. The feasibility, in terms of energy and power demand, of large-scale production of smolt, post-smolt and salmon in RAS also has to be addressed. The currently available data on energy use in RAS are scarce and earlier reported values show a large variation (Nistad, 2018; Badiola et al., 2018). Moreover, previously published values for energy use include species as cod, turbot and arctic char, and to a lesser degree salmon. The energy demand is sensitive to the species reared and location, and few values are directly relevant for smolt and salmon production in Norway. Therefore, the main aim of this thesis is to evaluate the current and future energy use for salmon, smolt and post-smolt production in RAS facilities in Norway.

1.2 Objectives and scope of study

This thesis aims at providing a better understanding of the current energy use in commercial RAS facilities in Norway. In light of potential changes in production strategies, it is also highly interesting to assess energy use if post-smolt production or salmon grow-out takes place in RAS. The following research questions are defined:

1. What is the current energy use in RAS producing smolt and post-smolt in Norway?
   - **a.** Which are the influential parameters and drivers for energy use?
   - **b.** What is the current energy efficiency potential in the industry?
2. What is the energy demand for the production of large post-smolt and market-sized salmon in RAS?
3. What is the total energy demand if production of large post-smolt and market-sized salmon takes place in RAS in Norway, and what are the associated GHG emissions and costs?

The first objective addresses the need to establish a solid empirical basis for current energy use in RAS in Norway, as only estimates are currently available. By collecting data from commercial RAS, producing smolt and post-smolt in Norway, a systematic review of energy use is done. Moreover, drivers and important processes are identified based on the data, which is essential to address energy efficiency in RAS. A few studies have assessed general energy efficiency measures in RAS (d'Orbcastel et al., 2009a; Badiola et al., 2018; Rosenberg et al., 2007), but too which degree measures are already implemented and the actual savings potential are unknown. Thus, one goal of this study is to quantify the energy efficiency potential in Norwegian RAS facilities.

The second objective is to estimate the energy demand for production of large post-smolt and salmon grow-out in RAS. This objective was chosen in light of the recent increased interest for land-based production of salmon in Norway. As RAS are energy-intensive systems, it is essential to quantify the energy required for production of larger fish. As only one company produces market-sized salmon in RAS in Norway yet, the energy demand is quantified using a model for energy use instead of empirical data.

Finally, the third objective is to determine the total energy demand, as well as associated GHG emissions and electricity costs, if post-smolt production or salmon grow-out takes place in RAS. This objective addresses the viability of future production in RAS in Norway, in terms of energy, which is an important question from a policy perspective.

This study will be limited to evaluating energy use in RAS in the Norwegian salmon farming industry. This scope of study was chosen to allow for collection of empirical data from operating RAS facilities. The collection of data from facilities rearing the same species in the same location allow for a comparison of energy use across facilities. Moreover, increased understanding of energy use in Norwegian RAS facilities is particularly relevant due to the recent changes in production strategies.

1.3 Structure of work

An overview of the workflow is given in Figure 1. This thesis is a continuation of the project thesis work, which aimed at identifying the main drivers for energy use in RAS. In the project thesis, an energy model for post-smolt production in RAS was developed based on a review of literature and design parameters. The left box indicates the work performed in the project thesis, which is now used as a starting point for answering the research questions stated. The main workflow is indicated in the middle, while intermediate steps and output are shown to the right. Step 1, 2 and 3 are performed to answer the first objective. This is based on an empirical approach, in order to determine the current energy use and energy efficiency potential in operating RAS facilities in Norway. Step 4 is the validation of the energy model developed in the project thesis, which is necessary to perform step 5 and 6 to answer the second and third research question respectively.

Step 1 and 3 have been highly dependent upon data and information from operating RAS facilities and various industry actors. A list of people that supplied information is included in Appendix A.

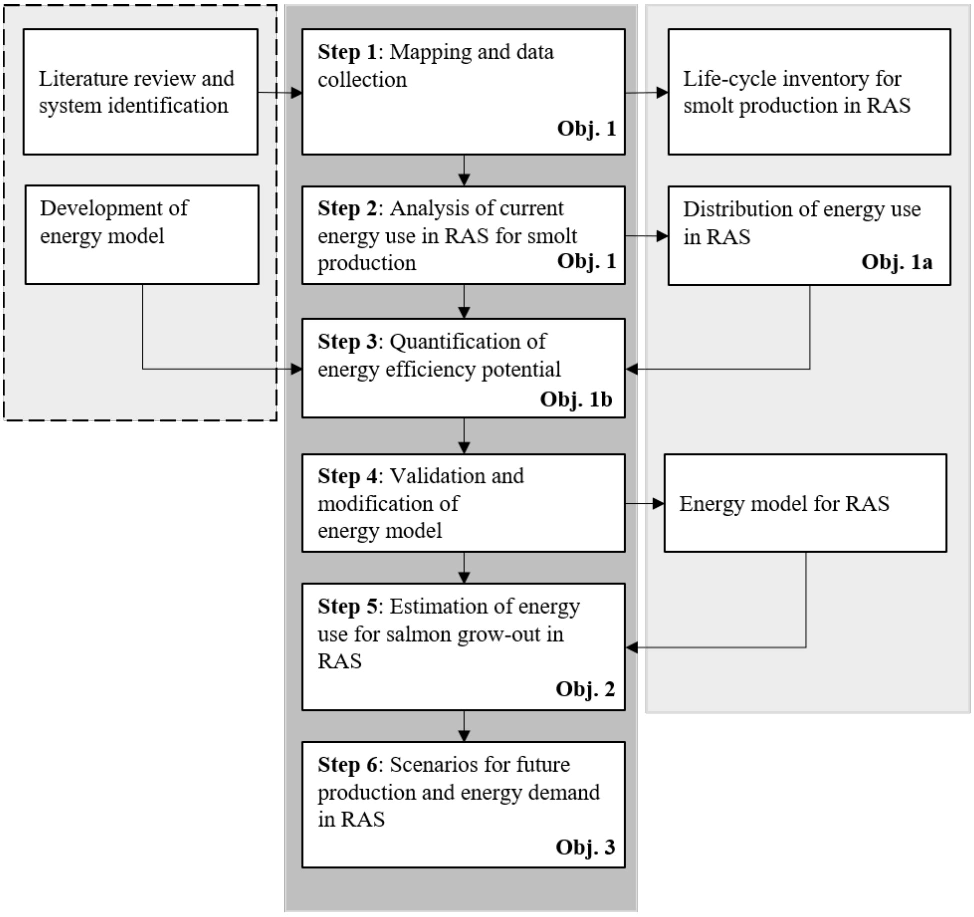

Figure 1: Workflow of study.

1.4 Outline

This thesis report is structured as follows: chapter two presents the role of RAS in current and future production strategies in Norwegian aquaculture, as well as existing knowledge on environmental impacts and energy use of RAS. Measures for energy efficiency in RAS are also presented. Chapter three presents an overview of the materials and methods used to assess the current and future energy use in RAS. The energy model developed in the project thesis is also shortly described. Chapter four presents and discusses the results. Chapter five summarizes the findings and concludes.

2 Literature and theory

2.1 Production strategies and the role of RAS technology

Currently, the salmon production value chain can be split into three stages: production in land-based systems, production in open net-pens in sea, and sales and distribution. In total, the production of salmon takes approximately three years. During the first 10 to 16 months the production takes place in a land-based freshwater system using either recirculation or flow-through technology. The production cycle starts with the fertilization of eggs, which develop into alevins and start feeding as fry. When reaching a weight of 60 to 80 g, the juveniles undergo smoltification, which is a series of physiological changes where they adapt from a life in freshwater to life in seawater (Solomon et al., 2013). Traditionally, the smolt is transferred to open net-pens in sea at this stage, with an average weight of about 70-80 g. The smolt is traditionally placed in sea twice a year, during autumn and spring (Haaland et al., 2017). The seawater production cycle lasts 14-24 months until the salmon has reached a final weight of 4 to 5 kg (Marine Harvest Group, 2018). Up until now, this has been the dominating production strategy in the industry, but recently alternative production strategies have been challenging the status quo, as seen in Figure 2.

The land-based production phase is extended in the Norwegian salmon industry in the last years. This is mainly driven by the wish to reduce retention time in sea and optimise the use of localities [1] (Iversen et al., 2018; Hilmarsen et al., 2018). In Western Norway, fish health problems and costs related to sea lice, pancreas disease (PD) and amoebic gill disease (AGD) are motivating the extension of the land-based production phase (Olsen, 2016). In Northern Norway, the longer land-based production phase is strongly driven by the possibility to keep a stable, optimal rearing temperature, which reduces the production time in sea and increases productivity (Olsen, 2016).

After the Norwegian Ministry of Fisheries opened for production of fish up to 1 kg in land-based systems in 2012, several producers have increased the smolt size considerably. The average smolt weight has increased to about 135 g (Iversen et al., 2018). However, several companies also produce larger fish with a weight of 0.5 to 1 kg, so-called post-smolt (Iversen et al., 2018). The production of larger smolt and the increase in biomass production volumes have resulted in increased investments in large RAS facilities, as freshwater resources have become a major restriction (Dalsgaard et al., 2013; Kristensen et al., 2009; Terjesen Fyhn, 2017). Many traditional flow-through hatcheries are converted to RAS, and most new constructions are built as RAS (Dalsgaard et al., 2013; Terjesen Fyhn, 2017). This is reflected in the increasing investments in smolt production facilities, as seen in Figure 3. In 2018, 375 million smolt were placed in sea (Fiskeridirektoratet, 2018), and approximately 50% of smolt biomass was produced in RAS (Nystøyl, 2019). This share is anticipated to increase to 60% in 2020 (PWC, 2017).

In future, production of post-smolt of even 1.5 kg in RAS is foreseen as an economically viable production strategy, which can shorten the seawater production phase to 6-10 months (Iversen et al., 2018). Another alternative is to produce smolt in land-based systems, followed by post-smolt production in closed sea-based systems (Iversen et al., 2013; Haaland et al., 2017). Hence, the division between smolt and on growing in sea is likely to diminish in future and be replaced by phases within open and closed systems (Terjesen Fyhn, 2017).

As seen in the lower panel in Figure 2, a last alternative production strategy is to move the whole production cycle on land. The Norwegian Ministry of Fisheries allowed for production of salmon in land-based

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[1] Production in RAS allow for transfer of smolt of varying size to sea throughout the year, which makes it possible to produce closer to the MAB limit (Iversen et al., 2013).

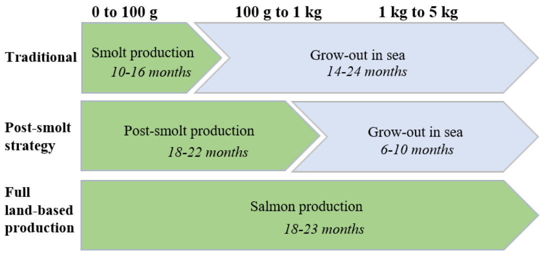

Figure 2: Potential production strategies in the Norwegian salmon farming industry. Green indicates land-based production and blue production in sea. Figure adapted from NordicAquafarms (2019) and tentative growth rates based on (Bjørndal and Tusvik, 2017; Haaland et al., 2017; Marine Harvest Group, 2018; Ø Haraldseid 2019, pers.comm.)

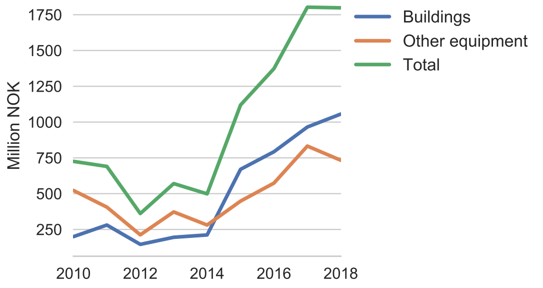

Figure 3: Recent investments in smolt production facilities. Data from Fiskeridirektoratet (2018).

systems in 2016 (Fiskeridirektoratet, 2016). This resulted in the initiation of several projects for land-based production, most of them using recirculating technology. However, only Fredrikstad Seafood has finalised the construction and started production (Kyst.no, 2019; Hilmarsen et al., 2018).

2.2 RAS technology

Recirculation systems are designed to reduce water consumption and waste production compared to flow-through systems (Badiola et al., 2017). This is done by reusing 95 to 99% of the water (Hilmarsen et al., 2018). Thus, RAS can be described as a closed system where continuous water treatment is needed to create the desired rearing environment. The main advantage is the possibility to create the desired environment for the species reared, without relying on environmental parameters (Ebeling and Timmons, 2012).

A RAS facility consists of different departments with a number of tanks connected to a water treatment system. Water treatment processes in most Norwegian RAS consist of a drum filter for mechanical filtration, a moving- or fixed bed biofilter, a degasser for CO_2 removal and oxygenation cones (Bregnballe, 2015; Hjeltnes et al., 2012). In addition, lime slurry or liquid sodium hydroxide is added for pH control (Hjeltnes et al., 2012). Recirculating systems that have a very low degree of water exchange additionally have phosphorus removal and denitrification installed (Bregnballe, 2015). The water from the fish tanks is continuously circulated in the water treatment loop by the use of pumps, but a minor share of water is exchanged with new water. Moreover, the inlet water is usually heated or cooled by heat pumps and a series of heat exchangers, and disinfected by UV (Bregnballe, 2015). The effluent water is filtered and the sludge is thereafter dewatered. While some RAS facilities transport the sludge at a dry matter (DM) content of less or equal to 25-30%, others thermally treat the sludge to increase the dry matter content to about 90% before transportation (Ø Prestvik 2019, pers. comm.). A simplified schematic of the system is shown in Figure 4. The effect of each treatment step is described in Table 2, in Section 2.4.3.

In the departments before smoltification, tanks are filled with freshwater. In the post-smolt departments, the salinity is increased and a mix of freshwater and seawater is used. Most RAS facilities in Norway are therefore located adjacent to a freshwater source and a fjord. In theory, RAS facilities can however be located wherever suitable water sources are available (Hilmarsen et al., 2018). The proximity to a fjord is in Norway today a natural location, as the smolt are transferred by a well-boat to the seawater site when they have reached the desired weight.

The volume of the system and the number of departments depend on the number of fish produced and their final weight. A RAS facility typically consists of a hatchery and a start-feeding department, as well as several grow-out departments. The number of grow-out departments depends on the number of gradings[2] and the final weight. The water treatment is always separate for each department, and in some cases even each tank. On the other hand, the heat pumps, heat exchangers and treatment of inlet and effluent water are often common for all departments.

In addition to the fish tanks and water treatment system, a RAS facility consists of office buildings and several other supporting functions such as oxygen production, dead fish handling and vaccination departments.

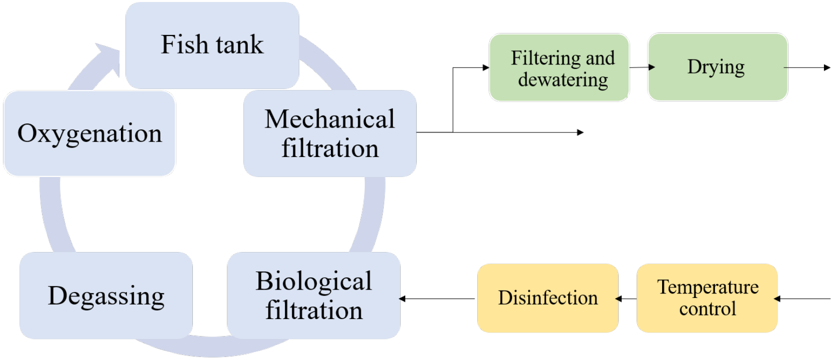

Figure 4: Overview of essential water treatment processes in a RAS with biological filtration. Water treatment loop in blue, sludge treatment in green and treatment of intake water in yellow. Figure adapted from Eide (2017).

2.3 Environmental impacts of RAS and other aquaculture technologies

Recent changes in production strategies have resulted in remarkable investments in recirculation technology and the importance of RAS in the industry is becoming larger. The following section presents the environmental impacts of recirculation technology in comparison to other aquaculture production technologies. Moreover, the potential shifts in environmental impacts that occur when production is moved from sea to land are presented. To assess the environmental impacts of aquaculture production systems, Life Cycle Assessment (LCA) is often applied (Bohnes and Laurent, 2019). LCA is a standardized method for quantitative assessment of environmental impacts over the whole life cycle of a product and is useful for identifying environmental trade-offs.

Philis et al. (2019) present a review of 24 LCA studies of salmonids production in relation to four technology clusters: open land-based (FTS), open sea-based, closed sea-based and closed land-based (RAS). They statistically compare cradle-to-gate impacts of 1 tonne of live-weight salmonids across the impact categories for global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and cumulative energy demand (CED). The study shows that RAS has the highest GWP, AP and CED impacts of the technologies, while EP impacts are the lowest. In the Norwegian context, salmon production in RAS is estimated to have a 28% higher GWP impact than salmon produced in open net-pens , but the conclusion is very sensitive to the feed conversion ratio (FCR) [3] (Hilmarsen et al., 2018).

The low EP impact is a result of the treatment and collection of wastewater which avoids releases of nutrient nitrogen and phosphorus (Samuel-Fitwi et al., 2013; Badiola et al., 2017). The collection of waste streams also allows for phosphorus- and energy recovery. Across all studies reviewed by Philis et al. (2019), RAS has a 65% lower EP impact than FTS. High GWP, AP and CED impacts are a consequence of the high energy demand for water treatment in RAS (Badiola et al., 2018; Samuel-Fitwi et al., 2013; Ayer and Tyedmers, 2009; Philis et al., 2019). The average cumulative energy demand in LCA studies of RAS, FTS and open net-pen systems is 133 GJ, 76 GJ and 38 GJ respectively per tonne live-weight

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[2] Grading is a common management strategy where the fish is grouped by weight and moved from one department to another. This is done to increase growth rates of smaller fish (Gunnes, 1976).

[3] FCR: unit of feed requirement per weight gain.

salmon (Philis et al., 2019). d'Orbcastel et al. (2009a) allocate 67% of the cumulative energy demand to the on-site energy consumed in a RAS for trout farming, while Song et al. (2019) allocate 43% to the direct energy consumed for production of salmon in a RAS in China.

The environmental impacts caused by intensive energy use are sensitive to the production location and the electricity mix considered (Badiola et al., 2017; Ayer and Tyedmers, 2009; Aubin et al., 2006; Liu et al., 2016; Samuel-Fitwi et al., 2013). In a study by Liu et al. (2016), on-site energy use was the main contributor to GHG emissions for salmon produced in RAS when electricity was supplied by the average US electricity mix. However, feed became the most important contributor to GHG emissions if the electricity mix consists of a high share of hydropower. Hilmarsen et al. (2018) found feed most important for GHG emissions in production of salmon in RAS in Norway, as the share of hydropower in the electricity mix is close to 100%.

Several environmental impacts of the aquaculture industry are not captured by LCA and certain benefits of closed systems are not assessed in LCA. The reduced risk of escapes and shorter retention time in sea, which reduce sea lice impacts, are important benefits of RAS not captured by LCA. Moreover, Aubin et al. (2006) argues that biodiversity depletion is necessary to include in LCA of aquaculture production technologies, while Philis et al. (2019) stress that disease and parasite treatment processes in open net-pen systems, which are excluded in previous LCAs, would likely increase the total impact of production in sea.

2.4 Energy use

2.4.1 On-site energy demand

Despite the high energy use in RAS compared to other aquaculture production technologies, only a few earlier studies have focused on energy use and efficiency in RAS. The published data on energy use in RAS show large variability and a review article by Badiola et al. (2018) finds that energy use ranges from 2.9 to 81.5 kWh per kg fish produced. The broad range is a result of different species reared, technical design, grow-out size, stocking density, location and recirculation degree (Badiola et al., 2018). The importance of location was demonstrated in a study considering salmon smolt production with the same FCR in Norway and Canada, where the energy use were 4.1 and 20 kWh/kg fish respectively (Bergheim and Nilsen, 2015). Finding a reference value for energy use in RAS is also difficult because of the rather poor documentation of underlying assumptions (feed load, smolt size etc.) and systems in many cases (Nistad, 2018; Badiola et al., 2017). Moreover, relatively few values for energy use are published for each species and studies operate with different system boundaries, which means that few systems are directly comparable.

Only a few studies are relevant for determining the energy demand of smolt and post-smolt production in RAS in Norway today (Nistad, 2018). Hilmarsen et al. (2018) report a total electricity use of 3-5 kWh per kg post-smolt with an average weight of 0.5 kg. This estimate has been determined by communication with industry actors (Ø Hilmarsen 2019, pers.comm.). Iversen et al. (2018) report an energy cost in smolt production of 0.4 NOK, 0.9 NOK and 2 NOK for smolt of 100, 200 and 500 g. Assuming an electricity price of 1 NOK/kWh, this results in an energy use of 4, 3.6 and 4 kWh per kg smolt. By personal communication with a RAS supplier, an estimated energy use of 5 kWh per kg post-smolt with a final weight of 500 g is obtained (Billund Aquaculture 2019, pers.comm.). On the contrary, studies of salmon smolt production from USA report a considerably higher energy demand of 16-26 kWh per kg smolt (Summerfelt et al., 2004; Colt et al., 2008).

For salmon grow-out in RAS, Hilmarsen et al. (2018) indicate an energy demand of 6-9 kWh per kg market-sized salmon, but the range is uncertain and is not based on data from operational RAS (Ø Hilmarsen 2019, pers.comm.). Song et al. (2019) performed an LCA of a RAS producing salmon in China and found that the on-site electricity use was 8.4 kWh per kg salmon. Liu et al. (2016) estimated an energy use of 5.46 kWh per kg market-sized salmon produced in a conceptual RAS in USA. The disparity of on-site energy demand can most likely be explained by the considerably higher stocking density in the system considered by Liu et al. (2016) (80 kg/m^3 versus 24 kg/m^3). Atlantic Sapphire, that have RAS facilities in operation and under construction, report an energy consumption of 6 kWh and 8 kWh per kg market-sized salmon in their facilities in Denmark and USA (Navarro, 2016).

Table 1: Reference values for energy use for production of smolt, post-smolt and market-sized salmon in RAS.

	Energy use kWh	**Stocking density** kg/m^3	**Location**	**Reference**
Smolt and post-smolt	3-5	65	Norway	Hilmarsen et al. (2018)
	3.6-4	-	Norway	Iversen et al. (2018)
	4.1	-	Norway	Bergheim and Nilsen (2015)
	5	-	Norway	(Billund Aquaculture 2019, pers.comm.)
Market-sized salmon	6-9	65	Norway	Hilmarsen et al. (2018)
	8.4	24	China	Song et al. (2019)
	5.4	80	USA	Liu et al. (2016)
	8	-	USA	Atlantic Shappire, Navarro (2016)
	6	-	Denmark	Langsand Laks, Navarro (2016)

2.4.2 Main energy consuming processes

A few past studies have performed energy audits of RAS facilities to determine the most energy-intensive processes. An energy audit is a systematic review of the current energy flows of a company or production plant. Colt et al. (2008) mapped the direct, indirect and transportation energy demand of a FTS and RAS for salmon smolt production. The distribution of direct energy use was broken down on water supply pumps, internal hatchery use and water treatment, as seen in Figure 5. Similarly, d'Orbcastel et al. (2009a) report direct and total energy demand and the distribution across different units. In total, water treatment and oxygenation account for more than 90% of the on-site energy use. d'Orbcastel et al. (2009b) also report energy use for a pilot-scale recirculating system in Denmark, where 67% of the energy consumed was allocated to the water treatment processes.

Badiola et al. (2017), integrated an energy audit with a LCA of cod production in Spain. The energy audit identified the heat pump as the main energy consuming unit, as shown in Figure 6. When cooling is excluded, the pumps are the main energy consuming units, representing 42% of the total. Ioakeimidis et al. (2013) proposed a framework for energy audits with focus on the integration of renewable energy and apply this to an aquaculture unit in Greece. They identified the boiler and pumps as the units with the highest energy consumption. Similarly, the pumps were the main energy consuming units in a RAS facility for salmon grow-out in China (Song et al., 2019). UV and biofilter blowers were other major energy consuming units. Finally, Summerfelt et al. (2004) and Summerfelt et al. (2009a) also identified the recirculation pumps as the main contributors to energy use in two partial recirculating systems in USA for production of salmon smolt and rainbow trout. The pumps consumed 80-90% of the on-site electricity considered.

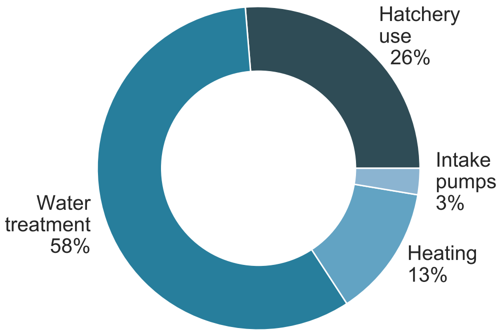

Figure 5: Distribution of energy use from Colt et al. (2008) for a salmon smolt facility in USA. Hatchery use includes, among other processes, lightning, heating and ventilation.

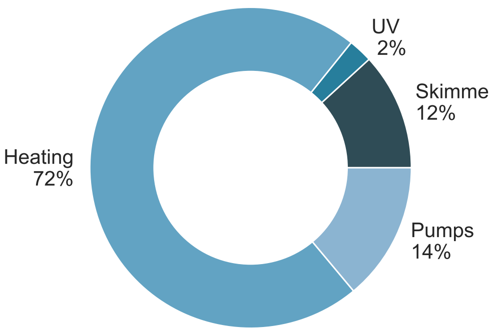

Figure 6: Distribution of energy use from Badiola et al. (2017) for a RAS facility for cod production in Spain.

The currently available distributions for energy use in RAS are highly variable. Energy use for pumping is in most studies identified as the main energy consuming process, but other important processes vary depending on the location and species reared. Understanding what the main processes for energy use in RAS are, is essential for improving energy efficiency. Hence, this study aims to identify the distribution of energy use in RAS in Norway. This was done by a theoretical approach in the project thesis, and will now be done based on empirical data from operating RAS facilities.

2.4.3 Project thesis

The project thesis leading up to this work studied the technical equipment in RAS and the drivers for energy use. An energy model was developed based on the configuration and operation of RAS for smolt and post-smolt production in Norway. A case for post-smolt production was also created to assess the cumulative energy demand and the distribution of energy use. The main findings from the project thesis are described in this section, while the full thesis can be found by the URL link in the list of references.

Based on a literature review and information from the industry the energy consuming units in RAS were identified. Energy is required for the water treatment processes, feeding and lightning in the fish tanks, heating and ventilation of buildings, and various other supporting functions such as dead fish handling and vaccination. The energy carrier used is mainly electricity, but diesel, oil or gas is in some cases used for water heating. Table 2 summarizes the equipment installed and their functioning.

The main drivers for energy use were also identified. The dimensions of the systems were found to be an important determinant of energy consumption in RAS. Specifically, the total dynamic head[4] and the water treatment flow rate were identified as important drivers for energy use. The water treatment flow rate is again determined by the system design and feed load. Furthermore, the recirculation degree and the configuration of the heating system were other important drivers. A summary of the main drivers for each process is presented in Table 2.

Based on the case study, which considered the growth of smolt from 150 g to 500 g, an energy demand of 2.6 kWh per kg fish was estimated. The recirculation pump was identified as the most energy consuming unit, accounting for 23% of total energy use. The heat pump and the heating and ventilation of buildings were other important processes, each contributing 15% to total energy use. Moreover, the degassing unit

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[4] The pressure the pumps need to overcome

and oxygenation unit contributed 13% and 10% to total energy consumption. However, the results were subject to uncertainty and were only validated against previous literature. Thus, a validation of the model against data from RAS in operation is vital, and will be performed in this study.

2.4.4 Energy efficiency measures

There is a lack of studies considering the energy efficiency potential in RAS. Some studies have identified relevant measures for energy efficiency (Rosenberg et al., 2007; d'Orbcastel et al., 2009a; Badiola et al., 2018), but to which degree these measures are already implemented in the Norwegian context is unknown (Nistad, 2018). An aim of this thesis is to identify relevant energy efficiency measures and assess the energy efficiency gap. In general, a number of measures can be taken to improve energy efficiency in industry. Tanaka (2011) and Bunse et al. (2011) summarize some of the options and highlight: upgrading processes to new and more efficient technology and streamlining processes, improvement of process control, re-using and recycling of products and materials, energy recovery and increasing productivity. Energy efficiency measures specific for RAS are presented below.

Energy management

Energy management is identified as an important aspect to improve energy efficiency in RAS (Badiola et al., 2012; Espinal and Matulić, 2019). Badiola et al. (2012) argue that a better understanding of key factors for energy use, water quality and fish requirements is needed instead of technical improvements. The process of energy management in industry includes the identification of energy consuming units and factors influencing energy demand, energy auditing and definition of energy indicators (Schulze et al., 2016; Bunse et al., 2011; Badiola et al., 2017; Ke et al., 2013). Furthermore, energy management includes the development of energy-related goals and increased competence (International Organization for Standardization, 2018). The introduction of energy auditing will not alter the production and operation, and can often be integrated into the existing monitoring and control system (Badiola et al., 2017). The introduction of energy management is estimated to reduce total energy use by 2-10% (Rosenberg et al., 2007).

Pumps

Centrifugal pumps are typically used to recirculate water in RAS. Two fundamental energy efficiency measures for pumps are highly relevant for RAS.

Firstly, the reduction of operating pressures of the pumps, and thereby the water treatment flow rate, will decrease energy consumption. This is easily achieved when pumps are equipped with variable frequency drives (VFD), which allow for adjustment of the motor speed in relation to the load requirement. The potential reduction in energy use is constrained by the water quality and flow velocity requirements, as sufficient flow velocity is important for fish trimming and settling of faeces and feed spills (Nistad, 2018). Based on insight into energy management practices reported to Enova by RAS facilities, a 10% reduction in pump pressure seems feasible (Enova, 2019a). This reduces water treatment flow rate by 5%, and results in a 15% reduction in power consumption for the pump. If the pressure is reduced by 5% instead, water treatment flow rate decreases by 2.5% and power consumption by 7.5% (see Appendix B.0.1 for calculations).

Secondly, the correct dimensioning of pumps and piping system is essential for energy efficient pumping (Arun Shankar et al., 2016; A Husby 2019, pers.comm.). In RAS, pumps are often under-dimensioned by consultants and suppliers to meet the requirement of low capital investments costs (Badiola et al., 2012; A Husby 2019, pers.comm.). An under-dimensioned pump will be able to deliver the required flow rate and pressure, but will work far from its best efficiency point (BEP) and thereby increase energy consumption. Correct dimensioning of pumps may result in 10 to 40% lower energy use for pumping (Rosenberg et al., 2007; Arun Shankar et al., 2016).

Table 2: Overview of main water treatment processes and drivers for energy use.

Process	Effect	Installed units	Main drivers for energy demand
Mechanical filtration *Drum filter*	Removal of suspended solids (TSS) to avoid gills damage, pathogens, degraded water quality and mechanical plugging [a].	Pumps	Water flow rate TSS concentration and distribution
Lightning	Important role in synchronizing smoltification, controlling feeding regimes and enhance growth rates [b]	LED or metal halogen lights	Tank dimensions Lamp type
Biological filtration *MBBR* *Fixed bed biofilter*	Converting ammonia caused by fish metabolism, urine, solid waste and excess feed to nitrate. Malfunctioning may reduce swimming and growth performance and lead to mortality[c]	Air blower Pump	Biofilter volume Flux through biofilter Head loss/bed height [d]
Degassing *Stripping towers*	Removal of CO_2 caused by fish metabolism, which can cause reduced growth and mortality [e]	Vaccum pump	Water flow rate CO_2 concentration Gas-to-liquid ratio
Oxygenation *Oxygenation cones* *LHO* *Deep-shaft*	Oxygenation increases the dissolved oxygen level. The content of dissolved oxygen is the first limiting factor in RAS and low levels can induce respiratory distress, lead to loss of appetite, growth and mortality[f].	Pump	Water flow rate O_2 consumption
Recirculation pump *Centrifugal pumps*	Move water in recirculation loop and compensate for head loss in other water treatment units	Pump	Water flow rate Lifting height and friction losses Efficiency
UV disinfection	Avoid biological risk by killing or inactivating microorganisms in intake water	High or medium pressure UV lamps	Water flow rate UV dose Water transmittance
Temperature control	Obtain a stable, optimal rearing temperature in the rearing tanks	Heat pumps Heat exchangers Boiler	Water source temperature Internal heat gain Efficiency
Sludge treatment	Filter effluent water and thicken sludge to a higher dry matter (DM) content to satisfy primary treatment criteria and reduce transport costs	Belt filter/Screw press /Sedimentation tank Belt dryer/Rotary dryer [g]	Feed load Dry matter content requirement

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[a] Ebeling and Vinci (2006)
[b] Kråkenes et al. (1991)
[c] Hjeltnes et al. (2012)
[d] Sandu et al. (2002)
[e] Hjeltnes et al. (2012)
[f] Rosten et al. (2011)
[g] Rosten et al. (2013)

Oxygenation

Oxygenation cones, deep-shaft or low head oxygenation (LHO) units are used to increase the dissolved oxygen (DO) saturation. The energy demand for oxygenation depends on the water treatment flow rate and pressure. Oxygenation cones operate at higher pressure, which increases the energy cost. Deep-shaft oxygenation cones are placed below the water surface level, and can operate at a lower pressure as they take advantage of the increased pressure difference. LHO units operate at low pressure and have low energy costs (Davenport et al., 2001; Espinal and Matulić, 2019), but can only be used in brackish and seawater systems (K Glomset 2018, pers.comm.). LHO units also have the benefit of stripping nitrogen, which is necessary to avoid nitrogen saturation (Prestvik, 2010).

By replacing the in-line[5] oxygen cone or deep-shaft unit with a LHO in the departments with brackish or seawater, energy use for oxygenation can be reduced by 18-35% in RAS for post-smolt production. If in-line oxygenation cones are replaced by deep-shaft oxygenation cones in the freshwater departments and a LHO is used in the brackish/seawater departments, energy use for oxygenation can be reduced by up to 60-70%.

Lightning

Some of the RAS facilities still use metal halogen lights today (Enova, 2019a). By replacing metal halogen lights with LED lights, the power consumption can be reduced by about 60% (Cheng and Cheng, 2006). This can reduce total energy use by 2-5% (Enova, 2019a). LED lights also provide an optimised light spectrum to the light sensitivity of the fish, which is positive for smoltification, can increase growth and reduce stress (Fretheim, 2016). Hence, switching to LED lights can provide important benefits for production and fish welfare, in addition to reduced energy consumption.

Heating and cooling

Replacing oil boiler by heat pump and heat exchangers

A few smolt facilities in Norway still have a fossil-based heating system, and use boilers for heating of intake water. If the boiler is replaced by a heat pump, the energy use for heating can be reduced by 70% (assuming a boiler efficiency of 85% and a coefficient of performance[6] (COP) of 3). If heat exchangers, recovering heat from the effluent water is installed in addition, the COP of the system can be increased to 10. This means that the electricity input required is only one-tenth of the heating demand. In this case, energy use for heating can be reduced by 90% (see Appendix B.0.2 for calculations).

Heat recovery of ventilation air from degassing

The removal of CO_2 in the degasser is typically done by blowing air in a co- or counter-current direction over the water treatment flow (Summerfelt et al., 2000). If the heat is recovered from this airflow, the energy demand for heating can be decreased. A pilot project is carried out at a RAS facility operated by Nordlaks AS (Enova, 2019b). The result of this will determine the final potential for implementation to other facilities as humidity, saline water and cold air may pose challenges (Ø Skjevling 2018, pers.comm.). Based on the data from the pilot study, the thermal heat demand is reduced by 6%. This results in a 2% saving in the total energy use. However, the need for heating versus cooling is depending on the location, and the need for heat recovery from ventilation air may be lower elsewhere. Hence, the energy saving potential is estimated to 0 to 2% of total energy use. If diesel/oil is used for heating, the energy savings are 0 to 6% (see Appendix B.0.3 for calculations).

Sludge treatment

Several different solutions are used for sludge treatment in RAS operating today. If the sludge is treated to a high DM content, drying processes increase energy use substantially. The installation of a heat recovery system can reduce the energy demand of the drying process by 62-70% (Berthelsen, 2018; Ø Prestvik 2019, pers.comm.). If the RAS facility treats the sludge to a low DM content, the production of biogas

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[5] Oxygen is added to the total water treatment flow rate.

[6] The coefficient of performance describes the ratio of heating or cooling provided to electricity input required in a heat pump.

by anaerobic digestion may be a viable solution. This could for instance be done in an Anaerobic Baffle Reactor (ABR) (Kvande et al., 2018; Sterner, 2019). Electricity and heat can then be generated by a small Combined Heat and Power (CHP) System or heat can be generated by a boiler (Sterner, 2019; Pöschl et al., 2010). The biogas produced can typically cover 2-5% of the total energy use on-site (Mirzoyan et al., 2010). Other studies on biogas production from sludge in RAS have reported a potential of covering up to 12% of the total energy demand (Yogev et al., 2017).

Frequency control

Many of the newly built RAS plants in Norway have frequency controllers installed on most units. Yet, some facilities still do not have frequency control installed to the degasser and ventilation units (Enova, 2019a). Frequency control of the degassing may reduce the energy consumption of the process by 30-70% (Enova, 2019a). For the ventilation system, the airflow rate can be adjusted based on measurements of temperature, relative humidity and pressure differences. Gehlert et al. (2018) argue that frequency control of ventilation systems in RAS has received little attention, as it does not directly relate to fish growth. In their model of a RAS facility, energy use for the blowers in the ventilation system was reduced by 85% when applying VFD. Rosenberg et al. (2007) estimate an energy saving potential of 40% and a 20% reduction in thermal energy demand for ventilation.

As described above, a range of measures are available to reduce energy use in RAS. To quantify the energy efficiency potential the state of the current RAS in operation in Norway first has to be known. More specifically, the contribution of each process to total energy demand and to which degree the measures are already implemented have to be analysed. Before returning to the energy efficiency potential in RAS, the methods and materials used, as well as the current energy use in RAS facilities are presented.

3 Methodology

This chapter presents the methodology used to address the research questions posed. As mentioned, this work is a continuation of the project thesis work. The preceding work included a review of literature related to energy use in RAS, identification of drivers for energy use and the development of an energy model. The output of this work has now been used to specify the data collection process, as described in Figure 1 in Section 1.3. Energy use data have first been collected from RAS facilities in Norway. Based on the data, the average current energy use, the distribution of energy use and a life-cycle inventory (LCI) for smolt production in Norwegian RAS have been developed. Thereafter, the energy efficiency potential in the RAS data have been collected from, has been quantified. The data collected has then been used to validate and improve the energy model. As no empirical energy data are available for production of large post-smolt or salmon grow-out in RAS, the energy model has been used to simulate energy use. Finally, scenarios for future production in RAS have been established to evaluate the future energy demand in land-based aquaculture in Norway.

First, the system considered and system boundaries are described. Second, the data collection process, available data and assumptions used to assess current energy use and efficiency potential are described. Third, the scope and structure of the energy model is shortly explained. Lastly, the assumptions and materials used to establish the future projections of energy use in RAS are outlined.

3.1 System description

A schematic description of a typical Norwegian RAS facility is displayed in Figure 7. Fertilized salmon roe is first inserted into the hatchery. When reaching 0.2 g they are transferred to the start-feeding department, and thereafter to a freshwater department when reaching approximately 5 g. The departments from start-feeding until the final weight are here lumped into the process "grow-out departments". Each department is connected to a water treatment system, which is supplied with temperature regulated and disinfected water. The effluent water is filtered and treated depending on the final desired DM content. The sludge is either only filtered and dewatered, or additionally thermally treated. In the first case, a DM lower or equal to 25-30% is obtained, while in the latter case the DM content is increased to 85-95%. Finally, supporting functions and building heating, ventilation and lighting are included.

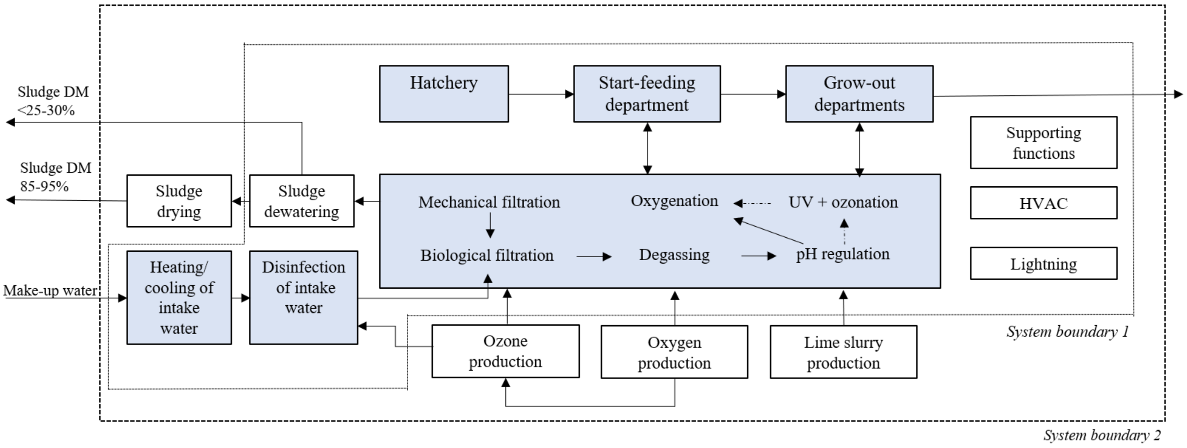

Figure 7: System description of RAS facilities in Norway. Processes in blue indicate processes for water treatment. HVAC stands for heating, ventilation and air conditioning.

The system boundary considered includes the energy used on-site, meaning that only the direct energy use is assessed. As seen in Figure 7, this leads to two different system boundaries, as some processes (sludge treatment. oxygen, ozone and lime slurry production) can be located on-site or off-site. The system boundary was limited to the on-site energy use to achieve as consistent and comparable values as possible. Furthermore, this meant manageable work for data providers, as the yearly energy consumption usually is easily available. The same system and system boundary have also been considered for the energy model.

3.2 Current energy use in RAS

3.2.1 Data collection and materials

No statistics for operating RAS facilities in Norway are currently available. Therefore, the first step of this study was to perform a mapping of the RAS facilities in operation and under construction. This has been performed using information obtained by personal communication with Simen Langeteig working for Lerøy and Tore Evjen working for NRS (in September 2019). The mapping identified 48 RAS facilities in operation, and 7 under construction. It is however likely that the list of facilities under construction is not complete. All of these plants have been contacted and 13 of the operating facilities have provided data. Additionally, data estimates have been obtained from one facility under construction. The data have been collected by phone, e-mail or visits. The survey included all of the large industry actors in Norway, i.e. MOWI, Lerøy, Grieg Seafood, Salmar, as well as some smaller companies.

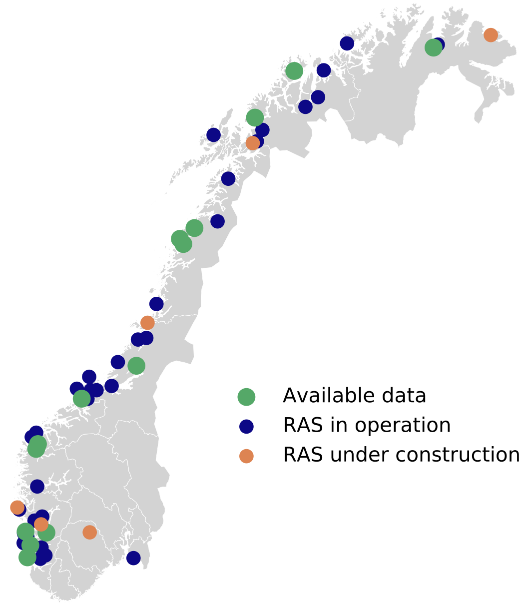

Figure 8: RAS facilities in Norway. The green dots indicate RAS facilities data have been collected from.

Yearly energy use and biomass production data have been collected, mainly for the year 2018. In a few cases [1], energy data from August 2018 to August 2019 have been provided, as the facility was under normal operation only in this time period. Some facilities [2] were not in normal operation in neither 2018 nor 2019, and have provided estimates for energy use and biomass production. Energy data with different level of detail have been obtained, from yearly aggregated energy use to hourly power consumption by process. Additionally, information about water volumes, flows, system design and operation has been gathered from 12 facilities. This has been used to analyse relationships between various parameters and energy use. An overview of the collected data from each RAS is displayed in Table 9 in Appendix C. Microsoft Excel and Jupyter Notebook have been used for data analysis.

3.2.2 Data classification

The facilities have been classified according to Figure 9, to keep a consistent system boundary and allow for comparison across facilities.

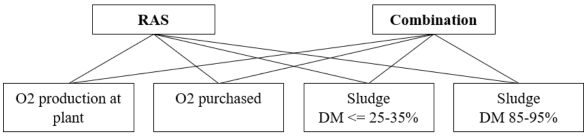

Figure 9: Classification of data collected.

Out of the 14 facilities data have been collected from,

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[1] RAS 1 and RAS 8

[2] RAS 3, RAS 4 and RAS 9

some use solely recirculation technology, while others use flow-through technology in some of the departments. Consequently, the facilities have been classified as "RAS" and "Combination" facilities. RAS facilities exclusively use recirculation technology, while Combination facilities still have some departments using flow-through technology, as they are rebuilt from FTS to RAS. Four of the facilities are classified as Combination.

The facilities have also been classified depending on whether oxygen is produced on-site or supplied, and the sludge treatment. Oxygen production and sludge treatment are both important processes for overall energy demand. As the considered energy consumption is limited to the on-site energy use, these processes may not be included in the total energy consumption as shown in Figure 7. Only one of the facilities produces oxygen on-site. Four facilities treat sludge to a high DM content, while the others treat sludge to a DM content equal to or lower than 30%.

3.2.3 Energy Performance Indicator

Based on the review of literature and the level of detail of the data collected, an Energy Performance Indicator (EPI) was used to allow for comparison of energy efficiency. EPIs link the production activity and the required energy (Lawrence et al., 2019). The specific energy consumption (SEC) has been used as the main EPI. SEC is also similar to life-cycle inventory (LCI) values, which is beneficial in order to compare the results against previous results and for further use, for instance in LCA.

The SEC represents the cumulative energy consumption in relation to biomass production and is defined as:

$$SEC = \frac{\sum E_{i,j}}{P_i} \tag{3.1}$$

where
$E_{i,j}$ is energy use of energy carrier j in year i
P_i is biomass production in year i

The energy carriers used in the plants are diesel and electricity. The diesel energy consumption is converted from liters to kWh using a conversion factor of 10.056 kWh/L diesel (Miljødirektoratet, 2017).

The energy use has been analysed with respect to different parameters: production intensity, load factor, average smolt weight, outside air temperature and water treatment flow rate. The production intensity describes the annual biomass production per production volume, and is defined as:

$$\text{Production intensity} = \frac{P_i}{V} \tag{3.2}$$

where
P_i is biomass production in year i
V is the water volume

The load factor (LF) has been specified to express the share of biomass production to the biomass production capacity, and is defined as:

$$LF = \frac{P_i}{P_{max}} \tag{3.3}$$

where
P_i is biomass production in year i
P_{max} is maximum production capacity

The average smolt weight was provided by the data suppliers. Outdoor air temperature has been used as a proxy for water temperature. The median outdoor temperature for the closest weather station has been obtained from Norsk Klimaservicesenter (2019). The water treatment flow rate refers to the water that is circulated from the fish tanks into the water treatment units. The water treatment flow rate has either been obtained directly from the data suppliers or been calculated based on information about the total water volume and HRT. The relation between water volume, water flow rate and HRT is given as:

$$\dot{V} = \frac{V}{HRT} \tag{3.4}$$

where
$\dot{V}$ is the water treatment flow rate
V is the water volume
HRT is the hydraulic retention time

The average of SEC and other parameters have been determined by the unweighted arithmetic mean. Out of the fourteen facilities data have been collected from, three facilities have provided only estimates for energy use and biomass production, and have been left out when determining the mean. One facility could not provide energy use for the start-feeding department and has also been left out to avoid inconsistent system boundaries.

3.2.4 Distribution of energy use

An important part of this study is to determine the distribution of energy use based on data from commercial RAS facilities. Moreover, this has been vital to quantify the energy efficiency potential and validate the energy model.

The distribution of energy use has first been determined for four main categories: water treatment processes, energy and intake water processes, building and ventilation, and supporting functions (level 1). The energy use has additionally been distributed across single units (level 2).

The following data and assumptions have been used:

- Hourly power consumption data for the main processes (level 1), as well as for the heat pump and intake water pumps (level 2), from two facilities (Figure 28 in Appendix C).
- Installed and predicted normal operating power for all units (level 1 and level 2) in two facilities. The assumptions made for the prediction of normal operating power are outlined in Appendix C.
- Installed power for units in the water treatment loop (level 2) for one facility. To determine the normal operating power the mean ratio between installed and predicted normal operating power for the two facilities above has been used.
- Energy use by main processes (level 1) from a RAS supplier (Kyvik, 2016).

A summary of the data available can be found in Table 11 in Appendix C.

The average distribution has been developed assuming that oxygen is purchased from suppliers, as this is identified as the most common practice. For sludge treatment, two different cases are examined. If sludge is treated to DM 25-30% only dewatering is needed, which has a modest energy demand. If sludge is treated to DM 85-95%, drying is additionally required which increases energy use. To determine the share of energy use for sludge treatment in the latter case, hourly power consumption data from a facility treating sludge to a DM of 95% has been used. At this plant, sludge treatment accounts for 15-20% of the total energy use (see Figure 28 in Appendix C). Additionally, data from one supplier of sludge treatment equipment indicate that the sludge process stands for 15% of total energy use. Energy use for filtering and dewatering requires close to 20% of the energy demand, while 80% is used for thermal treatment (Ø Prestvik 2019, pers.comm.). The shares of other processes have in this case been reduced, in relation to their contribution.

3.2.5 Energy efficiency potential

The current energy efficiency potential of the RAS facilities included in the study has been quantified to assess the energy efficiency gap. The most relevant measures for reducing energy consumption in RAS are described in Chapter 2.4.4. The measures have been categorised into measures that can be implemented to already existing RAS facilities and design considerations for new construction. The measures relevant for existing facilities are presented in Table 3.

For some of the measures only energy savings with respect to the energy use of the process were known. In this case, the energy savings relative to the total energy use have been estimated by multiplying the energy savings of each process by the general energy distribution. For other measures, only energy savings relative to the total energy use were available.

To quantify the energy efficiency potential of the facilities included in this study, the ten facilities providing reliable data for actual energy consumption were considered. The relevancy of each measure is determined by communication with data providers about the current configuration of the plant. Moreover, insight into energy efficiency measures reported to Enova by RAS facilities has provided information about potential measures and their applicability (Enova, 2019a). The facilities have been categorized as new and old. The newer facilities are all turn-key systems built in the last years. The older facilities are systems converted from FTS to RAS, and still have some departments that are constructed several years ago. 60% of the RAS facilities included in this study are considered new, while 40% of the facilities are older.

In summary, the following assumptions regarding the relevancy of each measure have been made:

- Introducing energy management, reducing the pressure of the recirculation pumps, demand controlled ventilation and heat recovery of ventilation air are relevant measures for all plants.
- Replacing metal halogen lights with LED lights is relevant for the oldest plants.
- Frequency control of the degassing units is relevant only for the oldest plants, as well as the plants stating this as an energy efficiency measure in the reports to Enova.
- Replacing the boilers with a heat pump and upgrading the heating system is a relevant measure for the plants using diesel/oil for heating today.
- Installing an ABR for biogas production and a methane boiler is relevant for the plants treating sludge to a low DM content today.
- Installing a heat recovery system to the drying unit is relevant for the plants that already treat sludge to DM85-95%, as drying units are installed already. The currently installed dryers are assumed to operate without heat recovery.

The number of facilities each measure is assumed applicable to is shown in the last column in Table 3.

In addition to technical and operational measures, increasing productivity is a viable strategy to improve energy efficiency. Several data providers underline the fact that most equipment in RAS is continuously operated, despite a lower biomass production. Hence, an increase in production will lead to a lower SEC. Ideally, data on biomass production and energy consumption for one plant should be analyzed over multiple years to evaluate this statement. Energy use and biomass production data were only available for two different years for three RAS facilities. The data can be found in Appendix B and have been used to determine the relative change in energy use with respect to a change in biomass production (expressed by the load factor LF). Based on the available data, the energy use, in average, changes by 50% of the change in LF. Due to the limited data, two different scenarios for the change in energy use with respect to production intensity are defined:

- Scenario 1: Increased biomass production is achievable without an increase in energy use (as described by data suppliers)
- Scenario 2: Energy use will be increased by 50% of the increase in biomass production (as described by available data)

Table 3: Energy efficiency measures and potential savings.

Measure	Description and assumptions	Savings of measure	Total savings	Number of facilities
Energy management	Introducing ISO 50001.		2-10% of total energy use	10
Reduce pressure of recirculation pumps	Pump pressure can be reduced by 10%, reducing water treatment flow rate by 5%.	15%	3% of electricity use	10
Demand controlled ventilation	VFD is installed to all ventilation units and control the ventilation rate depending on humidity and temperature.	85%	2% of electricity use	10
Frequency control of degassing unit	VFD is installed to the degassing unit and control airflow rate based on CO_2 levels.	26-72%	2-6% of electricity use	10
Switching to LED lights	All metal halogen lamps are replaced by LED lights.	60%	2-5% of electricity use	4
Upgrade heating system	The oil boiler is replaced by a heat pump and heat exchangers for heat recovery from effluent water.		73-92% of diesel use	4
Heat recovery ventilation	An air-to-air heat exchanger is installed to recover heat from the air vented from the degasser.		0-6% of diesel use if a boiler is installed or 0-2% of electricity use if a heat pump is installed	10
Heat recovery sludge treatment	A heat recovery unit is installed to the dryer.	62-72%	8-9% of electricity use	4
Biogas production	An ABR is installed to convert the sludge to biogas. A methane driven boiler utilises the biogas for heating influent water.		2-5% of total energy use	6

3.3 Energy model

As no empirical energy data are available for production of larger post-smolt or salmon in RAS, an energy model has been used to simulate the energy demand. The model developed is shortly described in the following section. Details regarding the modeling can be found in the report from the project thesis work (Nistad, 2018).

The model represents the system indicated by system boundary 1 in Figure 7, but the hatchery and start-feeding department are left out as data are lacking and the contribution to total energy demand when producing large fish is considered marginal[3]. It was decided to model the system described by this system boundary, as most facilities do not have oxygen, ozone and lime-slurry production on-site. Additionally, the data obtained for the sludge drying process were limited and inconsistent, and considered too uncertain to include in the model.

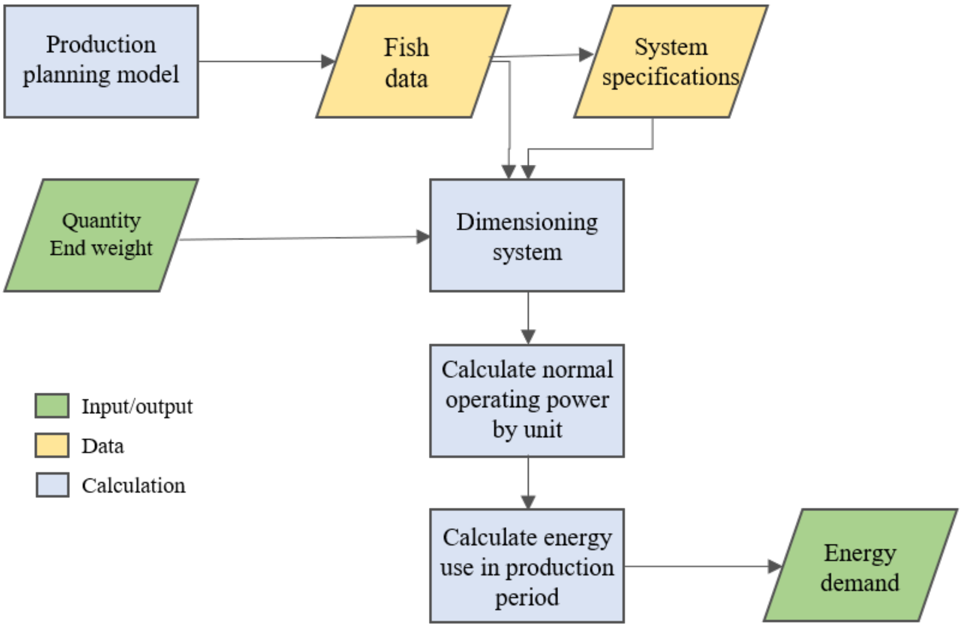

Figure 10: The flowchart describes the structure of the energy model. Data on production, fish performance and system specifications are taken as input to the model, which calculates the cumulative energy demand for production of salmon in RAS with a specified weight.

As seen in Figure 10, the number of fish produced and the final weight are taken as input. In addition, the start and end weight, stocking density, HRT, temperature, salinity and recirculation degree in each department have to be specified. Finally, growth rate, feed load and oxygen consumption are defined with a weekly resolution.

The growth rate, feed load and oxygen consumption are in this study calculated based on a production model developed by Morefish and SINTEF (see Nistad (2018) for a description of this model). This data can however easily be changed in a Microsoft Excel worksheet by the user. Knowing the growth, feed load and oxygen demand, the TSS, CO_2 and TAN production are estimated. From the maximum loads, flow rates and temperatures, the water treatment processes are dimensioned. Thereafter, the associated power consumption is determined and overall energy use in each department is calculated. The power consumption in each department is constant and equal to the maximum power demand of the dimensioned system, despite a lower stocking density in the first weeks. The final outputs of the model are the total energy use, SEC and the distribution of energy use.

The energy model has been implemented using Python v3.7.5 and the libraries *pandas* and *numpy*. Python

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[3] Based on data obtained by personal communication with Stian Iversen 2019.

is an open-source programming language, which means that no license is required to run the model. The model can be found in the following GitHub repository: `https://github.com/anistad/RAS-model-`. This repository provides a complete overview of the modeling and assumptions, as well as input and output files.

3.4 Future energy use in RAS

The future energy use in RAS is predicted using the energy model along with scenarios for future post-smolt and salmon production in RAS. Additionally, the consequences for GHG emissions and production costs are addressed.

3.4.1 Simulated RAS for salmon grow-out

To assess the specific energy use for larger salmon production in RAS, the system described in Table 4 has been simulated. The end weight and the number of fish produced are input parameters to the model. In addition the HRT, stocking density and recirculation degree are specified.

Table 4: Specifications of the system simulated by the energy model to evaluate the energy use for post-smolt production and salmon grow-out in RAS.

Department	**Start weight**	**End weight**	**HRT**	**Stocking density**		**Temp.**	**Salinity**
				case 1	case 2		
	g	g	min	kg/m^3	kg/m^3	°C	‰
1	5	30	40	45	45	14	3
2	30	100	40	50	50	14	3
3	100	500	40	65	65	12	3-12
4	500	1500	40	65	50	12	12
5	1500	2500	40	65	50	12	12
6	2500	4000	40	65	50	12	12

The recirculation degree is equal for all departments and is set to uniformly variate between 97.5% and 99.8%, which is the range observed in the collected data. The fresh- and seawater temperatures are set to vary uniformly between 4 to 10 °C. The salinity is set to 3‰ in the first departments, and 12‰ in the grow-out departments. Fredrikstad Seafood plan to run their RAS facility for salmon grow-out with a slightly higher salinity of 14-16‰ (Hilmarsen et al., 2018). This marginal difference would not change the result of the simulated energy demand.

Two different cases are considered for stocking density. In case 1, the stocking density is assumed to equal the stocking density used in the analysis of energy use for salmon grow-out in RAS by Hilmarsen et al. (2018). The effect of a lower stocking density is considered in case 2, and the values are based on an estimate by a RAS supplier (K Attramadal 2019, pers.comm.). The HRT is assumed to equal 40 min in all departments, which is the mean value of the collected data, but the effect of a lower HRT in the last departments will also be evaluated.

Energy consumption is simulated for a fish weight of 170 g to 4 kg. This covers the range from smolt production in RAS today to the harvest-weight of salmon produced in RAS at Fredrikstad Seafoods' facility (Kyst.no, 2019).

3.4.2 Scenarios for future production in RAS

Scenarios for future post-smolt and salmon production in RAS have been developed in line with recent changes in production strategies described in section 2.1. Two scenarios are described for post-smolt production and salmon grow-out to market-size in RAS respectively. For post-smolt, three different weights are assessed: 0.5 kg, 1 kg or 1.5 kg. The market-weight of salmon is assumed to equal 4 kg (Kyst.no, 2019).

The scenarios describe biomass production in RAS in Norway from 2020 to 2030. The scenarios and assumptions are described in Table 5. For reference, the current annual smolt production in RAS is approximately 25 kT, while the annual salmon production is currently about 1300 kT in Norway.

Table 5: Scenarios for future production of post-smolt and salmon in RAS.

Post-smolt	Scenario 1	The quantity of smolt produced in Norway stays constant between 2020 and 2030 and equals the 2018 production of 375 million. Post-smolt is produced instead of smolt leading to an increased average weight and a growth in biomass production. The share of biomass production in RAS increases linearly from 50% in 2020 to 100% in 2030.
	Scenario 2	Production of post-smolt in RAS increases between 2020 and 2030 to realise the goal of a five-fold increase in Norwegian salmon production within 2050 (Nærings og Fiskeridepartementet, 2015). The share of production in RAS increases linearly from 50% in 2020 to 100% in 2030.
Salmon	Scenario 1	A modest growth in salmon production in RAS is seen between 2020 and 2030. The scenario is based on forecasts from the RAS supplier Billund Aquaculture (Høidalen, 2019). The production increases linearly from 0 in 2019 to 35 kT in 2030.
	Scenario 2	Norwegian salmon production increases inline with the goal of a five-fold increase in 2050. The growth takes place in RAS, as the potential for growth in sea is currently limited. As a result, the production in RAS in 2030 will equal today's production in sea.

3.4.3 GHG emission intensity and cost of electricity

The GHG emission intensity of the Norwegian electricity mix has been used to quantify the GHG emissions of energy used in RAS towards 2030. The long-term marginal electricity supply mix has been used, meaning that the additional electricity demand in land-based aquaculture is met by the electricity generation technologies that is expected to cover additional demand between 2020 and 2030. The long-term marginal electricity supply mix was determined based on a report from the Norwegian Water Resources and Energy Directorate (Bartnes et al., 2018). The mix is composed of wind-, hydro- and solarpower. The GHG emission intensity of the long-term marginal electricity mix has been determined knowing the share of each generation technology and their life-cycle GHG emission intensities. The life-cycle GHG emission intensities used are displayed in Table 6.

Electricity costs towards 2030 have also been assessed, using forecasts from Bartnes et al. (2018). In addition to the cost of electricity, a grid tariff and taxes and supplementary charges add to the final price. The grid tariff is predicted to increase towards 2030, while taxes and supplementary charges are probable to stay constant between 2020 and 2030 (Statnett, 2018). The grid tariff has been assumed to follow the increase in electricity costs.

The long-term marginal electricity mix, electricity GHG intensity and cost are shown in Figure 32 in Appendix G.

Table 6: Life-cycle GHG emission intensities of electricity generation technologies.

Technology	**g CO2-eq./kWh**	**Reference**
Wind	20	NVE (2019)
Solar	55	Gibon et al. (2017)
Hydropower	6	NVE (2019)

4 Results and discussion

This chapter first presents the current energy use, the distribution of energy use and the LCI compiled. The current energy efficiency potential is then presented. Thereafter, the validation of and modifications to the energy model, and the simulated energy demand for production of large post-smolt and salmon in RAS is presented. Finally, the future energy demand in RAS under different scenarios is described and discussed. As the results are dependent on each other, the results are presented and discussed successively. The section concludes with a discussion regarding the main uncertainties and limitations, as well as recommendations for industry and future research.

4.1 Current energy use

4.1.1 Benchmarking current energy use

The on-site energy use relative to biomass production in the facilities data have been collected from is shown in Figure 11. The energy use and biomass production is based on data from 2018. As some of the facilities still have a minor part of the system using flow-through technology, the facilities are divided into RAS and Combination facilities. RAS facilities are systems using solely recirculation technology, while Combination facilities use both recirculation and flow-through technology. The first box refers to the average of all facilities. The energy use is highly variable across facilities, and the SEC ranges from 5.1 to 12.8 kWh per kg smolt produced. The mean on-site energy use for production of 1 kilo smolt for all facilities, RAS facilities and Combination facilities is 8.80, 8.38 and 9.78 kWh respectively.

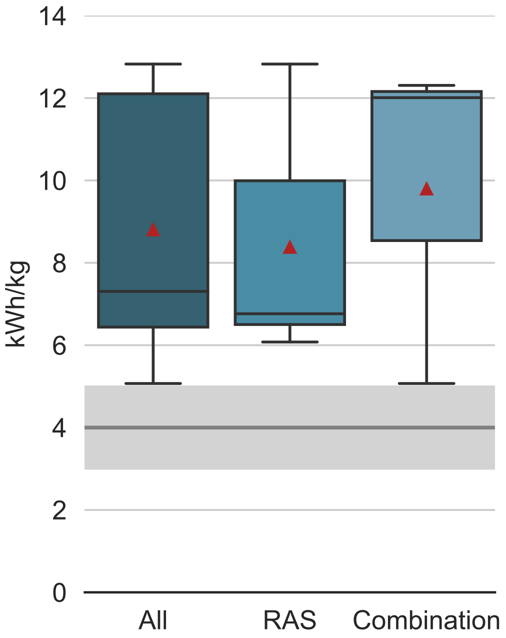

Figure 11: Specific energy consumption for smolt production in RAS based on the data collected. The grey area indicates previous estimates for energy use by Hilmarsen et al. (2018); Iversen et al. (2018); Bergheim and Nilsen (2015). The box shows the first and third quartile, and the line indicates the median. The whiskers show the minimum and maximum values. The red triangle indicates the mean.

The Combination facilities have a higher average SEC than the RAS facilities. One reason for the higher average SEC, is that they all have a fossil-based heating system. When evaluating the energy use with respect to the heating system installed, one sees that most of the facilities with a heat pump installed have a lower SEC than the facilities with a fossil-based heating system. However, this is not the case for all plants as seen from the boxplot in Figure 12. The reason for the higher SEC in systems with a fossil-based heating system is the considerably lower efficiency of such systems compared to a water-to-water heat pump. As described in Section 2.4.4, replacing an oil boiler with a heat pump and heat exchanger can reduce energy use for heating by 70 to 90%. The right panel in Figure 12, shows the energy use of all facilities, as well as the energy use of all facilities if the boiler is replaced with a heat pump. If all facilities have a heat pump installed, the variability in energy use is lower and the mean SEC is reduced from 8.8 to 7.7 kWh/kg. Still, energy use is highly variable, and the design of the heating system is not the only cause of variability. Another reason for the higher energy use could be that the Combination plants are older systems that operate with less-efficient technical installations.

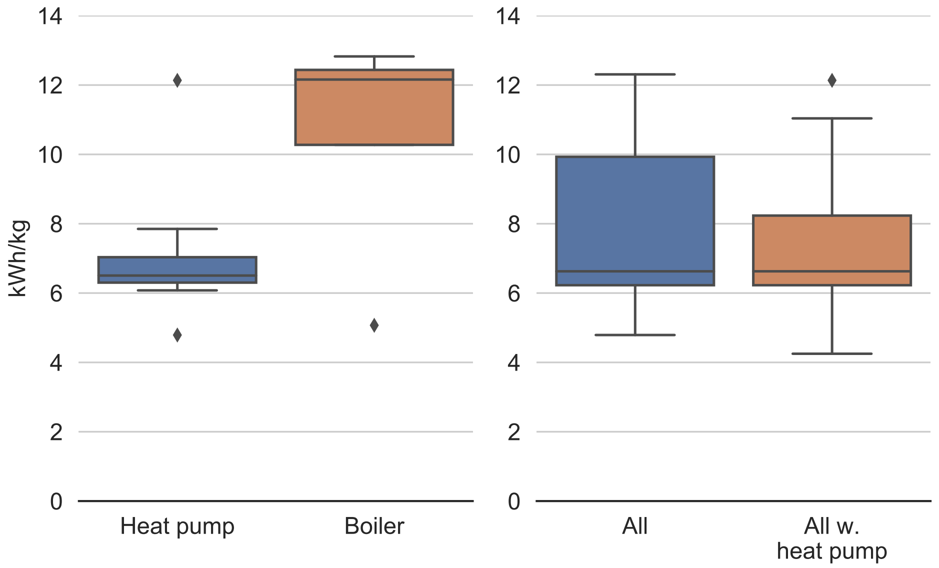

Figure 12: The left panel shows the energy use in facilities depending on the heating system installed - either a heat pump or a boiler. The right panel shows the specific energy use for all facilities, and the energy use if all facilities have a heat pump installed. The box shows the first and third quartile, and the line indicates the median. The whiskers show the minimum and maximum values, excluding the outliers that are plotted as dots.

The average energy use in the RAS facilities is twice as high as previous estimates for energy use for smolt production in RAS in Norway. The on-site energy use for the production of 1 kilo live-weight smolt has been estimated to 3 to 5 kWh, with an average value of 4 kWh (Hilmarsen et al., 2018; Iversen et al., 2018; Bergheim and Nilsen, 2015; Billund Aquaculture 2019, pers. comm.). The facility with the lowest SEC, has a SEC of 5.1 kWh/kg. The facilities with the highest energy consumption have a SEC that is four times as high as previous estimates. Hence, the current energy use in RAS in Norway is considerably higher than anticipated. This demonstrates that earlier estimates for SEC in RAS refer to systems with ideal and energy-efficient design and operation.

In total, the biomass production in the RAS facilities data have been collected from equals 10.2 kT, and total energy use amounts to 76 GWh (excluding the RAS only providing estimates). The total biomass production in RAS in 2018 was approximately 25.3 kT[1]. The facilities included in this study thereby represent about 40% of the total smolt production in RAS in Norway. Using the average SEC for RAS facilities of 8.38 kWh/kg smolt, the total energy consumption in RAS in Norway is 212 GWh today. This corresponds to the annual energy demand of 13 250 Norwegian households[2].

The variability in energy use is large, both for RAS and Combination facilities. In addition to the different types of facilities, a range of other factors could explain the variation observed. These parameters and their contribution to the observed variability are discussed below.

Rebuilding and new construction

Several facilities are built in the last years and other facilities are converted from FTS to RAS. As the data collected include all energy use on-site, electricity for construction is in some cases included and could not be disaggregated from the total electricity use. This is the case for two of the facilities with the highest SEC (12.3 and 12 kWh/kg).

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[1] Estimated from 375 million smolt produced in 2018 (Fiskeridirektoratet, 2018), an average smolt weight of 135 g (Iversen et al., 2018) and 50% of biomass produced in RAS (Nystøyl, 2019)

[2] Annual energy demand of Norwegian household 16 000 kWh/year (SSB, 2018b)

Another consequence of the recent rebuilding and construction is that multiple facilities have a low biomass production. After construction of a new RAS department, it can take several years to reach full production (Ilaks.no, 2017), especially as the biofilters need considerable time to build up (Ø Haraldseid 2019, pers.comm.). Several data providers have stated that the (high) energy consumption in their facility is a result of low biomass production in 2018. As most equipment usually run continuously in RAS, irrespective of biomass production (W Storøy 2019, pers.comm.; Ø Haraldseid 2019, pers.comm., K Attramadal 2019, pers.comm.), one would expect an exponential decay in SEC with respect to increasing production intensity. The left panel in Figure 14, shows the SEC in relation to annual production per production volume. A decrease in SEC with respect to increasing production intensity is to some degree observed in the energy data collected. The variation in annual production intensity is high, and ranges from 53 to 113 kg/m^3, when the facilities providing estimates are excluded. However, the variability in dimensioned production intensity is even higher, and ranges from 99 kg/m^3 to 220 kg/m^3.

The share of biomass production to the designed production capacity is expressed by the load factor. Biomass production is found to be considerably lower than the designed capacity of the facilities. The load factor ranges from 33 to 89% with an average of 67%. Hilmarsen et al. (2018) point out that the actual biomass production in RAS producing harvest-sized salmon often is lower than the dimensioned capacity. In some of the large commercial RAS, biomass production is only 40% to 80% of the dimensioned production capacity. Song et al. (2019) also found that the production intensity was 45% lower than dimensioned. Based on the data collected in this study, this seems to also be the case for production of smolt and post-smolt in RAS in Norway today. Besides the recent construction, too optimistic production plans and inefficient production can be reasons for a low LF.

System boundary

The system boundary includes all processes on-site and the energy use refers to the total direct energy use of the facilities. However, this causes inconsistency in the system boundary as some of the processes can be located either on- or off-site. This is the case for oxygen production, ozone production and sludge treatment. The plants have been classified depending on whether oxygen is produced on-site or delivered, and according to the sludge treatment. Only one of the plants produced oxygen on-site, so the variable SEC can not be explained by this (shown in Figure 30 in Appendix D). Four of the facilities treate sludge to a high DM content, and all of these were RAS facilities. Comparing the RAS facilities with and without thermal treatment of sludge, the average SEC is 38% higher for the RAS with thermal treatment of sludge. Hence, it is likely that sludge treatment can explain some of the variability in energy use observed for the RAS facilities.

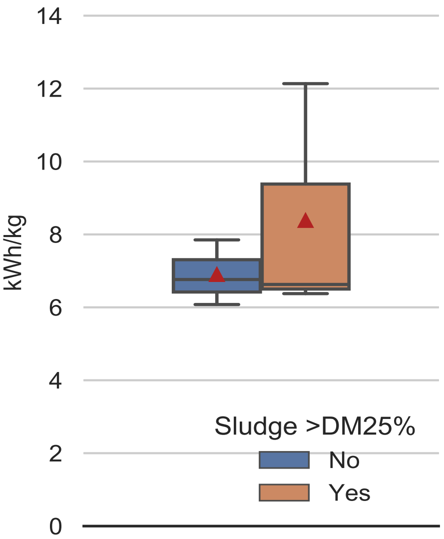

Figure 13: Specific energy consumption for RAS facilities with and without sludge treatment to a high DM content. The red triangles indicate the mean.

Fish weight

Iversen et al. (2018) indicate that the SEC for both smolt of 100 g and post-smolt of 500 g is about 4 kWh/kg, while a slightly lower SEC is estimated for production of 250 g post-smolt. Based on this, one would not assume that the fish weight would lead to substantial variation in SEC. However, the electricity costs relative to total production costs are increased when larger smolt is produced (Iversen et al., 2018) and one could expect that energy efficient design and operation may be more emphasised in facilities producing large smolt and post-smolt. This is to some degree observed in the energy data collected, as seen in the second panel in Figure 14. The average smolt weight ranges from 103 to 330 g, with a mean weight of 171 g.

Location

The location influences the intake water temperature and determines the heating/cooling demand. For smolt and small post-smolt, one would expect a heating demand for most months of the year, and lower water temperatures would result in a higher energy demand. The third panel in Figure 14 shows SEC versus the outdoor air temperature, as a proxy for water temperature. As expected, a negative linear trend can be observed with a correlation coefficient of -0.72. Thus, the location of the facility can to some degree explain the variability in energy use.

Water quality parameters

The SEC has also been analysed with respect to salinity, pH, water temperature and water treatment flow rate.

The reported water temperature in the different facilities ranges 8 to 17 °C, and from 7 to 15 °C in the last post-smolt department. Most facilities have temperatures ranging from 12 to 14 °C. The difference in system water temperature is to some degree related to the SEC. On one hand, one would expect that a higher water temperature would increase energy use, as the heat demand is higher. On the other hand, a higher temperature implies faster growth, which could reduce SEC. The energy use data collected here, shows that energy use decreases with increased water temperature (Figure 29 in Appendix D), but the data sample is too small and variable to quantify the effect.

The water treatment flow rate was identified as one of the most important parameters for energy use in the project thesis work (Nistad, 2018). As seen in the right panel in Figure 14, energy use increases linearly with flowrate in the recirculation loop. Consequently, an increase in HRT leads to a decrease in flow rate and lower energy use. HRT ranges from 33 to 60 min, with most of the facilities having a HRT less than 45 min. No concrete relationship can be established between HRT and SEC, but it is worth noting that the only facility that operates with a HRT higher than 45 min has the lowest SEC of all facilities.

With respect to salinity and pH, no systematic differences in SEC could be identified. The salinity in the start-feeding and grow-out departments is 1 to 3 ‰, while the salinity in the post-smolt departments ranges from 3 to 20 ‰, with an average of 12 ‰. pH varies from 6.4 to 7.4.

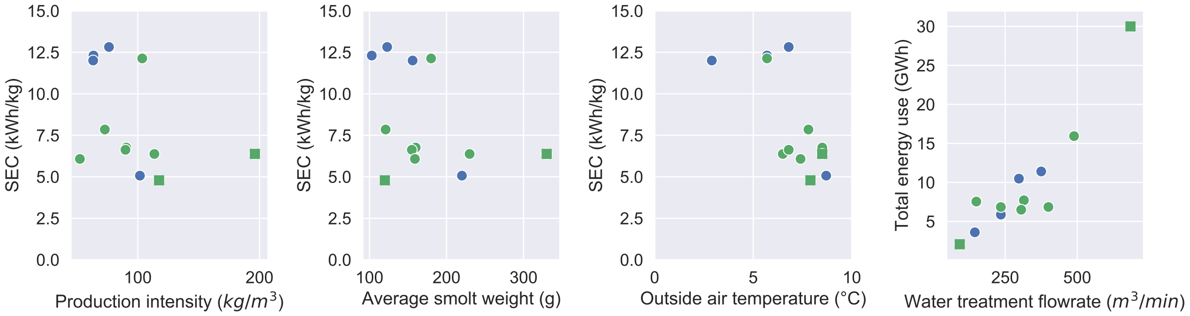

Figure 14: Energy use in relation to production intensity, average fish weight, outside temperature and water treatment flow rate. The blue dots indicate plants using diesel for heating, while the green dots indicate plants with heat pumps installed. The squares are plants were only estimates for energy use were available or system boundaries were inconsistent.

To summarize, the heating system, production intensity, location, energy use for construction and eventual thermal treatment of sludge, water temperatures and the number of years since construction are identified as aspects that can explain the variability in SEC. Final smolt weight and water parameters such as HRT, salinity and pH seem to be of less importance to differences in SEC.

4.1.2 Distribution of energy use

Figure 15 shows the distribution of energy use in RAS. The distribution is determined based on data from five operating systems and one RAS supplier. All five facilities are fairly recently constructed, use only recirculation technology and have a water-to-water heat pump installed. In average, processes in the water treatment loop account for 60% of total energy use. Heating/cooling and disinfection of intake water stand for 15% of total energy use. Supporting functions, such as vaccination machines, dead fish handling and sludge treatment also stand for 15%, if sludge is only filtered and dewatered. The building and ventilation system accounts for 10% of total energy use.

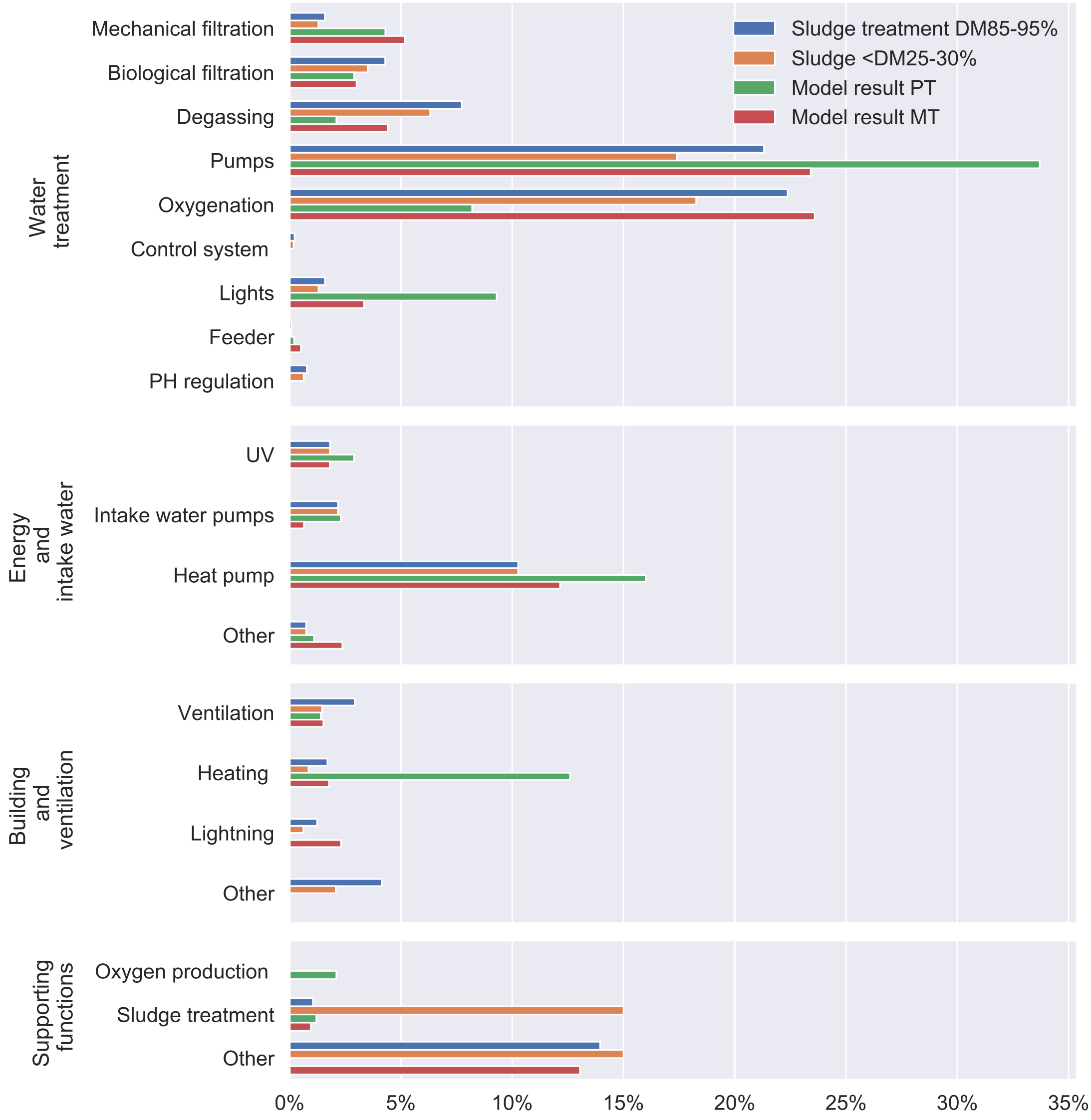

Figure 15: Share of energy use by each process relative to total energy use. The first bars show the distribution when sludge is treated to a lower DM content, while the second bars show the distribution including sludge treatment to a DM of 85-95%. The two last bars indicate the results from the energy demand model before (PT) and after (MT) validation.

The main energy consuming units are pumps, oxygenation cones, heat pumps and CO_2 degassers. In total, these account for about 60% of the overall energy use. It should be noted that the required head for the CO_2 degassers is included in the pumps. The process named other includes vaccination machines, cleaning systems and units for dead fish handling, and contribute close to 15% to overall energy use. The pumping and oxygenation contributes to about 20% of total energy use each. The heat pump accounts for 10% of total energy consumption, while the degassing stands for 8%. If the sludge is treated to a high DM content of 85-95%, the energy use for sludge treatment increases considerably as the drying process required is highly energy intensive. Based on data from one RAS facility and one supplier, sludge treatment is found to account for 15% of total energy use in this case. The share of the other processes has then been adjusted accordingly.

The average distribution displayed in Figure 15 will represent the distribution observed most of the year, as the equipment in RAS is relatively continuously operated (as seen in Figure 28 in Appendix C). The heat pump is the only process with a seasonal variation. Based on the data obtained, the energy use for the heat pump is identified as low in summer and higher in winter.

Previous studies from USA, Denmark and China have found that water treatment processes typically account for 60-70% of energy use in RAS (Colt et al., 2008; d'Orbcastel et al., 2009b; Song et al., 2019), which is in line with the distribution found here. The recirculation pumps have been identified as the main energy consuming units also in previous studies (Song et al., 2019; Summerfelt et al., 2004, 2009a; Ioakeimidis et al., 2013). However, the contribution of the recirculation pump to total energy consumption is higher in previous studies than in this study. Badiola et al. (2017) find that the heat pump stands for the largest share of energy use in a RAS facility in Spain, as the cooling demand is considerable. When cooling is excluded, the pumps are the main energy consuming units, representing 42% of the total. Similarly, Song et al. (2019) find that the recirculation pumps account for 40% of total energy. In other systems, the recirculation pumps stand for an even higher share of total energy use (Summerfelt et al., 2004, 2009a). The lower contribution of the recirculation pumps in this study is likely a result of the inclusion of all energy consuming units on-site, contrary to previous studies. Thus, the specific contribution of the recirculation pump is decreased. Moreover, the recent investments and the large focus on minimising the system head by RAS suppliers can explain the lower contribution.

The contribution of other processes varies significantly across past studies. For instance, the heating system accounts for 13% in a RAS located in USA (Colt et al., 2008) and 72% in a RAS in Spain (Badiola et al., 2017). Likewise, oxygenation was found to contribute only 1% to overall energy use (Song et al., 2019) in a RAS in China, while it is identified as one of the main energy consuming processes in this study. The divergent distributions are likely explained by the different plant designs, locations, species reared and the final harvest weight.

4.2 Life-cycle inventory for smolt production in RAS

The design of this study is quite similar to the study by Badiola et al. (2017), which demonstrated the benefits of integrating an energy audit with a LCA for cod production in RAS. Badiola et al. (2017) argue that the integration of energy audits into LCI allows for a more complete and precise LCA. As data on energy use, but also other parameters, have been gathered from operating RAS facilities in Norway a partial LCI is compiled. This LCI would be highly relevant for LCA practitioners performing LCA of the Norwegian salmon farming industry, especially as smolt production shifts from FTS to RAS.

The LCI values have been calculated using the weighted arithmetic mean of the collected data, as the LCI should represent the average smolt production in RAS in Norway. Additionally, land use has been estimated using images from Google Earth and the embedded tool for area calculation. The values represent the total area converted, i.e. buildings, paved area and the dock. Figure 16 shows the LCI values for the RAS facilities, in comparison to earlier published LCI values for smolt production in RAS. LCI values for the average of all facilities data have been collected from are included in Appendix E.

As seen in the left panel, energy use is highly variable across studies. Except for Colt et al. (2008), the average SEC found in this study is higher than previously published values. As noted earlier, the reported energy use in RAS is highly variable, and depends to a large degree on the location and design of the system. Moreover, the factors described in Section 4.1.1 can explain the disparity.

The land use calculated is considerably lower than values from Colt et al. (2008). An increased focus among RAS suppliers on reducing the footprint could be a reason for the lower land use seen in the Norwegian context. On the contrary, specific land use is considerably higher than estimated by Hilmarsen et al. (2018). The lower production compared to the dimensioned production capacity is an important reason for the difference. If the facilities had a biomass production equal to the dimensioned production capacity, the land use would be 0.018 m^2/kg. Moreover, the estimated area using images from Google Earth is 70% higher than the required land area reported by RAS suppliers and news articles. The reason for this discrepancy is probably that the reported required land use often only includes the buildings for fish rearing and water treatment, and not the office buildings and the converted circumambient area. The building area is in average 36% of the total estimated land use, but shows a large variability, ranging from 20% to 56% of the total area.

Average oxygen consumption and FCR values are in the same range across all studies. The water use is highly variable across the facilities considered in this study, also for the facilities with only RAS departments. The average water demand is twice as high as assumed by Hilmarsen et al. (2018). Again, the lower production intensity can explain the higher specific water use. Additionally, the fact that older recirculation systems have been included in this study, while Hilmarsen et al. (2018) considered a new-built RAS facility for post-smolt production could be a reason.

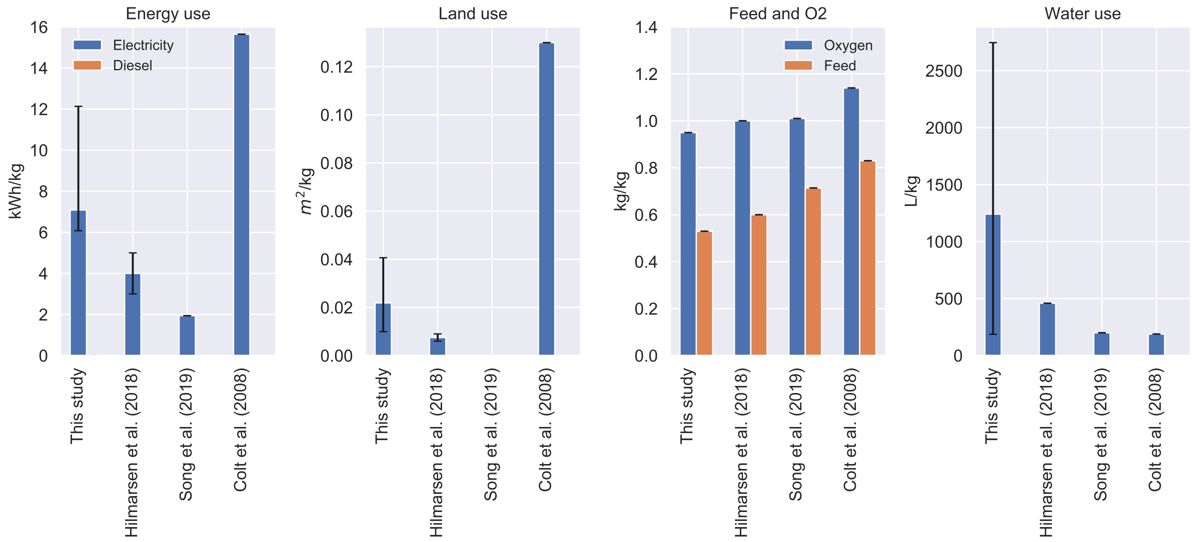

Figure 16: LCI values based on collected data from RAS facilities in comparison to previous studies of salmon smolt production in RAS. The bars indicate the average LCI value, while the whiskers refer to the minimum and maximum values.

4.3 Energy efficiency potential

4.3.1 Energy efficiency potential in existing RAS

Energy efficiency measures that either relate to RAS operation or that can be implemented at existing facilities are shown in Figure 17. The total energy reduction potential is 21% to 42% (Figure 17 displays the mean value), but all measures can not be implemented at the same time. Installation of a heat recovery unit to the dryer for sludge treatment and biogas production from sludge, are measures that are not applied together. If the sludge is treated to a high DM content, the energy savings potential is 19% to 37%. If sludge is utilized for biogas production instead, the energy use can be reduced by 13% to 33%. On top of that, the facilities that have a fossil-based heating system can realise additional savings by replacing the boiler with a water-to-water heat pump and heat exchangers. This could reduce energy use for heating by 70-90%.

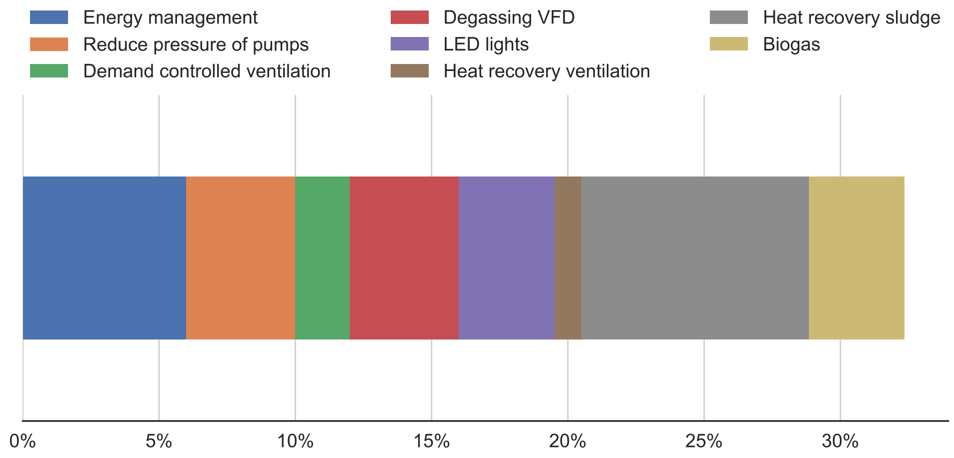

Figure 17: Energy savings potential for relevant measures in RAS. The values refer to the mean value. Each measure is described in Table 3 in Section 3.2.5.

Implementing energy management and reducing the pressure of the recirculation pump are the most effective measures to reduce energy consumption. These measures do not require any additional technical installations (if the pumps are frequency controlled), and may in total reduce energy demand by 5-15%. For RAS facilities that dry the sludge, the installation of a heat recovery system for this process is the most effective measure and can reduce total energy use by about 8%. Switching from a boiler to a heat pump and heat exchangers is a very effective measure for systems using diesel or oil for heating today. The savings of this measure, relative to the total energy use, will depend on the heat demand.

Based on the anticipated energy savings of each measure, and an evaluation of their relevancy, the energy efficiency potential for the facilities data have been collected from is quantified. This was done to provide an estimate for the total energy efficiency potential of Norwegian RAS facilities. The relevancy of each measure is determined based on insights into reports on energy management in different facilities by Enova, communication with data suppliers and assumptions outlined in Section 3.2.5.

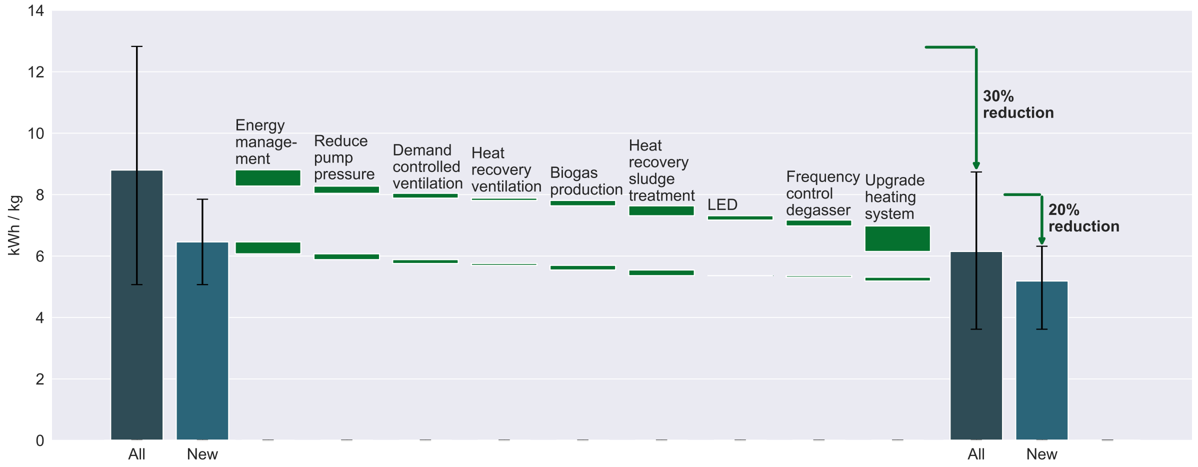

Figure 18: Potential energy savings from implementing energy efficiency measures at the facilities considered in this study. The reduction potential of each measure is indicated by the thickness of the green box. *All* refer to the average of all facilities, while *new* refer to the newest, most modern plants.

As seen in Figure 18, the average energy reduction potential is 30% for all facilities included in this study. Implementing all relevant measures would reduce the average energy use from 8.8 to 6.2 kWh/kg.

Upgrading the heating system in the facilities with a fossil-based system is the most effective measure, followed by the introduction of energy management. Considering only the facilities that are fairly recently constructed, the energy efficiency potential is lower, as measures such as LED lights, frequency control of degassers and heat pumps are assumed implemented already. In average, energy use can be reduced by 20% for the newest facilities. This reduces the average electricity consumption from 6.5 to 5.2 kWh/kg. In these facilities, introducing energy management, reducing the pressure of the recirculation pumps, and measures for sludge treatment are the most efficient actions for lowering energy use.

A few of the plants have already introduced energy management into their organizations and have anticipated a 5% reduction in total energy use. However, the data collection process in this study has shown that energy measurements are lacking the level of detail required to identify and prioritize measures for energy efficiency. Measurements are typically only available for the whole system or each department, and not on a process level. In many cases frequency controllers, which measures the actual power consumption, are installed to most of the equipment. Still many facilities do not log the power usage in their monitoring and control system. An increased focus on monitoring of energy use in RAS facilities should be the first step towards increasing energy efficiency. This would allow for identifying profitable energy investments, and decision support regarding energy efficiency measures (Bunse et al., 2011; Badiola et al., 2018; Lawrence et al., 2019).

The SEC as an energy indicator is not only influenced by energy use, but also biomass production. Thus, increasing biomass production and optimizing the utilisation of the system is an important strategy to improve energy efficiency. As mentioned earlier, most of the plants had lower production than the designed capacity in 2018, as expressed by the load factor LF. Thus, the potential reduction in SEC due to increased production has been evaluated. Based on communication with RAS operators and consecutive yearly data on energy use and biomass production from three different plants, the effect on energy use from an increased LF is assessed. As limited data have been available, two different scenarios are defined. In the first scenario, energy use is assumed to stay constant despite increased production. The second scenario is based on the available data, and energy use is increased by 50% of the increase in LF. In average, the yearly production can be increased by 33%. For the first scenario, the average SEC is reduced from 8.8 kWh/kg to 6.5 kWh/kg, while the average SEC is reduced from 8.8 to 7.6 kWh/kg in the second scenario. If additionally the energy efficiency measures described above are implemented, the SEC is further decreased. In total, the increased production and the implementation of energy efficiency measures can reduce the average SEC for all plants by 48% and 40% for the first and second scenario respectively. The average SEC would then be 4.6 kWh/kg and 5.3 kWh/kg.

To conclude, both technical measures and optimisation of biomass production are important strategies to improve energy efficiency in existing RAS. If energy savings from all relevant measures are realised and the production is optimized, the SEC can be reduced to the level of previous estimates of energy use for smolt and post-smolt production. This also confirms the finding that estimates for energy consumption typically refer to RAS facilities that are optimised in terms of technology and management. The reason for this is probably that previous studies to a large degree assess pilot-scale systems (d'Orbcastel et al., 2009a,b; Badiola et al., 2017), conceptual facilities (Liu et al., 2016; Colt et al., 2008) or refer to estimates from industry (Bergheim and Nilsen, 2015; Hilmarsen et al., 2018).

4.3.2 Design considerations for energy efficiency

Along with the measures presented in Figure 18, several considerations for energy efficiency should be integrated during the design phase. Some of these are discussed in the following section.

The installation of a low-head oxygenation system is a key factor for lowering energy use in RAS. LHO units operate at lower pressure and oxygenate the full flow, but can only be used in brackish- or seawater, as the oxygen transfer efficiency is too low in freshwater. Also deep-shaft units operate at lower pressure levels. In contrast, oxygen cones operate at higher pressure to achieve a high concentration in the partial flow treated (Espinal and Matulić, 2019). In many systems in Norway, deep-shaft oxygenation cones and LHO units are already installed, which reduces energy use considerably. If deep-shaft oxygenation cones are used in the freshwater departments, and LHO units in the departments with increased salinity, the energy consumption for oxygenation can be reduced by 50-60%[3] compared to a system with oxygenation cones.

Another important design consideration is the correct dimensioning of the pumps and piping system. An identified problem is that installed water treatment units, and especially pumps, often are under-dimensioned by consultants and suppliers to meet the requirement of low capital investments costs (Badiola et al., 2012; A Husby 2019, pers.comm.). An under-dimensioned pump will be able to deliver the required flow rate and pressure but will work far from its best efficiency point (BEP). Thus, energy use increases. Correct dimensioning of pumps may result in 10-15% to 35-40% lower energy use for pumping (Arun Shankar et al., 2016; A Husby 2019, pers.comm.) depending on the imbalance between design and operational demand. Introducing life cycle cost (LCC) considerations in the investment process can be an effective measure to avoid inefficient pumps (Enova, 2019a; Bloch and Budris, 2004). This is also relevant for other units in RAS, especially as most equipment run continuously which means that operating costs constitute a large share of LCC.

A few of the RAS data have been collected from, apply ozone and UV within the recirculation loop. Disinfection by ozone and UV account for 2-3% of the total energy use in these systems. In addition, the production of ozone requires 10 kWh per kg ozone produced (Summerfelt, 2003). A combination of ozone and UV is often used in systems where disinfection of the full flow is required (Summerfelt et al., 2009b; Gullian et al., 2012). In many cases, this is unnecessary, if disinfection of the intake water has excluded pathogens from the system (Gullian et al., 2012). Strong disinfection is also found to destabilise the microbial community in RAS (Attramadal et al., 2012). Thus, disinfection of only a partial flow or omitting ozone and UV in the recirculation loop can be a potential measure for lowering energy use.

4.4 Modification and validation of the energy model

The data from operating RAS facilities have been used to validate the energy model developed in the project thesis. The energy use distribution modeled originally is shown in Figure 15. In addition, the distribution obtained after several changes to the model is shown. The results from the validation of the energy model and changes implemented are described in this section. Details regarding the changes to the model are included in Appendix F.

The energy demand for the heat pump and space heating is highly overestimated in the model developed in the project thesis, and was also assigned a high uncertainty. A reason for this was the lack of knowledge about the heating system design and the exclusion of the heat exchangers recovering heat from effluent water. The heat demand for the water and the building is now revised and reduced.

On the other hand, the energy demand for degassing is underestimated in the first model draft. The estimate was regarded uncertain, as the energy demand of the air blower in the degassing unit was sensitive to the chosen pressure levels. No data have been obtained for the inlet and outlet pressure of the degasser, and the energy demand is modeled based on power consumption versus flow rate from three of the operating RAS.

The discrepancy between the energy demand for oxygenation, estimated by the model and from the collected data resulted from the fact that only a post-smolt department was modeled previously. A LHO unit was then assumed used, while deep-shaft or oxygenation cones are commonly used in freshwater departments. When the preceding freshwater departments are added, the contribution of oxygenation increases. The high contribution of lightning in the fish tanks estimated by the previous model is also

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[3] Based on data presented in Nistad (2018) and data obtained by (K Glomset 2018, pers.comm.). See Appendix B.0.4

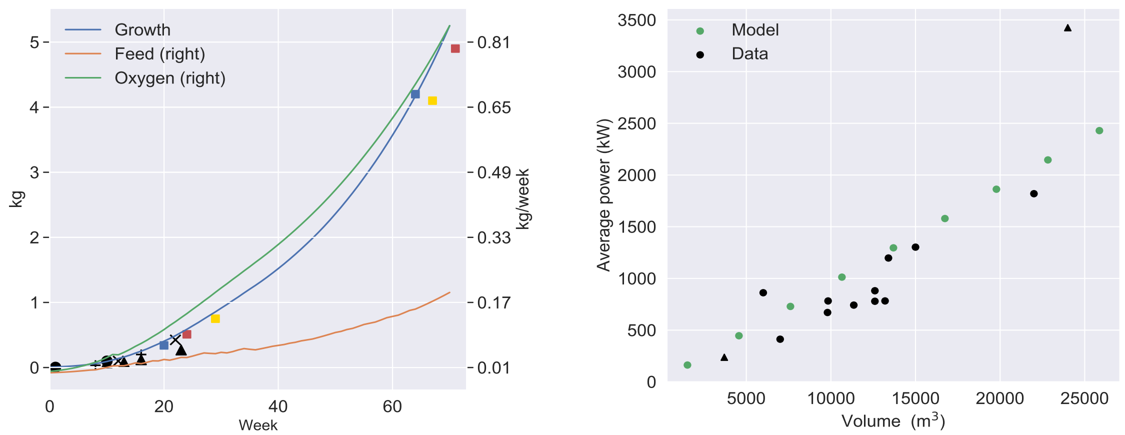
attributed to the fact that the model previously only covered a post-smolt department. As the fish tanks typically are smaller in the preceding departments, the power consumption for lightning decreases when additional departments are added to the model.

In the first version of the energy model, sludge was assumed treated to a DM content of 10%. Many of the facilities data have been collected either treat sludge to a DM content of 25-30% or 85-95%. A DM content of 25-30% is obtained by filtering and dewatering, while a DM content of 90-95% additionally requires drying. As a range of different solutions for drying exists today, and the available data on the energy use of the process is limited, this could not be included in the model. The uncertainty of energy use is too large to include the process, especially as the process can contribute considerably to total energy use. Hence, the model describes a system where sludge is filtered and dewatered to obtain a DM content of 25-30%.

Besides the changes mentioned above, the model has been restructured to cover several departments. The previous model included only one post-smolt department and covered only the growth from 150 to 500 g. Now the model is expanded and the growth from 5 g to 4 kg is covered. The number of gradings, meaning the start and end-weight of each department can also be specified. Moreover, the energy use for various supporting functions, such as vaccination machines, and systems for fish transport within the facility, is added. In total, various supporting functions are assumed to account for close to 15% of the total energy use. Lastly, some minor changes to the model for growth and substance production have been made.

Besides comparing the model against the energy use distribution, the model is checked against observed growth rates and power consumption in commercial RAS, as seen in Figure 19. The growth rate can be considered optimistic as it aligns with the upper range of the observed growth. Besides the growth rates displayed in the figure, Bjørndal and Tusvik (2017) assumed that growth from 0.2 g to 5 kg would take 18 months in their economic analysis of land-based aquaculture. A fairly similar growth rate is assumed in this study, as the growth from 5 g to 5 kg takes about 16 months, while the growth from 2 g to 5 g is done in about 2 to 3 months.

The installed water volume against average power consumption is plotted in Figure 19. As seen, a linear relationship between water volume and average power consumption is observed, with the exception of the RAS with the largest system volume. The model aligns well with the observed data, except for the largest facility. The reason for this may be that this facility provided only estimates for energy use. Additionally, they plan to operate with a higher production intensity than many of the other facilities, which may increase the power consumption per volume.



(a) Growth rate, feed rate and oxygen demand from the production planning model used as input to the energy model. The black triangles refer to the growth observed for smolt in an experiment by Mota et al. (2019), while the other points refer to growth observed in three commercial RAS. The colored squares indicate the growth rate (from post-smolt to harvest-sized salmon) observed by Davidson et al. (2016).

(b) Average power consumption in RAS in relation to system volume. The green dots indicate the model results for production of smolt with a weight of 170 g, while black dots are collected data. A stocking density of 45, 50 and 65 kg/m^3 is assumed in the first, second and third department respectively.

Figure 19: Validation of the modified energy model.

4.5 Energy use for large post-smolt and salmon grow-out in RAS

4.5.1 Specific energy demand

After the revision and validation of the energy model, the model has been run to assess the energy use for the production of large post-smolt and salmon grow-out in RAS.

The system described in Section 3.3 is simulated. The model simulates the production of one batch of fish with a specified final weight. The batch size is set to 150 000. This results in a required water volume of 20 000 to 25 000 m^3 for production of salmon with a harvest-weight of 4 kg, as the stocking densities in the departments are set to 65 kg/m^3 in the first case, and 50 kg/m^3 in the second. Thus, the RAS simulated has the same size as the largest RAS facilities for post-smolt production today. As indicated in Table 4 in Section 3.4.1, the RAS consists of six different departments. The growth rate and feed load shown in Figure 19a are used as input to the model. The resulting maximum daily feed load is 3300 kg/day, if salmon of 4 kg is produced.

Figure 20 shows the SEC for production of salmon of a specific size in the modeled RAS. The SEC represents the cumulative energy demand in the production period relative to biomass production. The range of estimated energy use in the two scenarios is indicated by the shaded area. The blue solid line indicates the mean SEC of the two different cases. The energy use estimated by Hilmarsen et al. (2018) is indicated by the green line, which assumes a stocking density of 65 kg/m^3. The red line shows the energy demand for smolt and post-smolt estimated by Iversen et al. (2018). The grey vertical lines indicate the transfer of fish from one department to another.

The estimated energy use for production of smolt of 170 g, which is the average weight of the collected data, is 2.5-3.3 kWh/kg. This is considerably lower than the current energy use in RAS in Norway, as seen in Figure 20. Similar to previous estimates for energy use in RAS, the simulated energy use by the model refers to systems that are energy efficiently operated and designed. As the model considers the production of one batch of fish, without taking a production schedule into account, the production

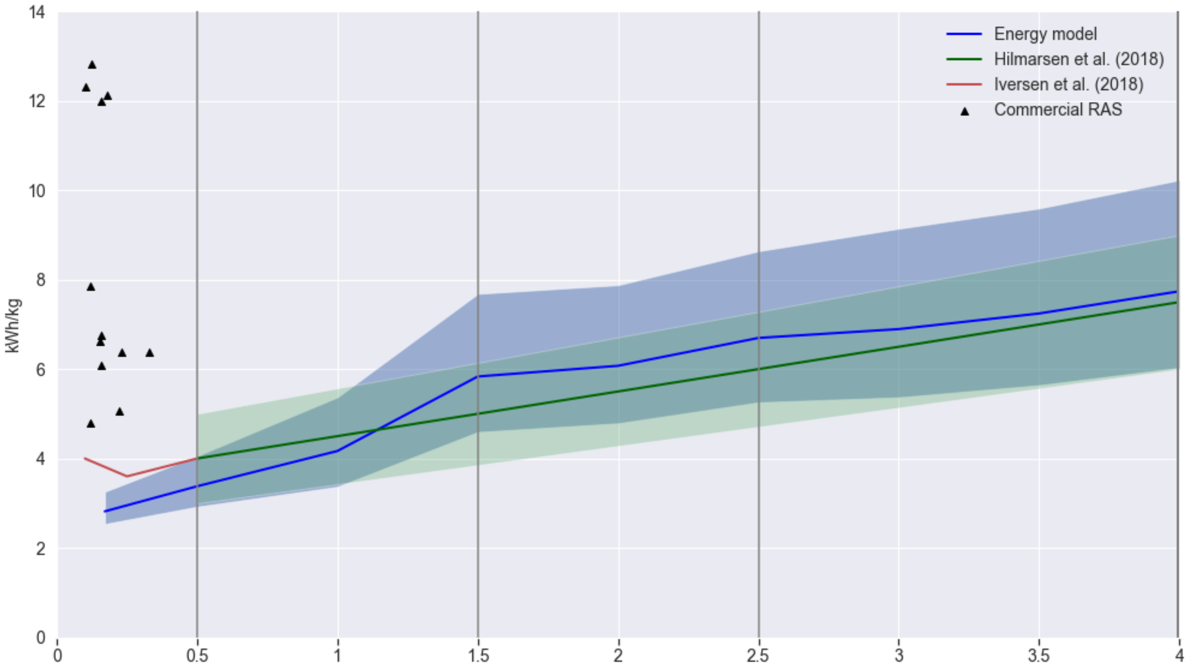


Figure 20: SEC for production of large post-smolt and salmon in RAS simulated by the energy demand model. The blue line indicates the average model results of the two cases defined (stocking density of 50 and 65 kg/m^3), while the blue shaded area is bounded by the minimum and maximum SEC in the two cases. The green and red lines indicate earlier estimates, while the data points are SEC from commercial RAS.

intensity of the simulated system is maximised. Thus, the estimates by the model will provide a lower bound for energy use in RAS. Currently, the average energy use in Norwegian RAS facilities is about three times as high as the model estimates.

The estimated energy use for production of post-smolt with an average weight of 500 g is 2.9-4.1 kWh/kg, while the energy demand for production of post-smolt of 1 kg equals 3.4-5.4 kWh/kg. If the post-smolt weight increases to 1.5 kg, the energy demand is 4.6-7.6 kWh/kg.

The estimate for SEC for 500 g post-smolt is slightly lower than previous estimates by Iversen et al. (2018), Hilmarsen et al. (2018) and Billund Aquaculture. A likely reason is that the hatchery and start-feeding departments are not included in the model. In total, the power consumption in these departments stands for about 10% of the normal operating power in a RAS producing smolt of 120 g (S Iversen 2019, pers.comm.). Thus, this will lead to a somewhat lower SEC for post-smolt of 500 g, as the share of energy use in the hatchery and start-feeding departments still have a sizeable contribution to overall energy use. When larger fish is produced, the share of energy use in the hatchery and start-feeding department diminishes and the exclusion of these departments does not have an effect on SEC. In addition, the model is developed assuming no fish mortality and losses, which can result in a lower SEC than previous estimates. The anticipated mortality is often 5-10% in the hatchery, start-feeding and first grow-out department, but decreases in the following departments (Olsen, 2012). If this is accounted for, SEC increases slightly.

For production of salmon with a harvest-weight of 4 kg, the estimated energy use is 6-10 kWh/kg. Unfortunately, no data have been obtained for actual energy use in operating systems for salmon grow-out in RAS. Thus, energy use is only compared against estimates. The SEC for production of market-sized salmon in Atlantic Shappire's facility in Miami is estimated to 8 kWh/kg, while Langsand Laks in Denmark reports a SEC of 6 kWh/kg (Navarro, 2016). The latter facility is dimensioned with a maximum stocking density of 85 and 100 kg/m^3 in the last grow-out departments, but it is unknown whether the energy use of 6 kWh/kg refers to these stocking densities. Past studies also report a SEC of 5-9 kWh/kg

(Song et al., 2019; Hilmarsen et al., 2018; Liu et al., 2016) for production of salmon in RAS. Based on the observed discrepancy between actual and estimated energy use in RAS facilities for smolt production, one can, however, expect that the energy use in RAS for salmon grow-out is higher than the model estimates presented here.

4.5.2 Sensitivity

The model results are sensitive to a number of parameters. In this section, the effect of stocking density, growth rate, flow rate, as well as the number of gradings is discussed.

To address the effect of production intensity, the model has been run with different stocking densities, while keeping everything else constant. The model was first run for two different cases, either a stocking density of 65 or 50 kg/m^3, and the mean SEC was 21% lower in the first case. Increasing stocking density further from 65 to 75 kg/m^3 decreases SEC by 13%, while a stocking density of 85 kg/m^3 yields a 23% reduction. A stocking density of 85 kg/m^3 yields an average energy use of 5.2 kWh/kg. This is similar to the SEC of 5.4 kWh/kg estimated for a conceptual RAS for salmon production by Liu et al. (2016), where the stocking density was 80 kg/m^3. The stocking density has been increased assuming that fish welfare and production performance is unchanged. However, a majority of studies suggest that increased stocking density has a negative effect on fish welfare, reduces growth and increases FCR at a given threshold (Calabrese et al., 2017). For post-smolt production, Calabrese et al. (2017) suggest that the stocking density should be limited to 75 kg/m^3.

The growth rate assumed in the simulation can be considered optimistic as it aligns with the upper range of the observed growth in commercial RAS. To address the effect of a slower growth rate, the energy use is calculated assuming a considerably slower growth rate. A 25% slower growth rate, will increase SEC by 27%. As for the stocking density, all other parameters are kept constant. In reality, a slower growth rate is likely to be a result of lower system temperatures or sub-optimal water quality which also can imply a lower energy use. Hence, the actual increase in SEC may be lower than estimated.

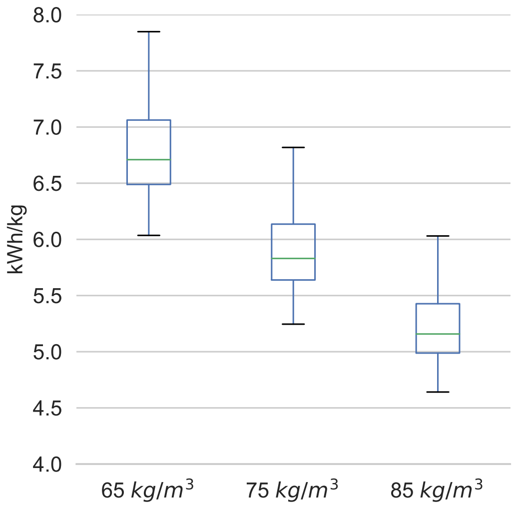


Figure 21: Simulated SEC for production of salmon with an weight of 4 kg at different stocking densities. The box indicates the first and third quartile, while the line is the median. The whiskers represent the minimum and maximum values.

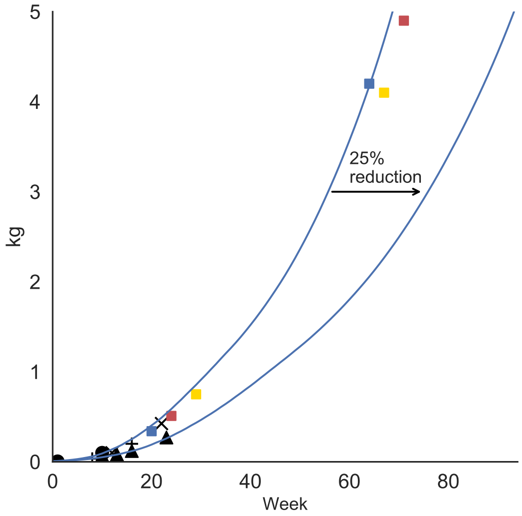


Figure 22: Original versus alternative (25% slower growth) growth rate. The black triangles refer to the growth observed for smolt in an experiment in RAS by Mota et al. (2019), while the other points refer to growth observed in three commercial RAS. The colored squares refer to growth for salmon grow-out observed by Davidson et al. (2016).

The HRT determines the flow rate in the water treatment loop, which to a large degree influences the energy use of the main energy consuming units (as seen in the Figure 14). In the base case, the HRT is assumed to equal 40 minutes in all departments. In the departments with increased salinity, O_2 saturation is lower and CO_2 removal efficiency and nitrification is degraded (Summerfelt, 2016). As a result, more frequent water treatment is required to maintain acceptable water quality and HRT is in many cases lower. If HRT is decreased from 40 to 30 min in the three last departments, SEC increases by 21%.

The estimated SEC is also sensitive to the number of gradings assumed. This is a result of the assumption that power consumption in each department is constant throughout the production period, despite a lower stocking density in the first weeks. Thus, the power consumption in each department is mainly a function of the department's dimensions. If additional departments are added to the model, the SEC decreases. The RAS simulated consists of six departments and the fish are moved every 3-4 months, as often seen for salmon grow-out in commercial RAS (Olsen, 2013). This provides an optimal compromise between keeping a high biomass density and avoiding stress associated with fish handling (K Attramadal 2019, pers.comm.). If the fish would be moved more frequently, the SEC simulated by the modeled decreases. Conversely, less frequent grading will increase SEC.

4.6 Future energy use

The specific energy demand for production of large post-smolt and salmon grow-out in RAS evaluated in the previous section is now used to assess the total energy demand for large-scale production in RAS in Norway. The next subchapters present and discuss the total energy demand, associated GHG emissions and costs under various scenarios for future production in RAS.

4.6.1 Annual energy use and power demand per facility

To discuss whether energy use can be a barrier for growth in land-based aquaculture, the yearly energy use and power demand of one facility must be known. The majority of projects for salmon grow-out to market-size in Norway plan for a yearly production of 5000 to 10000 tonnes (Strønen Riise, 2019). Hilmarsen et al. (2018) also pointed out this as a likely production capacity for future facilities. Economies of scale are likely achieved for production capacity up to about 5000 tonnes, but will subsequently flatten out (Bjørndal and Tusvik, 2019). Bjørndal and Tusvik (2019) assume that an annual production of 133 kg per m^3 production volume is achievable, but the future achievable production intensity in RAS is *highly* uncertain (Nystøyl, 2019). As seen for the Norwegian RAS facilities today, there are large variations in production intensity across facilities. If one assumes that an annual production of 133 kg per m^3 is achievable, this would result in a required water volume of 38 000 to 75 000 m^3, which is 1.5 to 3 times the size of the system simulated in this study. The annual energy use of a facility for salmon grow-out would then be approximately 38 GWh and 77 GWh respectively, which would result in an average power demand of 4.3 MW and 8.8 MW. The largest RAS data have been collected from in this study, is designed to produce 4700 tonne post-smolt per year. A facility of this dimension will have a yearly energy use of 20-30 GWh for production of post-smolt, with an average power consumption of 2 to 3.3 MW. For comparison, one on-shore wind turbine typically has a rated capacity of 3.6 MW (Fosen Vind, 2020).

4.6.2 Total energy use in land-based aquaculture under different scenarios

The anticipated expansion in land-based aquaculture will increase energy use, as both the production volumes and the average fish weight are foreseen to increase. Based on the scenarios presented in Section 3.4 and the results from the energy model, projections for cumulative energy demand in RAS are presented in this section.

Two different scenarios have been outlined for post-smolt and salmon production in RAS in Norway towards 2030. The first scenario for post-smolt production assumes that the production of smolt stays constant and equal to the 2018 production of 375 million. Nevertheless, the biomass production in RAS is assumed to rise as the smolt weight increases, and systems are rebuilt from FTS to RAS. If the smolt weight is increased to 500 g, 190 kT post-smolt is produced in RAS in 2030, as seen in Figure 23. If the smolt weight is 1.5 kg instead, biomass production increases to 560 kT in 2030. This is considerably higher than the current biomass production in RAS of approximately 25 kT. If each RAS facility has a yearly production capacity of 5000 tonne, this would imply that 40 facilities are needed for production of post-smolt of 500 g, and 110 facilities if 1.5 kg post-smolt are produced. Currently 194 land-based aquaculture facilities are in operation in Norway (Fiskeridirektoratet, 2018).

Based on the estimated average SEC of 3.4, 4.2 and 5.8 kWh/kg for smolt of 0.5, 1 and 1.5 kg, the yearly cumulative energy demand for post-smolt production in RAS is calculated. The total annual energy demand in 2030 ranges from 0.63 TWh for post-smolt of 0.5 kg to 3.28 TWh for post-smolt of 1.5 kg. This compares to the yearly energy use of 40 000 to 200 000 Norwegian households. If the upper range of the estimated SEC is used instead, the total energy use span from 0.8 to 4.3 TWh. The current total direct energy use of the Norwegian salmon farming industry is estimated to 3.2 TWh by Møller (2018). If the smolt weight is increased considerably, the energy use in RAS facilities can thereby equal the total direct energy use of the industry today.

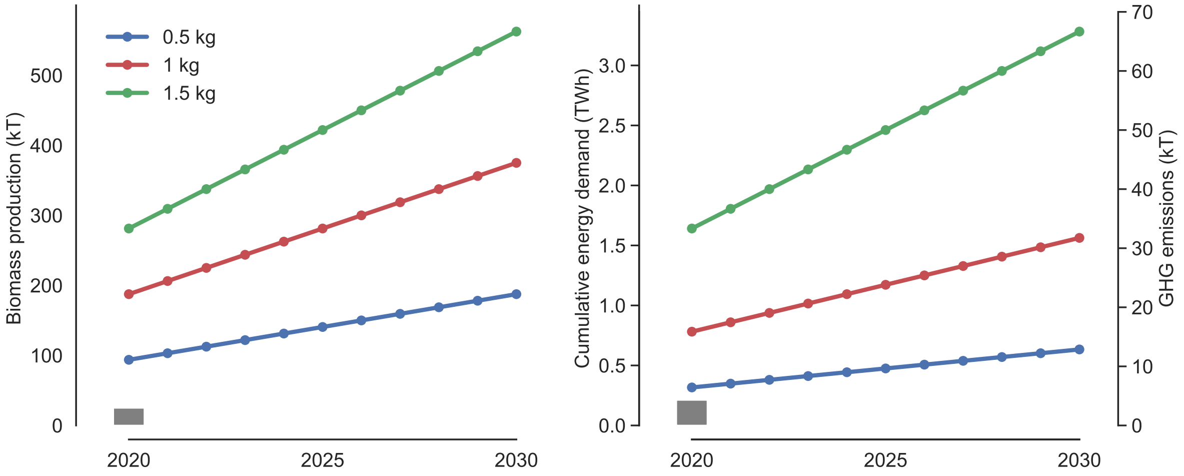


Figure 23: The left figure shows the projections for future post-smolt production in RAS outlined in scenario 1. The cumulative energy demand and GHG emissions are shown to the right. The grey bars indicate biomass production and energy use today. The GHG emissions are visualised using an emission intensity of 18.3 g/kWh, while the emission intensity of each year is shown in Figure 32 in Appendix G.

In the second scenario for post-smolt production in RAS, the smolt production is foreseen to increase to realise the industry's goal of a five-fold production increase within 2050. As a consequence, a significant growth in biomass production in RAS is assumed. In this scenario, biomass production in RAS in 2030 is 380 kT, 760 kT and 1140 kT if the post-smolt produced have a weight of 0.5, 1 or 1.5 kg respectively. The associated yearly energy use in 2030 is 1.3, 3.2 and 6.7 TWh respectively. Thus, if large post-smolt of 0.5 kg is produced in RAS and the smolt production increases to realise the goal of production growth in the industry, the yearly energy use in RAS is equivalent to the yearly energy use of 80 000 Norwegian households. If post-smolt of 1.5 kg is produced, the energy demand will equal the energy use of 400 000 households. Considering the upper range of the estimated SEC instead of the mean value would increase total energy use to 1.6 to 8.8 TWh, depending on the post-smolt weight.

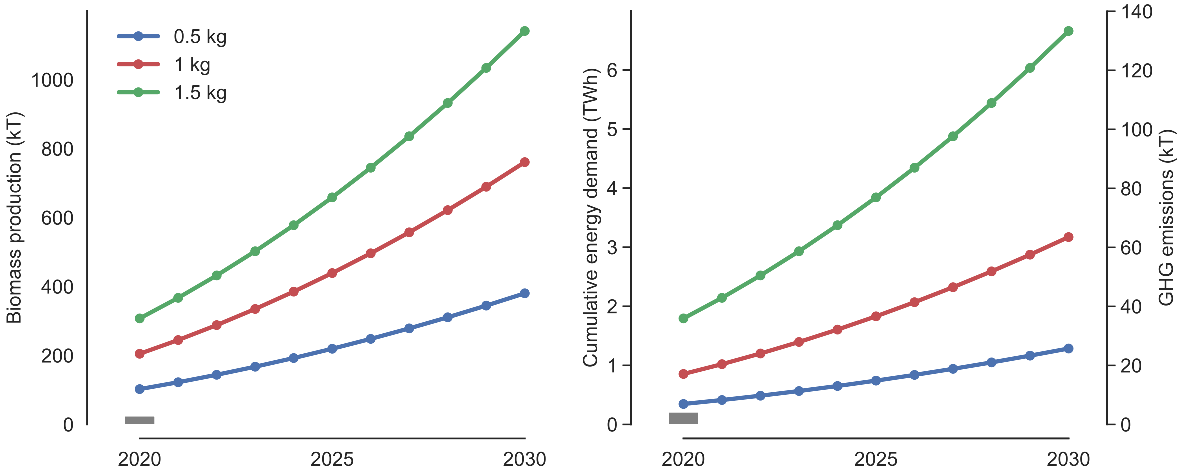


Figure 24: The left figure shows the projections for future post-smolt production in RAS outlined in scenario 2. The cumulative energy demand and GHG emissions are shown to the right. The GHG emissions are visualised using an emission intensity of 18.3 g/kWh. The grey bars indicate biomass production and energy use today.

The first scenario for salmon grow-out to market-size in RAS assumes modest growth in biomass production. The biomass production in 2030 is 35 kT, which is slightly higher than today's smolt production in RAS of 25 kT. Using the estimated average SEC of 7.7 kWh/kg, the cumulative yearly electricity use in 2030 is 0.27 TWh. This is comparable to the total current energy use in RAS producing smolt in Norway, as the average current energy use for smolt production is 8.8 kWh per kilo.

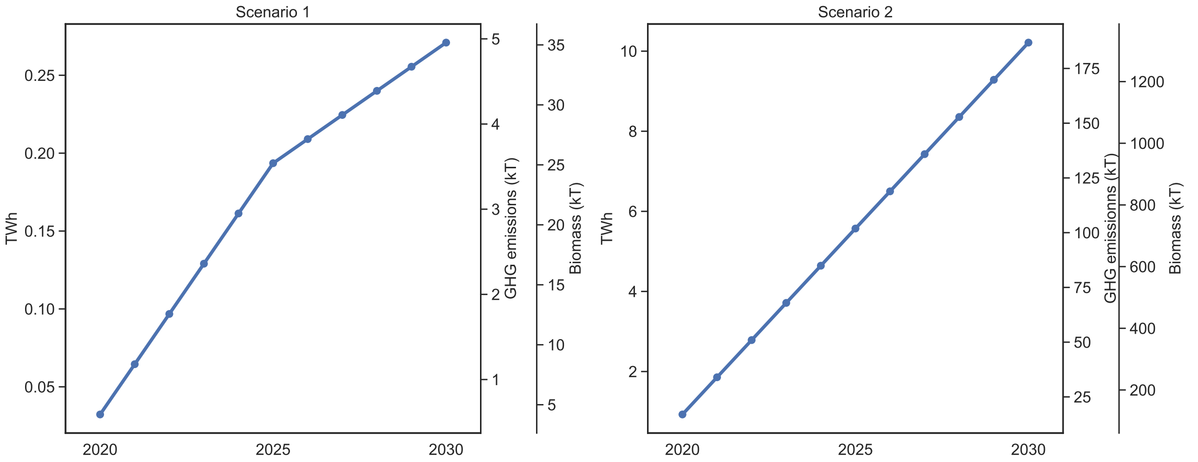


Figure 25: Future cumulative energy use, associated GHG emissions and biomass production for the two scenarios for salmon grow-out in RAS. Note the different scales of the axes. The GHG emissions are visualised using an emission intensity of 18.3 g/kWh.

In the second scenario for salmon grow-out in RAS, a considerable production growth is assumed. This scenario considers that the salmon farming industry increases the production towards 2030, to reach the goal of a five-fold increase in 2050. As the current potential for increased production in traditional open net-pens seems limited, the scenario considers that the production growth has to take place in land-based systems instead. The production in RAS in 2030 will in this case equal today's production in sea of 1300 kT. The total yearly energy demand would equal 10.2 TWh, if the average SEC of 7.7 kWh/kg is used. If the SEC equals 10 kWh/kg instead, the total yearly energy use would rather be 13 TWh. This demonstrates that a large energy demand is required for land-based production of salmon in RAS, as 10.2 TWh equals 7% of the yearly electricity production in Norway (SSB, 2018a). The yearly average power consumption of all RAS facilities would be 1.2 GW, which equals the installed capacity at the newly constructed wind farm at Fosen in Mid-Norway, which is Europe's largest onshore wind project (Fosen Vind, 2020).

4.6.3 GHG emissions and electricity costs

Figure 23, 24 and 25, also show the GHG emissions associated with energy use in different scenarios. This includes the indirect emissions from construction, operation and decommissioning of electricity generation facilities and the power grid. The direct emissions of energy use are also included but will equal zero, as electricity is the only energy carrier used in future RAS. The long-term marginal electricity mix is used to assess GHG emissions, as the energy use in RAS towards 2030 represents an additional electricity demand. The long-term marginal electricity mix consists of wind, hydro and too some degree solar power, and the GHG emission intensity in 2030 is estimated to 18.3 g/kWh.

Among the scenarios outlined, the energy use is highest in the second scenario for salmon grow-out in RAS. The total energy demand of 10.2 TWh, would equal GHG emissions of 187 kT due to the indirect emissions associated with electricity. The GHG emissions associated with electricity use in RAS, both for future post-smolt and salmon production, are modest compared to the direct GHG emissions of the salmon farming industry today. The GHG emissions from energy use associated with smolt production, the seawater production phase and transport vessels were estimated to 630 kT CO_2-eq. in 2017 by Møller (2018). This assessment included the GHG emissions of direct energy use, as well as indirect emissions associated with electricity generation. Contrary to this study, other indirect emissions from electricity generation were not included.

The reason for the modest future GHG emissions associated with energy use in RAS compared to seawater production is that the foreseen electricity mix has a very low GHG emission intensity and the current industry has a considerable fossil fuel use for vessels and feed barges. Increased production in RAS can lower the use of fossil fuels, and thereby contribute to reducing the direct GHG emissions of the sector. On the other hand, increased production in RAS will lead to a considerable direct energy demand compared to the current direct energy use of the sector. To obtain a complete overview of how total energy demand and associated emissions change in the sector if a larger share of production takes place in RAS, several other factors should be accounted for. For instance, would larger well-boats, with potentially higher fuel consumption, be needed for transportation if large post-smolt is produced in RAS. As another example, the construction of the facility lead to higher GHG emissions for RAS facilities than open-net pen systems (Hilmarsen et al., 2018; Liu et al., 2016). To assess the full implications in terms of energy and GHG emissions when the land-based production phase is extended, such factors should be included.

Based on the average electricity costs towards 2030 and the modeled energy demand, the importance of electricity costs for future production costs is examined. The average foreseen electricity cost towards 2030 is 1 NOK/kWh, with slightly higher prices in the south (price region NO3, NO5), compared to the north (price region NO4). However, these prices do depend on the realisation of a significant electricity surplus in the Nordic power market towards 2030 (Bartnes et al., 2018). As seen in Table 7, the estimated cost of electricity is 1.72, 4.2, 8.9 NOK per smolt of 0.5, 1 and 1.5 kg respectively. This would imply that electricity costs would account for 7% of the total production costs estimated by Bjørndal and Tusvik (2017) and Iversen et al. (2018), if post-smolt of 0.5 kg is produced. For post-smolt of 1 kg, the electricity cost would account for 9% of the total production costs.

For grow-out until harvest in RAS, the electricity cost is 7.7 NOK per kg live-weight produced. Thus, electricity costs constitute 19% of the total production cost estimated by Bjørndal and Tusvik (2017) of 40.9 NOK per kg live-weight. Despite large uncertainty regarding both the production costs and future electricity prices, this illustrates that energy costs will constitute an important share of the total future production costs. Compared to traditional production of smolt in RAS, energy costs will be considerably more important for the total production costs when post-smolt or market-sized salmon is produced in

RAS. In traditional smolt production, energy costs typically stand for only 3% of the total cost (Iversen et al., 2018). As the electricity costs will be of higher importance in future production in RAS, the focus and competence on energy efficiency should be increased. Energy efficient design and operation of RAS facilities will be crucial to maintain acceptable production costs when larger fish are produced on land. Whether the production costs on land in the end can challenge the production costs in open net-pens will to a large degree depend on the costs related to treatment of diseases and sea lice in the sea-based production phase.

Table 7: Future electricity costs in relation to other production costs. The other production costs are estimated by Bjørndal and Tusvik (2017) and Iversen et al. (2018).

Weight	Electricity cost	Other production cost	Share of total production costs
0.5 kg	1.7 NOK/smolt	24.2 NOK/smolt	7%
1 kg	4.2 NOK/smolt	41.9 NOK/smolt	9%
1.5 kg	8.7 NOK/smolt		
4 kg	7.7 NOK/kg	36.1 NOK/kg	18%

4.6.4 Energy as a barrier to growth in land-based aquaculture

Both production of large post-smolt and salmon grow-out in RAS can potentially lead to a substantial annual energy use. This increased demand for electricity needs to be met by new generation capacity. As seen in Figure 32 in Appendix G, 30 TWh new electricity generation capacity is expected in 2030, mainly hydro- and wind power. The increase in production capacity is followed by an increase in electricity consumption towards 2030, driven by increased energy use in industry, data centers and electrification of the transport sector (Bartnes et al., 2018; Statnett, 2019a). In total, the electricity surplus is anticipated to grow from 5 TWh today to 20 TWh in 2030 (Bartnes et al., 2018).

A likely strategy for post-smolt production, is that the smolt production stays equal to today's production, while the weight increases to 1 kg. In this case, the total energy demand in 2030 will equal 9% of the foreseen electricity surplus. The power demand would obviously be geographically spread, and if each facility has a production capacity of 5000 tonnes, 75 facilities are needed. These would each have an annual energy use of 21 GWh, which corresponds to the average energy use of 1300 Norwegian households. The average power demand would be 2.4 MW. If the goal of a substantial increase in salmon production is realised, and the production growth takes place in RAS, the energy required in 2030 would account for 50% of the foreseen electricity surplus. This is also comparable to the electricity required to electrify the Norwegian oil and gas industry, which is estimated to 15 TWh (Statnett, 2019a). If the facilities have an annual production capacity of 10000 tonnes, 130 facilities would be needed to produce 1300 kT yearly. The power demand of these facilities would be 8.8 MW in this case.

The projections for future energy use in RAS presented here, assumes that the facilities are energy efficiently designed and operated. The empirical energy use data collected from RAS facilities producing smolt in Norway show that the actual energy use is in average twice as high as the model estimates. As shown, the energy use of these facilities can be lowered if energy efficiency measures are implemented and biomass production is optimised. Based on this, the future energy demand for large post-smolt and salmon production in RAS can be substantially higher if Norwegian RAS facilities fail to improve energy efficiency and fully utilise the production capacity. If so, the energy demand of a substantial biomass production in RAS may be higher than the anticipated electricity surplus.

If the RAS facilities are designed and operated energy efficiently, the electricity surplus on the national level would be large enough to cover the additional demand for electricity in land-based aquaculture, considering the scenarios for both modest and high biomass production growth. Yet, the electricity demand in RAS will account for a considerable share of the yearly electricity surplus in Norway, and will potentially reduce the export to Europe substantially. The implications in terms of economics and GHG emissions of using the surplus electricity in Norway, instead of exporting the electricity to Europe, remain unknown and will depend on the energy source the electricity eventually replace in other markets.

Considering the future electricity surplus, the total energy consumption for production in RAS will probably not be the most prominent barrier to future growth. However, the ability to deliver the required power demand can become a crucial issue. Already today, the capacity in the local distribution grid is identified as a barrier to the construction of new land-based facilities (Riise Strønen and Adolfsen, 2019; Riise Strønen, 2019; Svarholt, 2019; Sundseth et al., 2017). The land-based aquaculture facilities are often placed along the coast in areas where the power grid is weak, as factors such as water and area are of high importance[4]. In a weak electrical grid, the connection of a land-based aquaculture facility can cause problems. First, only a limited amount of power can be transferred through the grid, and power lines, cables and transformers can overheat and break down if excessive amounts of electricity are transferred simultaneously (Kolstad, 2016; Skotland et al., 2016). Second, the connection can cause the voltage to exceed the acceptable limit of 5% deviation from the nominal voltage (Kolstad, 2016). This is more likely to happen in a weak compared to a strong power grid, as larger voltage variations are present (Kolstad, 2016). Before a new connection is accepted, the company owning and operating the grid has to ensure that the voltage and current levels are within acceptable limits after the connection and that the supply security for existing consumers is maintained (Statnett, 2017).

If the capacity of the power grid is exceeded due to the connection of a RAS facility, grid investments are required to allow for connection. The grid companies are obliged to connect new production and consumption to the grid, but if grid investments are needed the cost of upgrading the grid is partly or fully paid by the consumer (Statnett, 2017). Thus, the restrictions in the distribution grid can lead to substantially higher investment costs for the aquaculture companies, and become a barrier to new construction or expansion of existing facilities. RAS facilities will in few cases have a power demand that requires new investments in the grids with higher voltage levels[5]. Yet, they could be one of several loads in an area triggering demand for upgrading the grid (Riise Strønen and Adolfsen, 2019). If so, the connection to the grid may be impossible for the RAS facility, because new grid investments at the higher voltage levels can only be made if they provide a social benefit that is greater than the social cost (Statnett, 2017).

One strategy to avoid grid capacity problems is to locate the new RAS facilities in areas with more electricity generation capacity than transmission capacity. This could, for instance, be close to small hydropower plants[6]. Small hydropower plants are defined as plants with a generation capacity less than 10 MW (Kittelsen et al., 2006), and could therefore in many cases be sufficient to cover the power demand of future RAS facilities. Nevertheless, several requirements have to be fulfilled (Kittelsen et al., 2006). First, the hydropower plant has to be located close to the shore. Secondly, an alternative water source has to be available in case of disruption in electricity production. Thirdly, water quality has to be sufficient. Lastly, the water source temperature has to be sufficient to avoid high heating costs. For many hydropower plants, the water reservoir is located in the mountains above the generation stations, which can lead to lower temperatures than beneficial for a RAS facility. In some cases, this has been solved by using the cooling water from the generators in the hydropower station (Kittelsen et al., 2006; Badiola et al., 2018). At one RAS research facility in Norway, a temperature gain of 6-10 °C, compared to the water source temperature, was gained by using the cooling water from a hydropower station (Kittelsen et al., 2006).

On the regional level, the regions in the north (Finnmark, Troms and Nordland) are expected to have

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[4] In theory, RAS facilities can also be place in-land if suitable water sources are available. However, most RAS facilities built so far are located along the coast in order to take advantage of the current infrastructure (Hilmarsen et al., 2018)

[5] Transmission grid and regional grid

[6] Småkraftverk

an electricity surplus and limited transmission capacity to contiguous regions (Statnett, 2019b). Especially, the grid along the coast in southern and northern Nordland has available capacity for additional consumption (THEMA consulting group, 2017). Additionally, the electricity prices are expected to be lower than in the southern regions (Statnett, 2019b; Bartnes et al., 2018). Moreover, along the coast in Northern Trøndelag several land-based wind farms are recently constructed or under construction. As a consequence, large investments are made in the local distribution grids that increases the capacity (Statnett, 2019b). Moreover, the region will have a surplus of electricity when the wind turbines are producing. On the other hand, the grid in southern Trøndelag and Møre has a very limited capacity for new consumption (Statnett, 2019b), which is a challenge for land-based aquaculture projects in the region already today (Riise Strønen and Adolfsen, 2019).

In addition to the co-location of land-based aquaculture facilities and hydropower plants, the co-location with other types of industries that can provide waste heat could reduce energy consumption and the barrier of transmission capacity. However, as the water use and heat demand are fairly low in RAS, the potential reduction in energy consumption is limited. The use of waste heat will also have a lower economic benefit than for FTS (Evjemo and Sunde, 2019). Furthermore, the production of renewable energy on-site can reduce the dependency on transmission capacity in the grid. Biogas production based on the sludge produced and photovoltaic panels are solutions for on-site energy generation that have gained interest in Norway. One of the largest, recently constructed RAS facilities plan to install photovoltaic panels (Berge, 2017). This can potentially cover up to 8% of the yearly electricity use [7]. Production and utilisation of biogas can cover up to 12% of the total energy use on-site (Yogev et al., 2017). Still, these solutions can only cover a share of the total energy demand and will provide power only intermittently. Combined with a storage solution, the power demand can be reduced, but a grid connection is still highly required to secure power supply.

4.7 Uncertainty and limitations

Several factors contribute to uncertainty, both in the analysis of current and future energy use. In the following section, uncertainty and data gaps are described and discussed.

Current energy use

In this study, the current energy use in RAS in Norway has been evaluated based on data collected from commercial RAS facilities. Hence, the energy use presented is based on empirical data from several systems, contrary to preceding studies that have assessed the energy demand of a single RAS, often using data from a pilot-scale system (Badiola et al., 2017; d'Orbcastel et al., 2009b) or a model (Colt et al., 2008; Liu et al., 2016). By using empirical data, the results presented reflect the *actual* energy use in RAS in Norway, and one could argue that the uncertainty is lower compared to previous studies. The collection of data from a range of commercial RAS, also allows for establishing a precise LCI. As the data collected represents 40% of the smolt production in RAS in Norway, the LCI provides accurate values for the current production. This can reduce the uncertainty regarding the land-based production phase in LCAs of the Norwegian salmon farming industry. However, the collected data are still subject to uncertainty. First, some of the facilities could only supply data from a different time period than the year of 2018. Second, the reported energy use may include different processes at different facilities, even though the consistency of system boundaries was emphasised during the data collection process. Third, different start weights can be a cause of inconsistent data reporting, and it is not clear if all data providers included the hatchery in the energy use reported. Lastly, it was identified that energy use in a few cases included energy use for the construction of a new department, that could not be disaggregated from the total.

The indicator chosen for describing energy efficiency was the specific energy consumption. Using SEC as an indicator is beneficial to compare the results with previous studies, develop values for LCA, and make future projections for energy use in RAS. On the other hand, the use of SEC as an indicator for

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[7] Assuming a yearly production capacity of 100-170 kWh/m^2 in Norway (Norsk solenergiforening, n.d.)

energy efficiency in RAS is also a weakness, as the indicator is influenced by a range of parameters. This was handled by evaluating SEC in relation to other factors, such as production intensity and smolt weight. Nevertheless, no indicator was developed that would "correct" for the such parameters. This implies, for instance, that if two systems have the same energy use and volume, the facility with the highest production intensity will be considered more energy efficient, due to a lower SEC. Consequently, it was difficult to evaluate the actual energy efficiency of the system design and different technical solutions alone.

Based on the data collected from some of the facilities, the distribution of energy use in RAS was determined. For some of the processes, hourly power consumption data were available and obtained from an energy monitoring system. For other processes, especially the water treatment processes, only the installed and predicted operating power was available. The predicted operating power is subject to uncertainty, and the data providers underlined the importance of the parameter values (concurrency, utilisation factor and power factor) assumed. Thus, the actual distribution of energy use may deviate from the shares obtained. Nonetheless, the shares of the main water treatment processes could be checked against the data on hourly power consumption from other facilities, which reduces uncertainty. Ideally, data on hourly power consumption would be available for all components and a distribution could be compiled based on this.

Regarding the estimated energy efficiency potential, both the savings potential, as well as the relevancy of some individual measures contribute to uncertainty. The relevancy of different measures was to some degree established based on insight into planned energy efficiency measures reported to Enova by RAS facilities, but several assumptions were additionally needed. Thus, the estimated energy efficiency potential in the industry can only be considered as a rough estimate. The savings potential of introducing energy management, recovering heat from ventilation air and sludge drying, and reducing the pressure of the recirculation pump are regarded most uncertain. It is assumed that the introduction of energy management is a relevant measure for all facilities and that this could reduce energy use by 2-10%. Some of the facilities data have been collected from, have already introduced energy management into their organisations, and the reduction potential may be lower. Still, there seems to be remaining potential for energy efficiency as few of the RAS facilities work with energy management in a structured way. Nevertheless, it is uncertain whether savings of 2-10% are achievable. The saving potential for heat recovery from ventilation air is estimated based on limited, uncertain data from a pilot system in Northern Norway. Different system parameters, such as outside temperature, have not been accounted for and contribute to uncertainty. Moreover, the energy efficiency measures for the ventilation systems were assumed applicable to all facilities, following the argument by Gehlert et al. (2018) that energy efficiency of the ventilation systems up until now has been out of focus in RAS, but this argument is not necessarily valid for all facilities. The energy savings of installing a heat recovery unit to the sludge dryer are uncertain, due to the uncertainty of the contribution of the drying process to the overall energy use. Finally, the savings potential of reducing pump pressure is subject to uncertainty. This is mainly because it is unsure to which degree the different facilities can reduce the pump pressure without compromising water quality.

Energy model and future energy use

During the development of the energy model, a range of assumptions have been made, based on literature and data from industry. Compared to the first draft of the model developed in the project thesis work, the uncertainty is now greatly reduced as the model is validated and modified using empirical data. However, the model is only validated against RAS producing smolt and post-smolt, and the uncertainty for the simulated energy use for salmon grow-out is still considerable. The flow rate requirement, cooling/heating demand and energy use for CO_2 degassing are important factors contributing to uncertainty when the energy model is used to simulate salmon grow-out in RAS. As discussed in the section on sensitivity, the assumptions for stocking density, growth rate, HRT and the number of departments are also key factors for the resulting SEC.

A limitation of the current energy model is that water quality is not included, which implies that the energy use is not adjusted according to the observed water quality in the system. In theory, including mass balances and water quality in the model would allow for adjusting the water treatment flow rate in relation to the observed water quality. This has not been prioritised, as industrial actors have argued that the water treatment flow rate is not necessarily adjusted to the water quality because a certain flux is required for trimming the fish and settling of faeces etc. Moreover, only sludge filtering and dewatering are included in the model, and the eventual drying of the sludge is not accounted for. Varying values for the energy use of different drying solutions made it difficult to establish a solid estimate for energy use of the process. Lastly, an important assumption is that the departments for salmon grow-out have the same outline as a system for post-smolt production. However, some RAS for salmon grow-out have a considerably different design, which may result in a very different energy use.

As a result of the uncertain energy demand estimates for production of large post-smolt and salmon in RAS, and the inevitable uncertainty of projections for future production in RAS, the scenarios for future energy demand need to be considered with caution. It is highly uncertain whether the scenarios for biomass production in RAS will be realised, and the projections should be interpreted as "what-if" scenarios. This is especially the case for the projections for salmon grow-out to market-size in RAS, as it is possible that production will be located closer to the large markets rather than in Norway. Furthermore, it should be highlighted that the estimated future energy demand refers to recirculating systems that are optimally designed and operated with respect to energy efficiency. As seen for the current energy use for smolt production in RAS, it is possible that the future energy demand will deviate greatly from the estimates. Additionally, this study has based the projections for future energy use on the current technical design of RAS facilities, and future technical development in RAS is not considered.

The analysis of future GHG emissions associated with the energy use in RAS is undoubtedly very uncertain, as both the cumulative energy demand and the GHG emission intensity of the future marginal electricity mix yield high uncertainty. Moreover, the analysis of GHG emissions only includes direct emissions of energy use (which equals zero as only electricity is used) and the indirect emissions associated with the purchased electricity. However, a full assessment of GHG emissions for post-smolt production or salmon grow-out in RAS should also consider indirect emissions in the whole value chain. This is especially important in the Norwegian context, as the GHG emissions associated with energy use are known to only account for a minor share of the total carbon footprint. Additionally, the changes in production strategy towards land-based aquaculture production will clearly influence the energy use and GHG emissions of the seawater production phase as well. Hence, the implications of land-based production for energy use and GHG emissions in the Norwegian salmon farming industry, as a whole, should also be considered.

4.8 Recommendations and future work

This study has shown that the current energy use in Norwegian RAS facilities is in average twice as high as previous estimates. If the biomass production capacity is optimally utilised and currently available energy efficiency measures are implemented, the energy use can be lowered to the level of estimates by the industry and the energy model developed. The industry should address this energy efficiency gap, and improving the current monitoring of energy use in RAS is a natural starting point. Today, data on power consumption are in many facilities only available for each department or the total plant. Even though frequency controllers that measure power consumption are installed to a large share of the equipment in RAS, the data are seldom logged in the monitoring system. Increasing the resolution of and structuring energy data, would be beneficial both for prioritizing energy efficiency measures at the plant level and for further research regarding energy use in RAS. If data on energy consumption are available for each component in RAS, future work should compare the energy use of individual processes in different plants to identify the most energy efficient solutions.

Improving the monitoring and reporting of energy in RAS could also reduce the uncertainty in the reported energy use. As well as a lack of a standard for energy reporting, the age of the facility, system design, location and the production intensity can explain the variable energy use observed in RAS facilities in Norway. Future work should evaluate the reasons for variations in energy demand in further detail, for instance by more in-depth interviews concerning the current design and operation. This could allow for a better understanding of best practices for energy efficient design and operation.

The main energy consuming units in RAS are the main recirculation pumps, oxygenation units, heating system and CO_2 degassers. In systems with a fossil-based heating system the installation of a heat pump is essential for reducing energy use. In all systems, the correct dimensioning of pumps and the selection of oxygenation solution in the design phase is important for energy efficiency. To ensure that systems are energy efficiently designed, the introduction of life cycle cost considerations in the investment process would be an effective measure. Furthermore, the thermal treatment of sludge increases energy use considerably, and energy efficient solutions for drying and potential heat integration with other processes should be an important area of focus. In general, an increased focus on energy efficiency in RAS is necessary, as a clear energy efficiency gap exists. There is also a need to further examine to which degree the energy efficiency measures considered in this study are implemented in existing facilities, and eventually the reasons why they are not integrated yet.

An important output of this study is the energy model developed. This model can be used as an efficient tool to calculate expected energy use and quantify the savings potential of energy efficiency measures. A model for energy use is especially useful because carrying out experiments at full or pilot-scale is expensive, and in some cases impossible. However, the model needs to be validated against data on energy use in RAS for salmon grow-out. During this study, it was attempted to gather energy use data also from RAS for salmon grow-out, but due to the few facilities in operation and the limited time frame, data were not obtained. Therefore, the data collection process should be repeated in future work to validate the model against RAS facilities producing salmon instead of smolt.

The modeling of the energy use for the degassing process, as well as the heating/cooling system in case of salmon grow-out should also be improved in further work. The modeling of the heating/cooling system is rather simplistic, and the different units are not modeled in detail. The energy use for degassing is currently based on observed energy use in RAS producing post-smolt, but the changes to the energy demand of the process if the fish is larger should be examined. Moreover, only sludge treatment until a DM content of 25-30% is considered, as the data available for the energy use in the drying process were found to be highly varying. A monitoring of energy use has been initiated at one of the RAS facilities with a dryer installed, but due to technical problems measurements were not ready before the delivery of this thesis report. This data will reflect the actual energy use for sludge drying in relation to the feed load in the system, and can be checked against the energy use data for sludge drying already obtained from another RAS (Figure 28 in Appendix C). Based on this, the energy use for sludge drying can be implemented into the model.

The model is also useful as a starting point for evaluating the energy use in RAS in other locations than in Norway. This study is limited to energy use in RAS for salmon smolt and grow-out in Norway but the growth in land-based aquaculture is by many anticipated to occur closer to the markets. It is therefore relevant to use the model to compare the energy use in RAS in different locations, as design and water temperatures in many cases are different. If the model is further developed to better include water quality, the effect of the water quality in different locations could also be addressed.

The analysis of future biomass production and energy use demonstrates that the energy consumption of the industry may increase considerably if production of large post-smolt or salmon grow-out takes place in RAS. Additionally, the electricity costs are found to be more important for the total production cost when large post-smolt or salmon is produced instead of smolt. This implies that the energy use in RAS facilities will be more important for the industry in future, compared to today. As the electricity surplus in Norway is anticipated to increase towards 2030, the total energy supply required for production in RAS may not necessarily become a major constraint for future land-based production. However, the transmission capacity of the power grid is already today identified as a barrier for establishing new RAS facilities. To reduce the problem of grid transmission capacity and avoid additional costs for grid connection, co-location with (small) hydropower plans and industries supplying waste heat, and on-site production of renewable energy are possible solutions. It will also be essential to consider the energy demand and the local electricity grid next to the available area and water sources when the locations of new RAS facilities are determined. Future work should identify locations that can provide sufficient area, suitable water sources, and a surplus of nearby electricity generation with transmission constraints out of the area. An examination of the potential to reduce power consumption by on-site energy production, with a focus on storage possibilities and economic costs, will also be beneficial.

5 Conclusions

This study has evaluated the energy demand for the production of Atlantic salmon in RAS in Norway, both for smolt, post-smolt and salmon grow-out. The current energy demand for smolt production in RAS has been assessed based on data from operating RAS facilities in Norway. By comparing the observed energy use to previous estimates, the current energy efficiency gap in the sector is determined, and measures for reducing energy use are suggested. In future, post-smolt production or salmon grow-out in RAS are foreseen as likely production strategies. To evaluate the future energy demand in RAS, a model has been developed and applied to simulate energy use. Based on the estimated energy demand for post-smolt production and salmon grow-out, the total energy use is addressed under different scenarios for future production in RAS. As a result, this study provides empirical data on the current energy use for smolt and post-smolt production in RAS, as well as valuable insight into the total energy requirement for future production in RAS in Norway.

The current energy use in Norwegian RAS facilities, producing smolt and post-smolt, ranges from 5.1 to 12.8 kWh per kg live-weight smolt, with a mean value of 8.8 kWh/kg. The main energy consuming units are the recirculation pumps, oxygenation units, the heat pump and CO_2 degasser. If sludge is treated to a high DM content, energy use for drying also stands for a considerable share of the overall energy use. Previous estimates for smolt and post-smolt production in RAS are ranging from 3 to 5 kWh/kg. Hence, the current energy use is twice as high as anticipated, and the operating RAS facilities in Norway have a clear potential for improving energy efficiency. Optimising biomass production and introducing energy management are crucial measures for all facilities. Moreover, the replacement of boilers with heat pumps is an essential measure for plants that still have a fossil-based heating system. The implementation of currently available energy efficiency measures, can in average reduce the specific energy consumption by 30%. Additionally, if biomass production is optimised, the energy use can be lowered to the level of previous estimates.

Based on the data collected from operating RAS facilities, the energy model previously developed was validated and modified. The model was then applied to simulate a RAS for post-smolt production and salmon grow-out. The energy demand is estimated to 2.9 to 4.1 kWh/kg for post-smolt of 0.5 kg, and 3.4 to 5.4 kWh/kg for post-smolt of 1 kg. The specific energy consumption for post-smolt of 1.5 kg is estimated to 4.6-7.6 kWh/kg, and the estimate for salmon grow-out in RAS is 6 to 10 kWh/kg. The estimated energy use refers to systems that are optimally designed and operated considering energy efficiency. As seen for the current energy use for smolt production in RAS, the future energy demand may deviate greatly from the estimates if the energy efficiency is not improved. The estimates for energy use are also subject to uncertainty due to many underlying assumptions, especially the assumed stocking density, growth rate, water treatment flow rate and the number of gradings.

In light of the foreseen changes in production strategies in the Norwegian salmon farming industry, different scenarios for biomass production in RAS were generated and the total energy demand was evaluated. If the smolt production stays equal to today's production of 375 million, but the average weight increases to 0.5 kg, the total energy use in RAS will be 0.6 TWh. If post-smolt with a weight of 1.5 kg is produced instead, the resulting energy demand is 3.3 TWh. A production volume of market-sized salmon in RAS equal to today's production in sea, would lead to an annual energy demand of 10.2 TWh. The transmission capacity of the electricity grid seems likely to become a larger barrier for production growth in RAS than the total electricity required. To reduce this problem, the capacity of the existing grid should be accounted for when choosing locations for new RAS facilities. Areas with a higher electricity generation than transmission capacity are suitable, for instance close to small hydropower plants. The co-location with other industry, that can provide waste heat could also be beneficial. Furthermore, the production of renewable energy on-site can reduce the dependency on transmission capacity in the grid. Biogas production from sludge and the installation of photovoltaic panels are two attainable options.

To summarize, an extension of the land-based production phase can allow for production growth, and at the same time realise several of the environmental sustainability goals defined by the Norwegian salmon farming industry: control of sea lice and fish escapes, reduced discharge of nutrient salts and sludge, and reduced use of fossil fuels. On the other hand, this study has shown that future production in RAS may lead to a substantial energy demand. The projections for future energy use made in this study, based on the proposed model, do assume that the RAS facilities are energy efficiently operated and designed. However, the collected empirical data on energy use from Norwegian RAS facilities show that the current energy use is higher than anticipated, and there is a considerable energy efficiency potential. This study demonstrates that an increased focus on energy efficiency is required for RAS facilities in Norway to avoid a situation where high energy use, power grid restrictions and associated costs become a barrier for future growth in land-based aquaculture.

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A List of contacts

Ivan Alstad	Salmar	Supplied data
Robert Husby	Salmar	Guided visit and supplied
Øyvind Haraldseid	Bremnes Seashore	Discussion about RAS design, operation and supplied data
Anne Brith Haakull	Bremnes Seashore	Supplied data
Svein Tore Veim	Helgevold elektro	Supplied data
Simen Langeteig	Lerøy	Discussion about RAS design, operation and supplied data
Stian Amble	Nova Sea	Supplied data
Werner Storøy	Nova Sea	Discussion about RAS design, operation and supplied data
Jostein Iversen	Grieg Seafood	Supplied data
Signe Jordal	MOWI	Supplied data
Atle Jørsang	Grieg Seafood	Supplied data
Per Jørgen Haugan	Nordland Akva	Supplied data
Karoline Holen	MOWI	Supplied data
John-Ivar Sætre	MOWI	Supplied data
Per Tore Rekkedal	MOWI	Supplied data
Tore Evjen	NRS	Discussion about RAS design, operation and supplied data
André Spigseth	Morefish	Supplied data
Håvard Ramsfjell	Morefish	General discussion about study design and supplied a production planning tool
Øyvind Prestvik	Salsnes Filter	General discussion about study design and results. Supplied data for sludge treatment
Øyvind Hilmarsen	Sintef Nord	General discussion
Kari Attramadal	Nofitech	General discussion about study design and input on RAS operation and fish biology
Kenneth Glomseth	AGA	Discussion about oxygenation in RAS and supplied technical information
Asbjørn Husby	Xylem	Discussion about pumping in RAS and supplied technical information

B Estimation of savings potential for energy efficiency measures

B.0.1 Reducing pump operating pressure

A suggested energy efficiency measure is to reduce the operating pressure of the recirculation pumps. The related energy savings are calculated in this section. Affinity laws for pumps:

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \tag{B.1}$$

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 \tag{B.2}$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \tag{B.3}$$

where
Q is volumetric flow rate
H is the pressure
P is the pump power
N is the shaft rotational speed, controlled by the VFD
The water treatment flow rate is related to the HRT:

$$Q = \frac{V}{HRT} \tag{B.4}$$

where
V is the tank volume
HRT is the hydraulic retention time
One of the reports on energy efficiency measures reported to Enova, suggest that the pump pressure can be reduced from 0.2 bar to 0.18 bar. This yields:

$$\frac{N_1}{N_2} = \sqrt{\frac{0.18}{0.2}} = 0.949 \tag{B.5}$$

Using B.4 and B.1 the HRT is increased by 5% and the water treatment flow rate is reduced equally. Power consumption is reduced by 15%. If the pressure is reduced by 5%, water treatment flow rate is decreased by 2.5% and power consumption by 7.4%. The energy savings from a reduction in pump pressure is illustrated in Figure

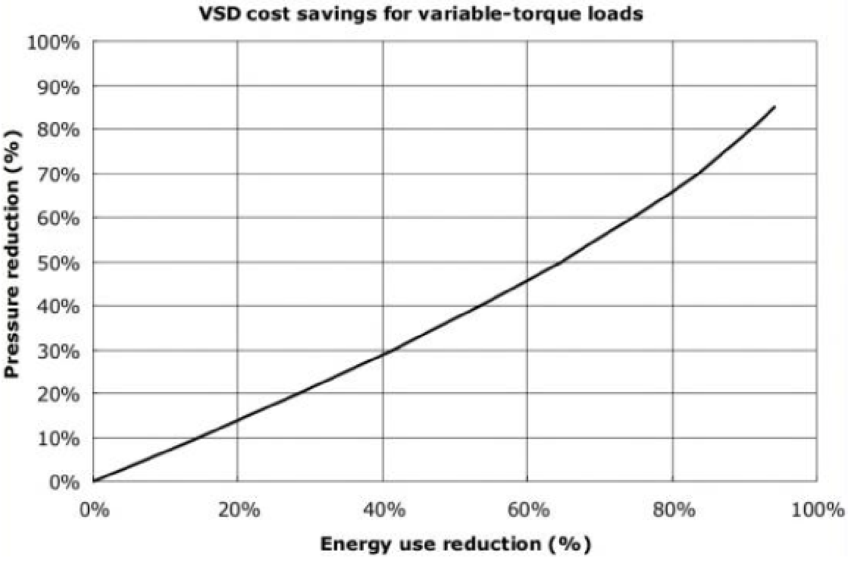

Figure 26: Pump energy use reduction in relation to pressure reduction. Figure from Kent (2018).

B.0.2 Replacing oil boiler with heat pump and installing heat recovery

Replacing the oil boiler with a heat pump and a system of heat exchangers can yield considerable savings as shown by the following calculations: The heating demand of the system where an oil boiler is installed is given by equation B.6.

$$Q_{demand} = \eta * E_{boiler} \tag{B.6}$$

where
η is the efficiency of the system - assumed to be 85%
E_{boiler} is the energy delivered by the diesel/oil

The energy delivered by the heat pump is given by equation B.7

$$E_{HP} = \frac{Q_{demand}}{COP} \tag{B.7}$$

Combining B.6 and B.7, the energy savings of the heating system can be calculated.

$$\triangle E = \frac{E_{boiler} - \frac{\eta * E_{boiler}}{COP}}{E_{boiler}} = \left(1 - \frac{\eta}{COP}\right) \tag{B.8}$$

Assuming a COP of 3 for a water-to-water heat pump and an oil boiler efficiency of 85% yields a 72% reduction in energy demand for heating. The heating/cooling system in a smolt facility can reach 10, if heat exchangers are installed in addition to the heat pump. This increases the saving potential to 92%.

B.0.3 Heat recovery of ventilation air

The energy savings based on recovery on ventilation air is a potential measure for energy efficiency. The estimates for achievable savings are calculated based on data from a pilot project at Innhavet RAS. Direct thermal energy savings from installing ventilation recovery unit at Innhavet RAS (Nordlaks) is 3300 MWh (Enova, 2019b).

$Q_{savings}$ = 3300 MWh

Data on energy use of the RAS at Innhavet from Sundseth et al. (2017):

Thermal energy demand Q = 51665 MWh
Electricity demand for heating $E_{heating}$ = 5083 MWh

Electricity demand for other processes $E_{process}$ = 8760 MWh

This yields a 6% reduction in thermal heat demand and equally a 6% reduction in electricity use for heating:

$$COP = \frac{Q}{E_{heating}} = \frac{51665MWh}{5083MWh} = 10 \tag{B.9}$$

$$\triangle E_{heating} = \triangle Q = \frac{Q_{savings}}{Q} = \frac{3200MWh}{51665MWh} = 6\% \tag{B.10}$$

This yields a 2% reduction in total energy use:

$$\triangle E = \frac{\frac{Q_{savings}}{COP}}{E_{process} + E_{heating}} = \frac{\frac{3300MWh}{10}}{5083MWh + 8760MWh} = 2\% \tag{B.11}$$

B.0.4 Oxygenation

The power consumption relative to water treatment flow rate shown in Figure 27 has been used to calculate the possible energy savings of applying a deepshaft cone or LHO unit. The data is obtained from a RAS facility, as well as by personal communication with AGA, a supplier of oxygenation units.

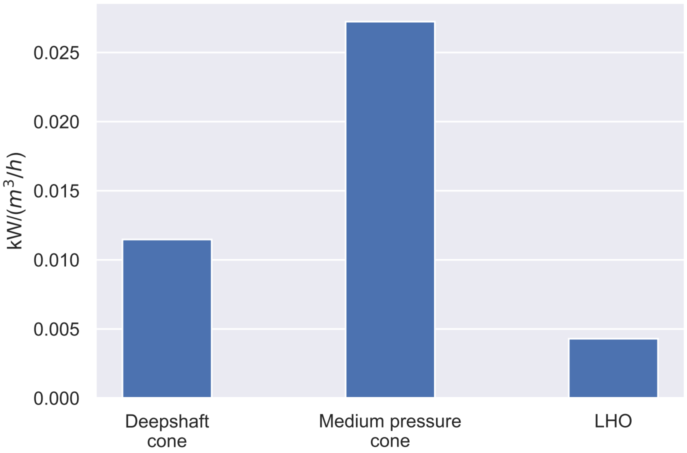

Figure 27: Power consumption of different oxygenation solutions relative to water treatment flowrate.

B.0.5 Increased biomass production

The data used to assess the change in energy use with respect to a change in load factor are shown in Table 8.

Table 8: Data on change in energy use related to change in LF. Relative change yields the relative change in energy use when LF is increased by 1%.

		RAS 1	**RAS 8**	**RAS 14**
LF	Year 1	0.60	0.18	0.33
	Year 2	0.76	0.65	0.35
Energy	Year 1	6823	2547	3555
	Year 2	7713	5808	3697
Relative change	LF	0.27	2.60	0.06
	Energy use	0.13	1.28	0.04
	Total	0.48	0.49	0.71

C Data for current energy use

Overview of collected data

Table 9: Overview of data collected from different RAS facilities

RAS plant	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Energy data														
Yearly energy use	x	x	x	x	x	x	x	x		x	x			
Quarterly energy use					x	x								
Monthly energy use		x								x				
Daily power consumption	x							x				x	x	x
Daily power consumption, disaggregated by process								x				x	x	x
List of installed water treatment units and installed power	x	x												
List of all energy consuming units and installed power	x	x							x					
Fossil fuel use						x	x							x
Biomass and water data														
Yearly biomass production	x			x	x	x	x	x		x	x			
Quarterly/monthly biomass production					x	x				x				
Feed	x	x								x				
O2 consumption								x				x	x	x
Water consumption	x	x			x	x	x	x		x	x			
Water quality and departments	x	x	x	x	x	x	x	x	x		x			

Data used to determine the distribution of energy use

The installed and predicted normal operating power was supplied by RAS 1 and RAS 2. For RAS 1 the normal operating power is calculated according to the formula:

$$P_{avg} = P_{installed} * \text{numer of units in use} * \frac{\text{concurrency} * \text{utilization factor}}{\eta * cos(\phi)} \tag{C.1}$$

where

- Concurrency: 0.8
- Utilization factor: 0.8
- η*$cos(\phi)$: 0.833

This implies that the normal operating power relative to the installed power of all units is assumed to equal 76.8%. Additionally, the number of units typically in operation for each process is accounted for,

For RAS 2 the share of normal to installed power was provided without specifying the assumptions. Table 10 displays the share of normal power consumption to installed power for each unit.

Table 10: Share of normal power consumption to installed power (in %) of different units.

Category	Subcategory	RAS 1	RAS 2
Water treatment	mechanical filtration	44.9	31.2
	biological filtration	47.7	25
	pumps	52.6	60
	degassing	76.8	70
	oxygenation	62.8	86.7
	control system	76.8	100
	lights	76.8	100
	feeder	76.8	100
	PH regulation	76.8	62.9
	ozonation		60
	UV		50
Energy and intake water	UV	54.6	
	intake water pumps	57.6	60
	heat pump	76.8	70
	other	76.8	75.7
Building and ventilation	ventilation	75.5	100
	heating	76.8	50
	lightning	76.8	75.4
	other	64.8	31.9
Supporting functions	oxygen production	76.8	
	ozone production		50
	sludge treatment	76.8	50

Table 11: Relative contribution of processes to overall energy use.

Process	RAS 1	RAS 2	RAS 8	RAS 12	RAS Supplier	Average
Water treatment	58%	43%	74%	60%	60%	60%
Energy and intake water	13%	23%				15%
Heat pump	6%	21%	9%	8%		
Intake water pumps	3%		3%	3%		
Building and ventilation	14%	12%		5%	15%	10%
Supporting functions	16%	22%				15%

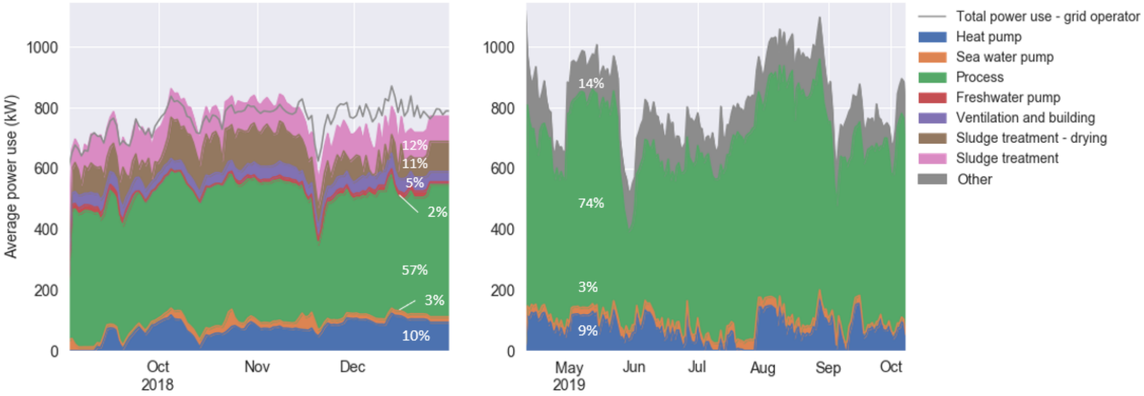

Figure 28: Daily average power consumption by subprocesses for two operating RAS facilities. RAS 12 to the left and RAS 8 to the right.

D Additional results current energy use

Energy use in relation to HRT, water temperature and load factor

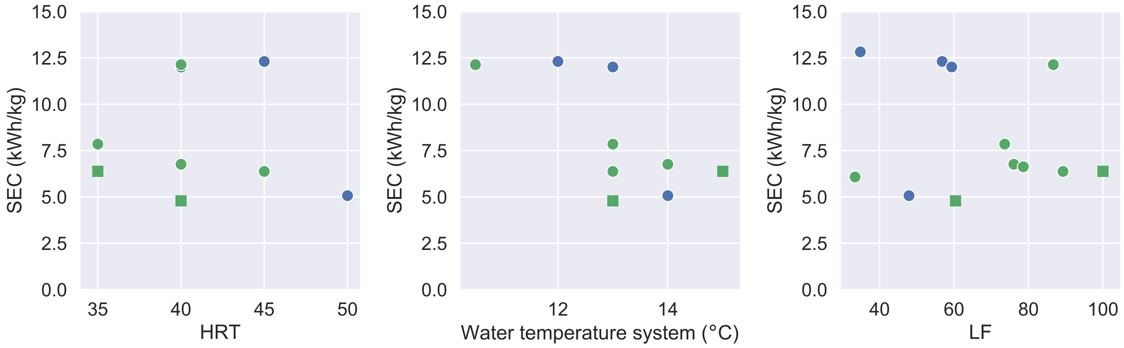

Figure 29: Energy use in relation to HRT, water temperature and load factor. The lower number of data points is due to the fact that not all facilities supplied data on temperature and HRT. The squares are facilities were only estimates for energy use were available. Blue indicates facilities using diesel for heating, while green indicates facilities with heat pumps installed.

Energy use for facilities with and without oxygen production and sludge treatment

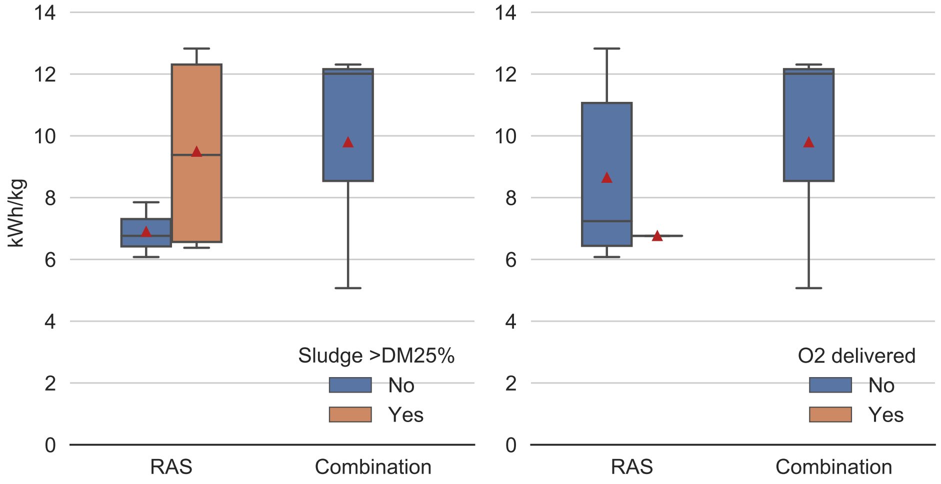

Figure 30: Specific energy consumption for plants with different practice for oxygen production and sludge treatment.

E LCI

Table 12 includes the numerical values for the LCI, based on the weighted average of RAS facilities.

Table 13 includes the numerical LCI values, based on the weighted average of *all* facilities data have been collected from. Figure 31 displays the LCI values for the average of all facilities, including the Combination facilities. While the values for feed and oxygen consumption are similar as for RAS facilities, the land use requirement and water demand is considerably higher. The energy use is slightly higher than for RAS facilities.

Table 12: Inputs required for production of 1 kg smolt in RAS.

	Weighted average	Unit	Min	Max	No. of facilities
Electricity	7.09	kWh	6.08	12.14	6
Diesel	0	kWh		6	
Land use	0.022	m^2	0.001	0.041	4
Feed	0.95	kg			1
Oxygen	0.53	kg			1
Water use	1241	L	186	2746	6

Table 13: Inputs required for production of 1 kg smolt in RAS and Combination facilities in Norway.

	Weighted average	Unit	Min	Max	No. of facilities
Electricity	7.39	kWh	4.17	12.14	10
Diesel	0.03	kWh	0	3.7	10
Land use	0.029	m^2	0.001	0.071	7
Feed	0.97	kg	0.95	0.99	2
Oxygen	0.62	kg	0.53	0.77	2
Water use	1263	L	186	3276	10

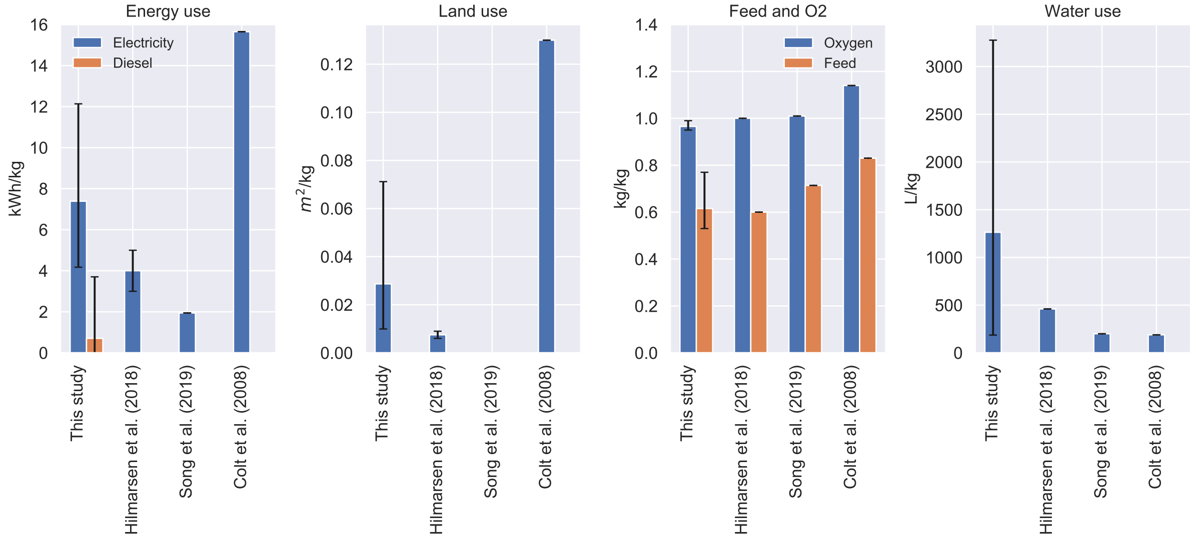

Figure 31: LCI values based on collected data from *all* facilities in comparison to previous studies considering salmon smolt production. The bars show the average LCI value, while the whiskers refer to the minimum and maximum values.

F Changes to the energy model

Table 14: Detailed description of the modifications made to the energy model.

Heat pump	The COP is adjusted to 12, to account for the heat gain from heat exchangers.
Oxygenation	For the departments before the post-smolt department an low-head oxygenation cone, oxygenating 15% of the flow is assumed used. The modeling of the energy use is described in the project thesis. In the post-smolt departments a LHO is modeled, as previously.
UV	The applied UV dose was set to 150 MJ/cm^2, as a safety factor was assumed. The RAS facilities visited operate with a UV dose of about 30 MJ/cm^2 and the safety factor is therefore omitted. The dose applied may however vary across facilities. The power consumption is calculated as a function of water flow and is based on data from three UV suppliers. The data is described in the project thesis' appendix.
Tank dimensions	The dimensions of the tanks in the pre-smolt and smolt departments had to be determined. The tanks in the pre-smolt department have a diameter of 9 m, and the ratio between diameter and height is 2.6. The tanks in the post-smolt department is 14 m and the ratio is set to 3.6 (Summerfelt et al., 2016).
Pump head	The height of the tanks and the height of the degasser is the static head the main pumps have to overcome. In addition 12.5% of the tank height is added as friction losses in the pipe system as assumed previously.
Lights and automatic feeder in fish tanks	The power consumption of the automatic feeder within the tanks is adjusted from 0.04 to 0.12 kW per tank, based on data collected. The power consumption for tank lightning is adjusted from 1 to 0.8 kW for the smallest tank and from 2 kW to 1.5 kW for the larger tanks.
Building and lightning	The energy demand for building heating is calculated based on the specific energy demand for heating in office buildings and light industry reported by Langseth (2016). Energy for lightning is added to the model, and specific energy demand is also taken from Langseth (2016). Specific energy demand is 70 kWh/m^2 and 35 kWh/m^2 for heating and lightning respectively. The building area is divided into fish department area, water treatment area, and office buildings. The fish department area is the squared tank diameter, and 35% of this area is added for office buildings and water treatment (Olsen, 2012). Heating is assumed required in the water treatment area and the office buildings, while lightning is required in all three zones.
Degasser	The power consumption of the vacuum fans for the degasser is based on the collected data from three RAS facilities. The average power consumption is 0.0046 $kW/(m^3/h)$, with a standard deviation of 0.0011 $kW/(m^3/h)$.
Sludge treatment	The energy use for filtering and dewatering is included in the model, meaning that sludge is assumed treated to a DM content of 25-30%. The energy use is based on data from a supplier of belt filters (Ø Prestvik 2019, pers.comm.), and the energy consumption is 0.035 kWh per kg feed.
Supporting functions	The energy use for various other supporting functions not explicitly modeled is assumed to account for 15% of the total energy use, as shown in Section 4.1.2.
Changes to growth and substance production model	The CO_2 production estimated was lower than expected, especially for post-smolt. Instead of scaling the CO_2 production by the feed load, the respiratory quotient (RQ) is used. RQ defines CO_2 produced to O_2 consumed. RQ is assumed equal to 0.81 (K Glomset 2018, pers.comm.).

G Future Norwegian electricity mix and costs

Marginal electricity mix, GHG emission intensity and electricity cost towards 2030

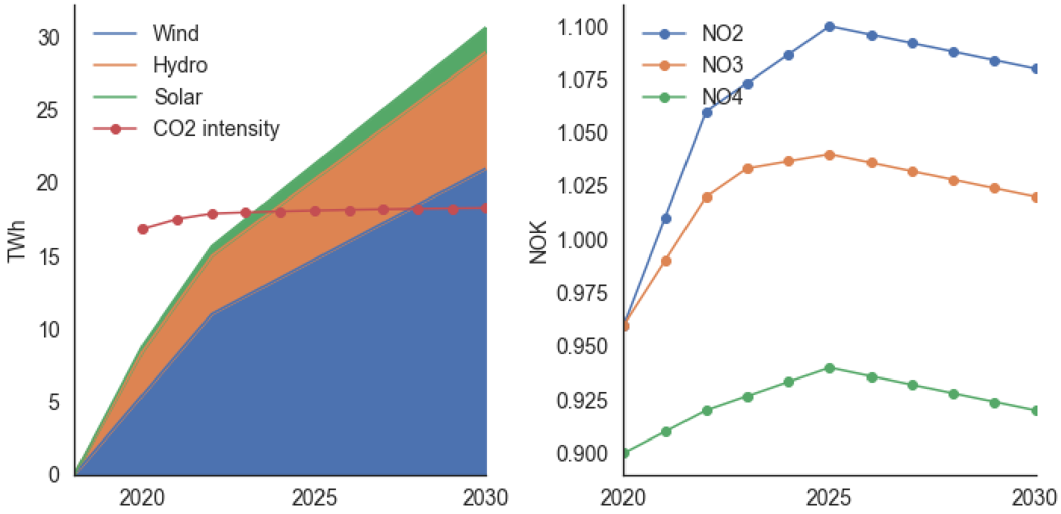

Figure 32: Projections for new electricity generation capacity in Norway between 2018 and 2030 by technology (left) and electricity cost projections (right) based on a power market analysis by NVE (Bartnes et al., 2018). GHG emission intensity is shown on the left panel in g CO_2-eq./kWh.

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