Andrea Arntzen Nistad

Energy use and efficiency in recirculating aquaculture systems

Trondheim, 12 2018

Project work

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

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NTNU – Trondheim
Norwegian University of Science and Technology

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Faculty of Engineering
Department of Energy and Process Engineering

EPT-P-2018-84

PROJECT WORK

for

Andrea Arntzen Nistad

Autumn 2018

Energy-efficient recirculating aquaculture systems (RAS)

Energieffektive resirkuleringsanlegg (RAS)

Background and objective
Recirculation aquaculture systems (RAS) are closed-containment systems used in onshore aquaculture, e.g., salmon early stage (pre-smolt) before fish are moved to ocean net-pens. Lately, post-smolt and prolonged growth in RAS is increasingly used to control fish lice problems in salmon production. In general, RAS has lower environmental impacts than comparable systems, with energy use as an exception. RAS use a lot of energy to purify and pump water, thus better energy management and energy-efficient RAS will be an important area of improvement for the sustainability of Norwegian salmon aquaculture in the future.

RAS operating today usually measure the total energy consumption, but there is limited data on energy demand in each treatment process. The objective of the project is to identify energy consumption hotspots and suggest measures for lowering energy demand.

The following tasks are to be considered:

1 Describe "state of the art" RAS and the system considered.
2 Describe factors and parameters driving energy demand in each process.
3 Estimate energy consumption in each process.
4 Analyse energy consumption and identify specific measures for increasing energy-efficiency in Norwegian recirculating aquaculture systems in future.

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The project work comprises 15 ECTS credits.

The work shall be edited as a scientific report, including a table of contents, a summary in Norwegian, conclusion, an index of literature etc. When writing the report, the candidate must emphasise a clearly arranged and well-written text. To facilitate the reading of the report, it is important that references for corresponding text, tables and figures are clearly stated both places.

By the evaluation of the work the following will be greatly emphasised: The results should be thoroughly treated, presented in clearly arranged tables and/or graphics and discussed in detail.

The candidate is responsible for keeping contact with the subject teacher and teaching supervisors.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

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Submission deadline: 21 December 2018.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department for Energy and Process Engineering, 20th Des 2018

~~NN~~
Supervisor

Co-Supervisor(s):

Abstract

A growth in the use of recirculation technology for production of smolt is seen in the Norwegian salmon industry the last 10-15 years. Flow-through hatcheries are converted to recirculating aquaculture systems (RAS), and almost all new facilities use this technology. Recently, there is an increased interest for production of larger smolt because of problems with lice and escapes in traditional open-net pen systems. Life cycle assessments show that eutrophication potential and water demand are reduced in RAS, while energy use increases. Few studies have been published on energy use in RAS, which is of increasing importance in Norway.

This study analyses drivers for energy use in RAS. A case is developed to determine main energy consuming units and potential measures for energy efficiency. The water treatment flow rate, recirculation degree, head and configuration of the heating system are identified as main drivers. The energy use for production of post-smolt from 150 to 500 g is 2.57 kWh per kilo fish, and the recirculation pump is identified as the main unit. Energy use of post-smolt production is found to increase significantly in RAS compared to open-net pens, which underlines the importance of an increased focus on energy efficiency in RAS.

Sammendrag

Det har det siste 10-15 årene vært en økende bruk av resirkuleringsteknologi for produksjon av smolt i norsk lakseoppdrett. Mange gjennomstrømingsanlegg er ombygd til resirkulerende systemer (RAS) og de fleste nye anlegg bygges som RAS. I senere tid er det sett en økende interesse for produksjon av større smolt på grunn av problemer knyttet til lus og rømning i tradisjonell oppdrett. Livssyklusanalyser av RAS viser at eutrofiering potensial og vannforbruk er redusert, mens energibruk øker. Få studier publisert ser på energibruk i RAS, som i lys av senere utvikling vil være viktigere enn tidligere.

Denne studien analyserer drivere for energibruk i RAS. I tillegg er de viktigste prosessene med tanke på energibruk og relevante tiltak for reduksjon av energibruk identifisert. Vannstrøm i vannbehandlingssløyfa, resirkuleringsgrad, løftehøyde og konfigurasjonen av varmesystemet er de viktigste driverne for energibruk. Energibruk for produksjon av post-smolt fra 150 til 500 g er 2.57 kWh per kilo fisk, og resirkuleringspumpen har høyest energiforbruk. Energibruk for produksjon av post-smolt vil øke kraftig i RAS sammenlignet med produksjon i åpne merder. Dette understreker viktigheten av økt fokus på energieffektivitet i RAS.

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Nomenclature

bFCR	Biological feed conversion ratio
DM	Dry matter
DMx%	Dry matter concentration
FTS	Flow-through systems
GHG	Greenhouse gas
GWP	Global warming potential
HRT	Hydraulic retention time
LCA	Life cycle assessment
LHO	Low head oxygenation unit
MBBR	Moving bed bio reactor
RAS	Recirculating aquaculture systems
SFP	Specific fan power
TAN	Total ammonium nitrogen
TSS	Total suspended solids

1 Introduction

1.1 Aquaculture growth and sustainability issues

Whereas the growth of fisheries has been fairly stable since the late 1980s, the aquaculture industry has seen a substantial growth. In 1974 it provided only 7% of fish for human consumption, while this share increased to 26% in 1994, 39% in 2004 and 47% in 2016 [1], [2]. Despite the slower growth compared to the peak by the end of the 1980s and 90s, aquaculture continues to grow faster than any other major food production sector [1]. Its share is anticipated to further increase as the use of wild fish stocks reach or exceed their sustainable limits, while aquaculture technology and management continue to improve [3]. Previously the size of the aquaculture industry was assumed to be too small to have a significant negative impact on the environment. However, together with the recent remarkable growth the environmental impacts have increased [4]. The sustainability of intensive aquaculture and its potential impacts, has been identified as a key limiting factor to growth [5]. Several sustainability issues have recently raised concern, such as production of feed ingredients, escapes from sea cages into the wild, discharge of wastes to environment and water pollution [6], [7].

In the Norwegian salmon context, salmon lice, escapes and emission of organic matter, nutrients and fish pathogens are pointed out as main environmental threats in traditional open-pen systems [8]. Salmon lice has large economic impact, and can represent a threat to wild salmon and trout [8]. The current situation concerning lice poses large challenges to the Norwegian aquaculture industry, and operations related to lice treatment increased by a factor of 1.4 from 2012 to 2017, despite only a minor increase in biomass production [9]. Escapes are considered as one of the other main threats in Norwegian aquaculture industry today, while emissions of organic matter and regional eutrophication is considered less of a concern [8]. A "traffic light" system has recently been introduced to indicate the environmental impacts of aquaculture in different Norwegian production areas [10], [11]. The last evaluation resulted in 2 out of 13 areas being red, meaning unacceptable environmental impacts, while 3 were assigned yellow, meaning moderate impacts. A reduction of production in red areas will follow if the status is unchanged in 2019 [12].

In this context, closed-contaminant aquaculture systems are gaining interest, both within Norway and internationally [13]. It is reported that production of salmon in closed land-based systems can be both economically and environmentally viable under stable conditions [7], especially if located close to markets [13]. Recirculating aquaculture systems (RAS) is an alternative closed-contaminant aquaculture technology, where a large share of water is recirculated and continuously treated contrary to other production systems where untreated water discharge into environment. This reduces water consumption and waste emissions in comparison with traditional flow-through or open net-pen system. Typically 90 to 99% of the water is reused, in contrast to flow-through systems where the same amount of water is taken in and discharged [7]. Moreover, it allows for control of the rearing environment, excludes parasites and offers flexibility with regard to location [14].

1.2 Scope of study

An increase in investment of RAS and conversion of flow-through systems to RAS is lately seen in the Norwegian salmon industry. In addition, as a consequences of significant problems with lice and escapes, several projects for land-based production of market-sized salmon are under development. Implications of these changes in production methods need to be understood. Life cycle assessments (LCA) and systemic approaches is beneficial to identify processes with large environmental impacts and potential problem shifts. LCA of RAS technology highlights reduction of eutrophication potential and water demand. On the other hand, energy use and related impacts, such as global warming potential (GWP), is significantly increased. Together with feed, energy is the most important contributor to environmental impacts associated with RAS. Moreover, it is demonstrated that energy demand is higher for larger fish [13], which is essential to keep in mind when larger smolt or even market-sized fish is produced.

To minimize environmental impacts of RAS, energy demand and/or carbon intensity of the electricity mix have to be reduced [15]. There is a need to develop new technical solutions for reduced energy demand in RAS [13]. Better energy management and energy-efficiency in RAS is important for future sustainability of the Norwegian salmon aquaculture. Knowledge of drivers for energy demand and identification of the most important energy consuming units is thus essential. Many RAS operating today usually measure the total energy consumption [16], but there is limited data on energy demand in each process.

The aim of this project is to identify drivers for energy demand and suggest measures for energy-efficiency in RAS for production of post-smolt. The following tasks are to be considered:

- Describe state-of-the-art RAS technology
- Describe drivers for energy demand
- Develop a case to identify main energy consuming processes
- Analyse energy consumption in Norwegian RAS for post-smolt and identify measures for energy-efficiency

This first section presents the current development of RAS in Norway, literature on environmental performance and energy use in RAS. The second section presents RAS technology and drivers for energy in each process. Section three presents the case study and the model for energy use. Section four presents results, and discusses modeling choices, limitations and sensitivity. In addition, relevant measures energy-efficiency are presented. Section five concludes and summarizes the main findings.

2 Theory

2.1 Development of RAS in Norway

In the Norwegian salmon industry, a growth of RAS technology used for smolt production is seen the last 10-15 years [17]. Many traditional flow-through hatcheries are converted to RAS, and most new constructions are built as RAS [17], [18]. After the Norwegian Ministry of Fisheries allowed for production of larger smolt (post-smolt) up to 1 kg in closed-containment systems in 2012, the industry has been investing in post-smolt production [19]. There is increasing interest for production of larger smolt (post-smolt), up to 100-200g or even 1 kg, which then is transferred to open net-pens [13], [20], [21]. The size of smolt has steadily increased the last years, from an average of 80 g in 2010 to 110 g in 2015 [22]. This is mainly driven by the wish to reduce retention time in ocean, which may reduce economical burdens related to mortality due to lice and environmental impacts due to operations related to lice treatment [13]. Better fish welfare and faster growth due to temperature control are additional benefits [13].

The last three years, 4.6 billion NOK was invested in RAS technology [23]. 90 RAS facilities was in operation in 2016, which constitutes 35 % of facilities for smolt production [21]. According to a recent analysis by PwC, 60 % of smolt biomass is expected to be produced in RAS within 2020. They expect that most RAS facilities will produce smolt, as investment costs are lower per fish with a lower average weight (smolt or post-smolt) than market-sized salmon [11]. Nonetheless, 12 projects for harvest-sized salmon are currently under development and Fredrikstad Seafoods' facility is under construction [13]. Aalysis done by PwC and DnB markets indicate that the development of such initiatives will depend on the ability of traditional farming to support further growth [11], [21]. The report by DnB markets point to several reasons why land-based farming based on RAS now is interesting: (1) high salmon price due to increased demand and stagnating growth in traditional farming, (2) converging costs for land-based using RAS and traditional farming due to biological challenges within traditional, technology improvement of RAS and increasing license cost for traditional farming, (3) increasing demand and focus on sustainability [21].

Other important trends related to RAS in Norway is the rapidly increasing capacity of smolt farms and larger volumes requested to technology suppliers, as a consequence of increasing focus on post-smolt and intensification of production [24]. The division between smolt and ongrowing in sea is likely to diminish in future and be replaced of phases within open and closed systems [18]. To meet the goal of 5 million tonnes of sustainable aquaculture production stated by the Norwegian government, several challenges must be overcome. Different solutions may emerge, with the whole production cycle in closed systems on land, closed systems in sea, production of large post-smolt before transfer to sea or displacement of open net-pens from fjords to ocean as potential options [18].

2.2 Life cycle assessments

LCA is a standardized method for evaluation of potential environmental impacts during the whole life cycle of a product [25], and has been applied to several aquaculture production systems for the last 15 years [26]. LCA can provide knowledge to decision-makers about the products or technologies with least impact on the environment and allow for analysis of environmental trade-offs [25]. Hence, LCA can be used as a tool to compare the environmental performance of recirculation technology to other methods of aquaculture production.

A few studies (see appendix A.1) present LCA of RAS, often in comparison to other production technologies. Different species are considered in literature, where two examine Atlantic salmon ([14], [27]). All studies presented in appendix A.1 consider only market-sized fish, except for the study by Hilmarsen et al. [13] that also present the carbon footprint of post-smolt in Norwegian RAS. Across all studies, water demand, eutrophication potential and energy use are main differences between recirculating systems and open/flow through-systems. While the two former decrease in RAS, the latter is substantially increased. Reduction in water use is the aim of applying RAS technology, and water dependency is naturally decreased due to recirculation of water. Moreover, releases of nutrient nitrogen and phosphorus are avoided in RAS through use of water treatment and collection of waste water [28], [7]. However, the water treatment units require energy for operation, and the energy use is substantial in RAS compared to other production systems. Other environmental impacts are linked to feed consumption [29], and is typically similar (if the same FCR is assumed) when comparing a flow-through system to RAS technology.

Samuel-Fitwi et al. [28] and d'Orbcastel et al. [29] did comparative LCA of different production systems for trout, and found substantially lower eutrophication potential and water dependency for RAS compared to other technologies. The eutrophication potential is reduced by 92% in comparison to a flow-through system in the analysis done by Samuel-Fitwi et al.[28], while water use is reduced by 99%. d'Orbcastel et al. [29] report 93% lower water consumption and 26-38% lower eutrophication potential. Energy consumption is increased by 24-40% in RAS compared to the flow-through system in the study by d'Orbcastel et al. [29].

The total energy use over the life-cycle stems from feed production and on-site energy use, which in total account for 91-99% of total consumption [7]. d'Orbcastel et al. [29] allocate 67% of total energy use to water treatment and 31% to feed production. As energy use is increased, related impacts such as abiotic depletion, GWP and acidification potential is substantially higher [16], [27], [28]. A comparison of RAS and flow-through systems for rainbow trout shows a three times higher acidification potential and GWP for RAS, due to large shares of fossil fuels [30].

Fish and feed production processes are the most important contributors to environmental impacts for flow-through system, while energy is most important in all impact categories for recirculating systems in the study presented by Samuel-Fitwi et al. [28]. In contrast, a carbon footprint analysis of RAS for salmon post-smolt in Norway identify feed production and transport as main contributors [13]. The reduced impact of energy in the Norwegian context is most likely due to the high share of electricity and low carbon intensity compared to other production locations. 77% of the carbon footprint is due to feed production and transport, while electricity use contribute to 11% of the total footprint. The rest is allocated to buildings, equipment, sludge treatment, oxygen production etc. Using a feed factor (eFCR) of 1 and electricity use of 3 kWh/kg fish, the resulting GWP presented is 4.1 kgCO_2/kg smolt.

The same study [13] also analyse the carbon footprint if harvest-sized salmon is produced instead of smolt in RAS. The energy use is assumed to increase to 6 kWh/kg and feed factor to 1.15. In this case electricity stands for 17% of total carbon footprint, while feed is decreased to 72%. Sludge treatment stands for 2% of the total footprint in this case, and involves drying processes in order to increase the dry matter content of the effluent process water. Hence, this also requires electricity, which can be added to the 17%. The total carbon footprint is 5.1 kg CO_2eq/kg fish. Comparing the carbon footprint of post-smolt to harvest-sized salmon one see that the relative contribution of energy use increases when larger fish is produced. Finally, the carbon footprint of a harvest-sized fish produced in RAS is 28% higher than traditional open net-pen production.

Ayer & Tyedmers [27] argues that deployment of closed-containment salmonid production represents a case of environmental problem shifting, as energy and material demand related impacts increases drastically while others are reduced. It should be noted that this conclusion is based on a comparative LCA of different production systems in Canada, where a Canadian el-mix is assumed (61 % hydro, 13 % nuclear, 26% fossil). Many studies underline the sensitivity of impacts associated with energy and its dependence on the electricity mix considered [7], [28], [27], [30]. The carbon footprint analysis done by Liu et al. [14] finds that the carbon footprint of RAS is determined by the electricity mix considered. Due to this, some of the studies so far have looked into the possibility of integrating renewable energy in recirculating production systems [28], [16].

LCA aim to do a thorough environmental assessment, considering a range of different impacts along the life cycle. However, the main environmental concerns for the aquaculture industry in Norway are lice and escapes [31], which is not captured by these analysis. Aubin et al. [30] argues that other impacts such as biodiversity depletion, which is relevant in terms of lice and escape problems, also should be included in integrative assessments of production technologies [30].

Other benefits with RAS technology not captured by LCA studies are the potential to control temperature and water quality, allowing for better control of production, better fish welfare and increased quality [32], [13]. The production of post-smolt in RAS is expected to reduce exposure to diseases and lice when placed in open net-pens [33]. Consequently, this can allow for delousing without medicament and decreased overall mortality [33]. An other aspect, is that RAS can be built closer to large markets (Asia, US), which potentially can allow for easier logistics and reduced environmental footprint [13].

2.3 Studies of energy use in RAS

Few studies focus on energy use in RAS (presented in appendix A.2). Some general suggestions for energy-efficiency are also presented in aforementioned LCA studies. Colt et al. [34] compared energy and resource consumption for production of salmon smolt of 80 g in flow-through systems and RAS. They found feed and power to be most important for greenhouse gas emissions, with power as the main driver. Direct, indirect and transportation energy is reported, and direct energy use is broken down on water supply pumps, internal hatchery use and water treatment. Energy use for water treatment is high in the recirculation system, while less is required for temperature control and water supply pumping.

d'Orbcastel et al. [35] reported energy use for water treatment and total energy use, and allocated 67% to water treatment. The study also investigated the possibility of reducing water flow without decreasing water quality, and registered that this can provide energy savings. Another study by d'Orbcastel et al. [29] broke energy use down on different units (make-up water, water treatment, oxygenation, feed and fish handling) and reported on-site and total life-cycle energy use. This study concludes that by optimizing system design and water flow rate the energy consumption can be reduced close to the level of a flow-through system.

Badiola et al. [7] presents along with the LCA of production of cod, an energy audit for a RAS located in Spain. Energy use by different units (pumps, UV, protein skimmer and heat pump) is presented, with the heat pump representing 72% of the total energy demand. Furthermore, they demonstrated fluctuations in energy demand, due to intermittent operation of the heat pump.

Summerfelt et. al [36], [37] did two different studies on energy use in partial reuse systems (87-89% recirculation degree) in USA for production of salmon smolt and rainbow trout. Power demand for different units are reported in these studies, along with hours of operation. The first study considers only a model of a system, while the latter consider an actual facility. However, this facility is fairly small and has very low stocking density compared to typical Norwegian RAS for salmon today.

The most recent study on energy use in RAS is by Badiola et al. [16]. This review article presents earlier reported values for energy use in RAS. The variation in reported total energy use in RAS is large, ranging from 2.9 kWh to 81.48 kWh per kilo fish produced. The broad range is a result of different species, recirculation degree, technical choices, grow-out size, stocking density and location [16]. The importance of location for energy use was demonstrated in a study considering salmon smolt production with same FCR in Norway and Canada, where the energy use were 4.1

and 20 kWh/kg fish respectively [38]. The values are obtained by monitoring energy use at Grieg Seafoods hatcheries in Norway and Canada, which operates at high recirculation degrees (97-99%) and with FCR of 0.9-1.1. The only other study found reporting energy use in RAS for production of salmon smolt in Norway is done by Hilmarsen et al. [13], which report a total electricity use of 3-5 kWh per kg post-smolt with an average weight of 0.5 kg. The same study report 6-9 kWh/kg for harvest-sized salmon. This energy use is based on reference values from the industry and RAS suppliers. In addition, some values of energy consumption is reported by RAS technology suppliers. 2 kWh/kg fish is reported by AKVAgroup [39], who delivers systems based on modern recirculation technology, where recirculation degree is high and rearing temperature between 12-16 °C. The final smolt weight is not known.

Values for energy use considered most relevant for Norwegian post-smolt production is summarized in table 1. It should be underlined that the values are based on different systems and assumptions. Finding a reference value for energy use is difficult, as the documentation of underlying assumptions (feed load, smolt size etc.) and systems is in many cases rather poor. This was also noted in the study by Badiola et al. [7].

Table 1: Values for energy use considered relevant for post-smolt production in RAS in Norway.

Energy use per kilo fish produced	**Reference**
4.1 kWh/kg	Bergheim et al. [38]
3-5 kWh/kg	Hilmarsen et al. [13]
2 kWh/kg	AKVAgroup [39]
1.56 kWh/kg	Colt et al. [34]

2.4 Principles of RAS

There are in general two main production methods for land based aquaculture systems: flow-through and recirculating aquaculture systems. Flow-through systems have low circulation degree of the water, typically from 30-70% in modern systems [13]. RAS is defined as systems with higher degree of recirculation, typically from 95 to 99% [13]. RAS can also be described as a closed system with fish tanks, filtration, water treatment and limited water exchange [40]. Recirculating systems are designed to reduce the water consumption and waste production compared to flow-through systems [7]. The main advantage is the possibility to create the desired environment for the species reared, without relying on environmental parameters such as in a flow-through system [41].

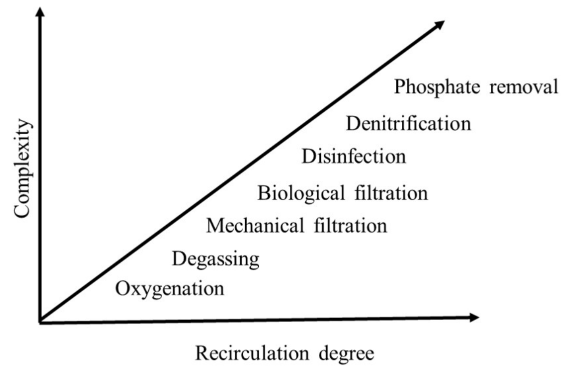

Figure 1: The relation between recirculation degree and water treatment required. Taken from: [40]

RAS has many similarities with traditional water treatment plants. The water flow supplies fish with oxygen, transfers the wastes from the fish tank to the various treatment processes, before returning the cleaned water [13]. The treatment processes required are depending on the degree of recirculation as illustrated by figure 1.

The basic water treatment processes needed in any RAS is mechanical filtration, biological filtration, degassing and oxygenation [42] as displayed in figure 2. In addition temperature control and disinfection of intake water is required. Sludge is treated or directly released.

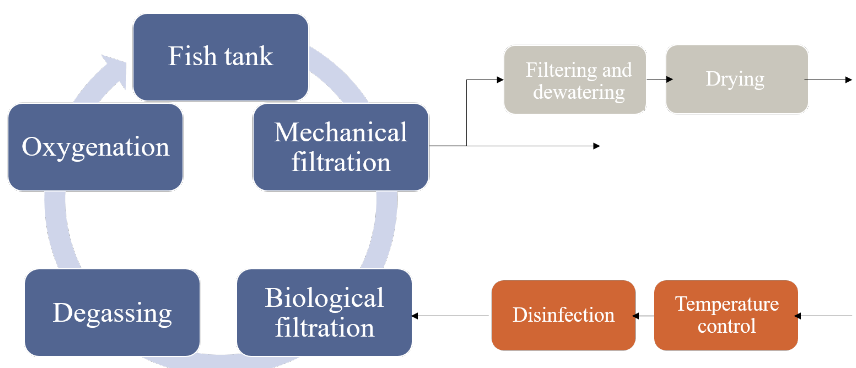

Figure 2: Overview of a basic RAS system with biological filtration. Water treatment loop in blue,sludge treatment in grey and treatment of make-up water in red. Figure adapted from [43]

Other treatment units such as disinfection by UV or ozone within the treatment loop, denitrification, automatic pH regulation and phosphate removal can also be necessary. In addition to this comes rearing basins, pumps and building operations. Each of the processes are described in detail below, with a focus on commonly used technology and energy requirements. The water quality parameters relevant are displayed in table 2.

Table 2: Water quality parameters. Values taken from [40].

Parameter	**Value**
pH	6.2-6.8
Dissolved O_2	80-120% saturation
CO_2	$<$ 15 mg/L
TAN	$<$ 2 mg/L
Nitrite (NO_2^-)	$<$ 0.1 mg/L (freshwater)

2.5 Fish tanks

The fish tanks are circular or octangonal with typically diameter 10-24 m and 3.5-5 m height in case of post-smolt. In terms of energy demand lightning and automatic feeders are the two components within the fish tanks requiring energy. Lightning is required in fish tanks as it plays an important role in synchronizing smoltification and sexual maturation [44]. Different lightning regimes are applied, with continuous lightning being used in many post-smolt cases[45] [46]. This increases the growth rate, as continuous feeding is applied [44].

Energy requirements

Illumination lamps are usually LED and halogen systems. Tank dimensions and clarity of water determines the installed capacity. Automatic feeding is done by different types of systems, which all aim for uniform distribution of the feed.

2.6 Water treatment processes

2.6.1 Mechanical filtration

Mechanical filtration is essential to remove suspended solids. Suspended solids is a result of uneaten feed, fish excretions and dead and living bacteria. Rapid filtration is essential to avoid malfunctioning of other units, for instance by mechanical plugging. Additionally, filtration is essential for fish health, as suspended solids may damage gills, degrade water quality and harbor pathogens [47]. Particles with size larger than 100 μu is usually removed within the rearing basin by a settlement device. Further, solids are usually filtered by microscreens with a filter cloth of 40 to 100 microns.

Rotating drum filters are the most common type of microscreen used in Norway [40], [48]. Drum filters are beneficial due to the ability to handle large volume flows and easy maintenance through backwashing. The working principle is as follows: water is either fed by gravity or pumped into the filter unit, where solids adhere to the screen surface and the water flow through the filter is impeded. As a consequence the water level inside the drum rises, which activates the backwash system. During backwashing, nozzles spray water from outside, and solids rinsed off are discharged via a collection trough. This sludge is then transported out of the unit for further treatment, either by gravity or by pumping.

Energy requirements

Drum filters require energy for the drum rotation, backwashing and pumping required to overcome head loss. The energy demand is variable, with a low average energy consumption to rotate the drum and an increase up to 5 times average during washing [16] The backwash cycle is initiated when the water level rises above a set point. The backwash frequency, and thereby energy use, depends on water flow rate, particle concentration and distribution.

2.6.2 Biological filtration

Biofilters are essential when systems with an higher degree of recirculation is considered. The biological filtration process is essential for conversion of ammonia to nitrate. Ammonia is a by-product of fish amino acid and fish metabolism, as well as urine, solid wastes and excess feed [40]. Chronic exposure to high levels of ammonia increases metabolic rate and reduce growth rate and disease resistance. Ammonia is first converted to nitrite, and thereafter nitrate. Nitrite can also be toxic, and reduce swimming performance, growth and lead to mortality. [40]. The tolerance to nitrate is high, and is usually not a significant problem [40].

The ammonia removal process can be preformed by a range of different filters such as moving or fixed bed filters, rotating biological contactors and trickling filters [16]. In Norwegian RAS, moving bed bioreactors (MBBR) is often preferred to fixed bed filters and trickling filters [17]. In a MBBR, nitrifying bacteria first convert ammonia to nitrite and finally to nitrate. In addition, organic compounds are broken down by heterotrophic bacteria oxidizing organic matter by consuming oxygen and producing CO_2 [42]. The biomass is grown on plastic carriers that move freely within the reactor. Movement of the carriers is set up by an aeration device in aerobic systems [49]. MBBR have the advantage of high specific biofilm surface area, no backwashing, low maintenance and negligible head loss [49], [16].

Energy requirements

Energy required by MBBR is determined by the aeration demand. This will again depend on:

- Waste loading from fish excrement and lost feed
- Oxygen demand
- Oxygen transfer efficiency of air supply system

The first bullet point refers to the ammonia and organic matter load. Aeration is required for two different purposes: to supply oxygen for the microorganisms and ensure mixing of carrier media. In RAS oxygen levels are high, so no additional oxygen is needed for microorganisms. Aeration for sufficient carrier mixing is the dimensioning parameter for power consumption [50]. This is dependent on water flux through the filter and volume, since the flux transports carriers towards the outlet and aeration is required to counteract this [51]. Larger water flows therefore implies higher aeration demand, but the main influencing factor is the volume of the MBBR [52], [50].

2.6.3 Degassing

Fish excrete metabolically produced CO_2 through the gills, which over time accumulate in the system if not removed [40]. In addition, the microbial activity in biofilters produce additional CO_2, which adds to the total load. In intensive aquaculture systems, such as RAS, carbon dioxide control emerges as an important issue. This is due to the low water exchange rates and the use of pure oxygen addition, which does not remove CO_2 [53]. Elevated CO_2 levels decrease the ability of hemoglobin to transport oxygen, decrease oxygen binding capacity and increase blood acidity [53]. Reduced growth rate and mortality are general effects.

CO_2 concentration is pH-dependent, and two different methods can be used to control its concentration: degassing and pH. Usually a combination of the two methods is used [53], as the nitrifying bacteria in the biofilter is sensitive to pH [54]. pH-adjustment is done by addition of lime slurry or liquid sodium hydroxide [54]. Only degassing requires direct energy input on site, and pH-adjustment is thus left out. Degassing is often done by stripping towers placed in the recycling loop or in the fish tanks. Stripping towers consist of cylindrical vessels that is filled with packing material, often of plastic. The water in the recycling loop falls downwards, while air is blown either in a co- or counter-current direction [53].

Energy requirements

The ratio between air being forced upwards by a blower and the water passing through is called the gas-to-liquid ratio. This, together with the height of the tower determine the removal efficiency [55]. The type of packaging (plastic rings) will also affect efficiency, and the air pressure drop through the tower. The main energy requirements are due to:

- Pump: compensating for head loss (height of tower)
- Air blower: forcing the air flow upwards/downwards
- Ventilation unit: vent out air blown through stripper to avoid accumulation of CO_2 in the building

The power consumption of the pump and air blower is determined by water treatment flow rate. Power demand of the ventilation unit also depends on flow rate, as well as CO_2 levels and outdoor temperature.

2.6.4 Pumping

The water must be continuously cleaned and recycled, so pumps are essential in any RAS, either to move water to a higher elevation or to increase pressure for water treatment processes [16]. Centrifugal pumps are widely used in RAS, while some solutions use air-lifts and/or axial-flow propeller pumps [16], [56]. The number of pumps installed is variable [40].

Energy requirements

Pump energy required is determined by water flow, total dynamic head and efficiency. Energy consumption is directly proportional to the total lifting height [40].

2.6.5 Oxygenation

Oxygenation systems are used to enable higher specific density and biomass, by removing oxygen as a limiting factor to the carrying capacity of the system [53]. Content of dissolved oxygen is the first limiting factor in RAS and low levels can induce respiratory distress, leading to loss of appetite and growth, and ultimately mortality [8]. The oxygen consumption depends on body mass, temperature, feeding rate, growth rate, swimming velocity and stress level [40].

Aeration is sufficient to provide oxygen at stocking densities lower than 45 kg/m^3, while oxygenation is required in more intensive systems [41]. Oxygen addition is done in each water treatment loop and/or in each tank [33]. Low head oxygenation (LHO) units or oxygenation cones are typically used in larger RAS in Norway today.

Oxygenation cones operate at a pressure higher than atmospheric pressure [53], and the water flow is pressurized by a pump before oxygen injection. Supersaturation can be reached due to higher pressure. If operated at higher pressure, only 15-20% of the total treatment flow [57] is oxygenated. If low pressure in-line cones are used, oxygen is added to the total treatment flow [57].

Open-type or LHO units have the benefit of venting more off-gas than closed oxygenation cones [53]. In RAS using brackish or sea water nitrogen saturation is a common issue, which can have negative effects on the fish if exceeding 102% [46]. Many systems have a degassing unit installed before the water is returning to the tank to vent N_2 gas [57]. With an open oxygenation unit within the tank this can be avoided, as the unit also vents nitrogen gas [57]. However, the oxygen transfer efficiency of LHO units is reduced in freshwater.

Oxygen is either produced on site by pressure swing adsorption (PSA) or purchased in bulk liquid or gas form from industrial manufacturers using cryogenic air separation units [41].

Energy requirements

Energy is required for O_2 production and the pump increasing the pressure within the oxygen addition device. Energy demand depends on the water treatment flow and pressure. Oxygenation cones increase pumping requirements relative to low head oxygenation units due to higher operating pressure. In addition, transfer efficiency is important, as more energy for oxygen production is required if efficiency is low. Oxygen production has an energy requirement of 0.5 kWh per kilo O_2 if produced by PSA on site [58]. If oxygen is provided from an industrial producer the energy use is typically 0.2 kWh per kilo oxygen [58].

2.6.6 Intake water

Based on the salinity in the RAS, water is taken from either a freshwater source, a seawater source or both. In some cases, the freshwater is fed by gravity into the RAS, for instance if the facility is located close to a hydropower station. Sea water is usually pumped from a fjord nearby. The water is disinfected to avoid any biological risk. According to "Akvakulturdriftforskriften" intake water first has to be filtrated through a filter with mesh size less than 300 μu, and then treated by UV to kill or inactivate microorganism. The mechanical filtration is done by a drum filter.

The UV-dose requirement is set to 25 mJ/cm^2 [33], but a dose of 100-250 mJ/cm^2 is often applied [59], [60]. UV treatment is performed after the mechanical filtration to benefit from better transmittance as solid concentration is reduced [40].

Freshwater is additionally treated with ozone in many cases to inactivate fish pathogens and oxidize organic wastes and nitrite [61]. A dose of approximately 3mg/L is applied to the freshwater inlet [60].

Energy requirements

UV is created by powering a unit filled with gas, typically mercury. The UV-dose applied (mJ/cm^2) is the driver for energy consumption. The dose applied depends on water flow, lamp intensity and water transmittance (suspended solids and organic compounds concentration) [61].
If a drum filter is used, power requirement is the same as described for mechancial filtration.

The energy required for pumping of intake water is influenced by the depth of the intake, the distance and flow rate. The depth of the inlet varies, but is typically 50-100 m [33], [60].

Ozone treatment requires energy for production of ozone, which typically is done in a corona discharge reactor on site [61]. Pure oxygen gas is used as a feed gas. The total energy requirement is approximately 10 kWh/kg O_3 [61]. The ozone transfer can be done by systems similar to the oxygenation cones described earlier, which requires energy to increase the pressure.

2.7 Sludge treatment

Sludge is produced as a results of fish excretes and feed losses filtrated out in the mechanical filtration process. The effluent sludge water from the drum filter is further treated depending on the end use. The dry matter content determines the potential use. Sludge with a dry matter concentration of 10-20% (DM10-20%) can be spread on agricultural fields, 70-90% DM is applicable for biogas production and 95% DM is suitable as an ingredient in fertilizer production [62].

As presented in figure 3, sludge treatment consist of primary filtration, dewatering and in some cases thermal treatment [48]. A dry matter content of 20-30% is reached through dewatering by centrifuges and filter presses, while higher DM content only is possible by thermal and/or composting techniques [48].

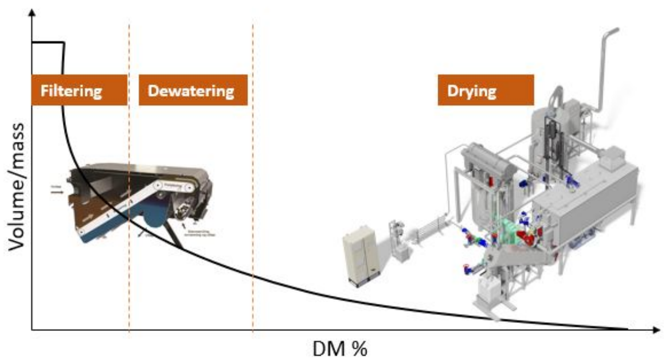

Figure 3: Different treatment processes are required depending on the final dry matter content. Volume is rapidly increased when dry matter content increases. Simplified figure from [63]

Energy requirements

The energy demand of the filtering processes is similar to the mechanical filtration, with power needed for operation and backwashing. When thermal treatment is used to reach higher dry matter concentrations, the energy demand is drastically increased [62]. Energy is required for heat transfer to the heating medium. Energy demand relates to the amount of sludge produced (depending on biomass and feed load), as well as the desired dry matter content.

2.8 Cooling and heating

Temperature regulation is necessary to obtain a stable rearing temperature. A survey among suppliers RAS technology presented by Hjeltnes et al. [40] point out the need for heating only in the coldest winter months, while cooling is necessary in summer. This is due to the internal heat load from the water treatment units and fish stock. Heating and cooling is typically done by heat exchangers and/or heat pumps, which often is sea water based [40].

Energy demand is the required electricity to run the heat pump, which is significantly lower than heating demand. If a sea water based heat pump is installed, the power demand relates to the sea water temperature and the heat demand, which again depends on the internal heat generation.

2.9 Building requirements

Building requirements mainly consist of heating and ventilation demand. Ventilation is essential to control temperature, humidity and removal of potential pollutants [64]. Energy demand is influenced by the design of the ventilation system, as described by specific fan power (SFP) and the ventilation rate. The ventilation rate is determined by the air exchange rate, describing how often the total building volume is exchanged.

The energy demand for space heating is contingent upon building design, building tightness and internal heat generation. Internal heat generation is significant, as the building contains considerable amounts of technical equipment. The air temperature is typically kept 2-4 °C above the water temperature to reduce condensation [65].

Additionally, energy use in buildings is driven by lightning and other electrical components, such as control systems. This is not considered in this study.

3 Method

3.1 System description

In light of the recent trends in Norwegian aquaculture industry, where larger smolt is produced and projects for production of harvest-sized fish are under development, the importance of energy use in RAS is increasing. There is a need to find new technical solutions for reducing energy demand. To achieve this, a good understanding of drivers for energy demand in each process is essential. Currently, the smolt is usually 70-120 g when placed in sea [66]. Nonetheless, production of smolt up to 500 g is considered by several producers, such as Marine Harvest [66]. A case is developed to give insight to how this change will influence energy use and to identify main energy consuming units in post-smolt production. The case considers production of post-smolt with an initial weight of 150 g, which is slightly above large smolt delivered today. The final weight is 500 g, which is a potential weight of post-smolt in future. The total production volume is about 200 ton and is done in 14 tanks with a diameter of 10 m. Total system volume is 3299 m^3. The system is defined based on review of projects, communication with suppliers and literature. The system is internal recirculating, meaning that each tank is connected to a separate water treatment loop [52].

Energy use included is on-site energy demand for fish tanks, treatment of recirculating water, intake water and sludge, control of water temperature and building operations.

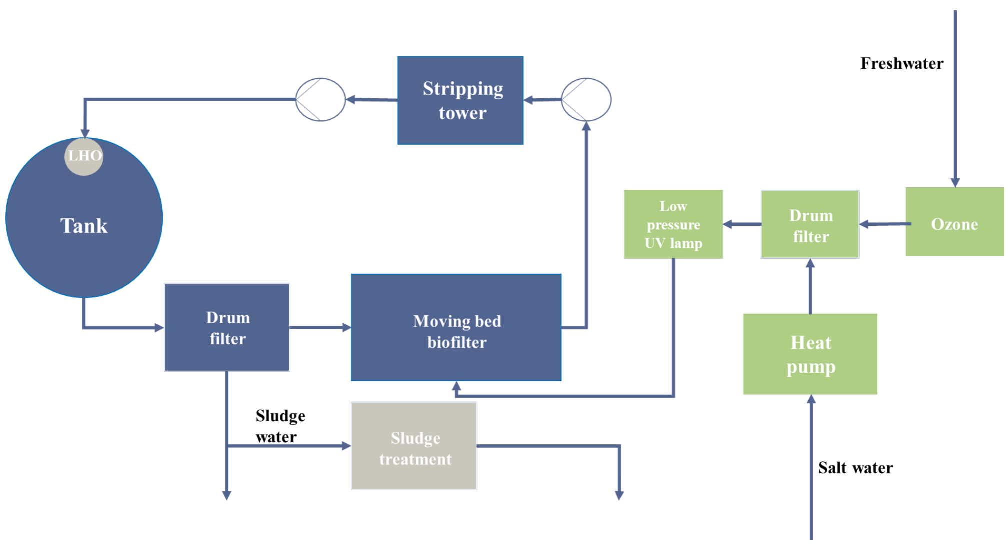

Figure 4: System overview.

The fish tank process includes the growth of fish, feed fed and waste produced. The feed load, and the subsequent waste initiates the water treatment process. This process determines the operation of the rest of the system, and can in this regard be seen as an input. In terms of energy demand, an automatic feeder and lights are the energy consuming units within the tank.

The water is first mechanically filtered by a rotating drum filter. When the filtered is backwashed a waste stream is produced, which is led to the sludge treatment process. Afterwards, biological filtration takes place in a MBBR. The intake water is included in the recirculation loop in the MBBR. The water in the recirculating loop flows by gravity up until this point. Degassing is then done through a stripping tower with counterflow air stream, and a pump is installed before the unit. After the degassing unit water is pumped to compensate for head and friction losses before oxygenation. Three different options are considered for oxygenation. First, a low head oxygenation unit is used within each tank. Second, a high-pressure oxygenation cone supersaturating 15 % of the total water flow is considered. Third, a low-pressure oxygenation cone adding oxygen to the total flow is used. The energy required for oxygen production is included in the system, as d'Orbcastel et al. [29] find that this is a significant share of total energy use. Oxygen is assumed bought from an industrial manufacturer.

Both a fresh and saltwater intake is used, but pumping is only required for sea water supply. The intake water is cooled/heated to 12 °C by a heat pump and disinfected. The water is first filtered by a small rotating drum filter, and afterwards disinfected by UV. The freshwater is additionally treated with ozone. Energy for ozone production is included within the system as this is done on-site.

Two different cases are considered for sludge treatment. Either it is pumped from the RAS facility and released into the fjord, or filtered and dewatered to reach a dry matter content of about 10-20%. The system boundary is set at the point the sludge leaves the facility.

Building operations include the heating system for keeping the indoor air at approximately 15-16 °C and the ventilation system.

The recirculation degree of the system is set to meet the typical requirement of 300-500 L water per kilo feed with a considerable margin. [13]. This implies that the RAS can be operated without denitrification, which removes nitrate. This seems like the most common system solution in Norway [13].

3.2 Model of growth, feed and waste loading

A production modeling tool in Microsoft Excel is used to calculate growth and feed rate. The model is provided by Morefish [67], and is developed together with Sintef. Based on temperature, start weight, number of fish and mortality, weekly growth is calculated. From this, the required feed load is estimated using data from the feed manufacturer Aker Biomarine. Oxygen demand is also calculated by the model, and values from literature is used [68].

A growth table for salmon provided by Aker Biomarine yields specific growth rate (SGR), meaning the percentage increase in size per day. SGR is dependent on temperature and size, giving a matrix. This matrix is available in the model, yielding 1.8 $\%/day$ as average for smolt between 150 and 500 g. SGR is defined as shown in equation 3.1 [69], [70].

$$SGR = \frac{lnBW_i - lnBW_{(i+1)} * 100}{\triangle t} \tag{3.1}$$

Where
$\triangle t$ = time period, 1 week in model
BW_i = fish body weight, beginning of time period in g
$BW_{(i+1)}$ = fish body weight, end of time period in g

Body weight and number of alive and dead fish in each week (i) is then calculated using the following equations:

$$BW_{(i+1)} = BW_i \left(\left(1 + \frac{SGR}{100}\right)^7 \right) \tag{3.2}$$

$$n_{(i+1)} = n_i \left(1 - \frac{m}{100}\right) \tag{3.3}$$

Where
$n_{(i+1)}$ = number of fish alive in start of week $(i+1)$/end of week i
n_i = number of fish alive in start of week i
m = mortality rate, in $\%/week$

$$nd_{(i+1)} = n_i \frac{m}{100} \tag{3.4}$$

Where
$nd_{(i+1)}$ = number of dead fish by start of week $(i+1)$/end of week i

Finally, the feed load in week i, given in $kg/week$, is calculated by equation 3.5.

$$F_i = \left(\left(\frac{BW_{(i+1)} - BW_i}{1000} \right) * bFCR * n_{(i+1)} \right) + \left(\left(\frac{\overline{BW_i} - BW_i}{1000} \right) * bFCR * nd_{(i+1)} \right) \tag{3.5}$$

Where
$bFCR$ = biologial food conversion ratio
$BW_{(i+1)}$ = fish body weight in g, end of week i

BW_i = fish body weight in g, start of week i
$\overline{BW_i}$ = average fish body weight in g in week i
$n_{(i+1)}$ = number of fish alive end of week i
$nd_{(i+1)}$ = number of fish dead end of week i

Using the equations presented and input parameters as shown in table 3, growth and feed load in each week are estimated. The grow-out from 150 g to 500 g is done in ten weeks at 12 °C.

Table 3: Input data to production planning model

Parameter	**Value**	**Reference**
T	12 °C	[71]
SGR_{avg}	1.8 $\%/day$	[72]
BW_0	150 g	
BW_{end}	500 g	
m	0.2 $\%/week$	[73], [74]
$bFCR$	0.8	[72], [17]
n_0	390 000	

Having computed the biomass growth and feed rate, the production of the most important water treatment variables is estimated: CO_2, O_2, total suspended solids (TSS) and total ammonium nitrogen (TAN). The production of the different substances determines the dimensions of the water treatment units. Production rates are calculated according to the equations below, all with unit kg/day.

$$P_{\mathrm{CO_2}} = 0.409 * F_i \tag{3.6}$$

as used by Terjesen et al. [75].
Equation 3.7 and 3.8 are taken from Timmons & Ebeling [41].

$$P_{TAN} = PC * 0.095 * F_i \tag{3.7}$$

Where
PC = protein content = 0.54 [72]

$$P_{TSS} = 0.25 * F_i \tag{3.8}$$

Oxygen consumption is dependent on body mass among other factors, and $P_{\mathrm{O_2}}$ is estimated based on values provided in the production planning model [68]. The average oxygen consumption estimated for post-smolt between 150 and 500 g reared at 12 °C is 3.3 $mg/kg/min$.

3.3 Basic system design

The system is designed according to the parameters presented in table 4. These values were also used in the production planning model. The parameters are chosen based on typical values found in literature describing recirculating systems for post-smolt in Norway. The volume dimensions were based on the goal of producing 200 ton of post-smolt at 500 g.

Table 4: Design parameters

Design parameter	Value	Reference	
Hydraulic retention time (HRT)	40 min	[76], [40]	
Recirculation share	98 %	[13], [52], [71], [73]	Flow rate > 400 L/kg_{feed}
Specific species density	60 kg/m^3	[71]	< 75 kg/m^3
Diameter tank	10 m	[67], [77]	
Height	3 m	[67]	Ratio diameter:height 3:1
Number of tanks	14		
Total rearing volume	3299 m^3		

Water flow rate ($\dot{V}$) in the treatment loop is the variable driving energy consumption in most treatment processes. Equation 3.9 shows the formula for volumetric flow rate in the water treatment loop, given total volume and HRT.

$$\dot{V} = \frac{V}{HRT} \tag{3.9}$$

V = total volume of tanks connected to water treatment system
HRT = hydraulic retention time

The flow of make-up water is assumed to be constant throughout the ten weeks, with a recirculation degree of 98%. The flow rate of make-up water is calculated according to equation 3.10.

$$\frac{\dot{V}}{\dot{V_m} + \dot{V}} * 100 = 98\% \tag{3.10}$$

Where
V_m = flow rate of make-up water
V = flow rate in water treatment loop

3.4 Model for power consumption

3.4.1 Fish tank

The power consumption for illumination lamps and automatic feeding system is mainly dependent on the number of tanks and dimensions. To estimate energy consumption of lightning, rated power of the lamp in each tank is multiplied with hours within the production period, as continuous lightning is assumed. For tanks with diameter around 10 m, 2 kW is used [67]. If the tanks are shallower, 1 kW is a more reasonable estimate [67]. Similarly, this is done for the automatic feeding system, as this also operates continuously. Depending on the solution, installed power is typically in the range 30-50 W [78], [79], and 40 W is used.

3.4.2 Recirculating loop

Mechanical filtration

The motor driving the rotation of the drum operates continuously. The rated power is related to the maximum flow through the drum filter, and is taken from the specifications of the Hydrotech drum filter (appendix A.5). Additionally, power is required to run the backwashing cycle. Power consumption during backwashing is often 5-10 times the average power consumption [16], with 5 being most reasonable for this system [52]. The required power of the rotation and bachwash motor is 0.37 kW and 1.85 kW respectively.

To arrive at energy consumption, power of the rotation motor is multiplied with total operation hours, as it is assumed to operate continuously. The operating hours for the backwash motor is however related to the backwashing frequency, i.e. how often the drum filter is cleaned. This is again related to the flow and concentration of TSS. It is difficult to find reliable data or methods to relate this frequency to the producion of TSS.

One case study by Summerfelt et al. [80] reports that the motor driving the backwashing pump operates 36% of the time. The system is smaller than considered in this study, and the recirculating flow to each tank is significantly lower, but only a partial flow is passed through the drum filter. The concentration of TSS is substantially higher than considered here. Another case study by Summerfelt et al. [37] of smolt up to 137 g found that the backwashing pump operated 20% of the time in average. This system has higher recirculation flow rates and significantly lower concentration than the above mentioned study. To determine if these backwashing frequencies are representative for this case, the capacity of the drum filter, meaning the mass of TSS settled before backwashing is initiated should be known. Moreover, particle size and distribution is likely to influence frequency of washing. As a crude approximation the backwashing frequency is assumed to increase linearly from 20% in the first week to 40% by the end of the production period. Energy consumption for the motor driving the backwashing pump is found by multiplication of the rated power, backwashing frequency in each week and operating hours.

Biological filtration

The power consumption of the blower for aeration of the MBBR depends on the volume of the reactor. Hence, the MBBR is first dimensioned, before power consumption is established.

<u>Dimensioning MBBR</u>

The MBBR consists of three chambers, and is dimensioned considering the highest TAN load (as estimated by the production terms in section 3.2). Nitrification rates are estimated using equation

3.11[81].

$$r_i = k * (C_{TAN,out,i})^n \tag{3.11}$$

Where
r_i = nitrifification rate, $g\mathrm{NH_4{-}N}/m^2 * day$
$C_{TAN,out,i}$ = outlet concentration of $\mathrm{NH_4{-}N}$ in each chamber, mg/L, [75]
k = reaction rate constant
n = reaction order constant = 0.7 [81]

Reaction rates constants is dependent on temperature, and is approximated by equation 3.12. [81]

$$k_{T2} = k_{T1} * \theta^{(T_2 - T_1)} \tag{3.12}$$

Where k_{T1} = reaction rate constant = 0.82 at T = 15°C. [43]
θ = temperature coefficient = 1.09 [81]
k_{T2} = at 12°C = 0.633

The removal rate of TAN $R_{TAN,i}$ in each chamber i is calculated by 3.13.[43]

$$R_{TAN,i} = P_{TAN} \frac{C_{TAN,in,i} - C_{TAN,out,i}}{C_{TAN,in} - C_{TAN,out}} \tag{3.13}$$

Where
P_{TAN} = production of TAN, $\frac{g}{day}$, from 3.7
$C_{TAN,in,i}$ = influent TAN concentration in chamber i, table **??**
$C_{TAN,out,i}$ = effluent TAN concentration in chamber i
$C_{TAN,in}$ = TAN concentration into MBBR
$C_{TAN,in}$ = TAN concentration out of MBBR

Values for concentrations are shown in table 5.

Table 5: Inlet and outlet concentration of TAN for each chamber i in the MBBR

Chamber i	$C_{TAN,in,i}$ mg/L	$C_{TAN,out,i}$ mg/L
1	2	0.9
2	0.9	0.35
3	0.35	0.15

This yields a removal rate of 0.15 $\frac{g}{m^2 * day}$ for the last chamber, which is in the same range as those reported by [49].

The volume of each chamber i is estimated by equation 3.14.

$$V_i = \frac{R_{TAN,i}}{r_i} * \frac{1}{ff * A_s} \tag{3.14}$$

Where
ff = fill factor = 50% [49], [75]
A_s = specific surface area = 900 $\frac{m^2}{m^3}$ [75]

The total volume of MBBR is the sum of volume of each chamber [75]. The system is assumed to have average TAN removal rate of 0.35 g per square meter media surface and day, which is comparable to the average range reported by Rusten et al. [49]. The outlet TAN concentration, before return to fish tanks, is 0.15 mg/L, indicating a removal efficiency of 92.5 %. This is comparable with efficiencies indicated by other systems [75], [82].

Power consumption
As mentioned, the power consumption of the MBBR is volume dependent. Average power factor used is 15 W/m^3_{MBBR} [50].

Degassing

The height of the stripping tower and G:L ratio need to be designed before power consumption is estimated.
Design of stripping tower
The MBBR may produce or strip CO_2 depending on aeration levels [75], which is not accounted for. The design parameters are displayed in table 6. Moran [83] reports removal efficiencies for both fresh and saltwater of a cascade column with countercurrent air flow. At an influent CO_2 concentration of 10 mg/L, efficiencies in fresh and saline water (35 ppt) were 75-77% and 67-68%, respectively. Since salinity is lower in this system an efficiency of 72% is assumed.

Table 6: Design parameters for stripping tower.

Design parameter	Value	Reference
Gas:Liquid ratio	5	[52]
Water breakup	Random packaging, NOR-PAC, 5cm	[84], [75]
Influent CO_2	10 mg/L	[75]
Treatment efficiency	72 %	
Height	1.7 m	

Assuming a treatment efficiency of about 72 %, G:L and height is determined using the relations developed by Summerfelt et al. [53] shown in figure 5. (The figure refer to influent concentration of 20 mg/L, but Terjesen et al. [75] argues that treatment efficiencies up to 78% is achieveable

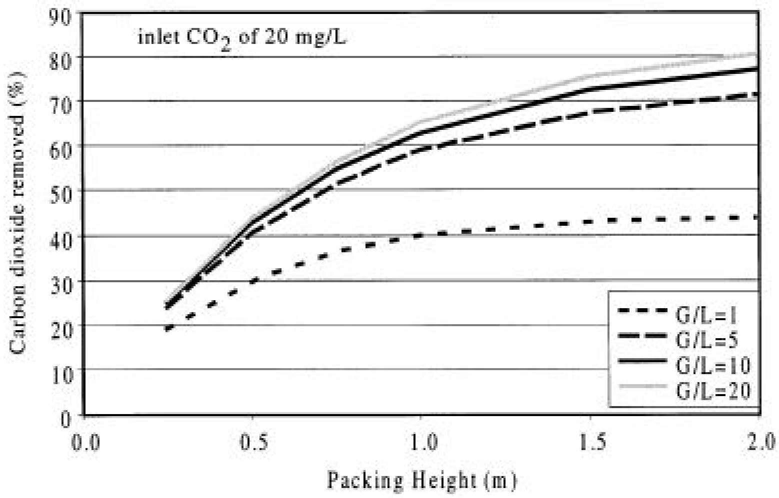

Figure 5: Relation between height, removal efficiency and G/L ratio. Figure taken from [53]

with G:L of 5, and height of 1.6 m)

Considering the designed stripping tower the CO_2-concentration of degasser effluent is assumed to be 2.8 mg/L. This is similar to the demonstrated removal efficiency of state-of-the-art degasser technology used in modern RAS [85]. The actual unit installed typically has a safety margin in terms of height, to ensure that concentrations are met [75]. For power calculations the unit is assumed to be 2 m.

Power consumption

The power of the pump is determined by total dynamic head, flow rate and efficiency. Total dynamic head will in this case just equal the height of the stripping tower, being 2 m. The installed power of the pump is estimated to 34 kW. See appendix A.4 for details.

The power consumption of the blower is dependent on the flow rate of air, inlet temperature and the pressure needed to force the gas upwards. The flow rate of air is again related to the volumetric flow rate of water by the gas to liquid ratio. Hence, power requirement for the blower is related to the flow in the water treatment loop. The relation can be derived from adiabatic compression and ideal gas law [86].

$$P = \frac{\frac{G}{L}\dot{V}P_1}{17.4\eta}\left[\left(\frac{P_2}{P_1}\right)^{0.283} - 1\right] \tag{3.15}$$

Where

G/L = gas-to-liquid ratio
$\dot{V}$ = volumetric flow rate of water in treatment loop
η = blower efficiency = assumed 0.7 [87]
P_1 = inlet pressure of air in kPa = assumed approx. 1 bar
P_2 = outlet pressure of air in kPa

P_2 had to be determined, which is difficult to predict without knowing the detailed design of the stripping tower, which is out of scope of this study. In general, increasing gas or liquid flow will increase the pressure in the tower. At one point, flooding occurs, meaning that the liquid/gas flow is increased beyond its capacity. Towers are designed so that this does not occur [55]. The pressure right before flooding can be determined by analytic relations, while the pressure drop at any flow rates are determined by parameters and charts (for instance [88]). As this charts rely on designed parameters not specified here, the pressure before flooding is used as an approximation [88].

$$\triangle P_{flood} = 0.00958 * F_p^{0.7} \tag{3.16}$$

Where
F_p = packaging factor in ft^{-1} = 12 for "Nor-Pac, 5cm" [88]

Hence, P_2 is assumed to equal 1.12 bar and the power requirement for the blower is 1.68 kW.

An exhaust fan is placed close to the degassing unit to vent the air out of the building. The specific fan power can be used to approximate its power requirement, and is defined as

$$SFP = \frac{P}{\dot{V}_{air}} \tag{3.17}$$

Where
P = power consumption of fan
$\dot{V}_i$ = volumetric flow rate of air vented out, m^3/sec
And,

$$\eta_{tot} SFP = \triangle p \tag{3.18}$$

Where
η_{tot} = efficiency of system
$\triangle p$ = total pressure loss

As seen in equation 3.18, SFP is depending on the efficiency of the fan system and the total pressure loss in ventilation system. Pressure loss is again related to the air flow in ducts, where an increase in air flow increases pressure drop exponentially. SFP does however not increase with the same rate, as η_{tot} decreases at lower air flow rates [89]. Due to the abovementioned factors, it is difficult to estimate the correct SFP without specific knowledge about the pressure losses in ducts and specific knowledge on fan characteristics. Typical pressure losses in ventilation systems is presented by Schild & Mysen [89], and this is used to assume a pressure loss of 405 Pa. Average fan system efficiency in commercials buildings in Norway is 44% [89]. This results in a SFP of approximately 1. Flow rate $\dot{V}_{air}$ is estimated based on recommended limits for CO_2 concentration indoor and CO_2 vented out of the degasser. The power required varies with CO_2 production, and is increasing during the production period. Maximum power is 5.7 kW. See appendix A.4 for details.

Pumping

To estimate power demand for pumping equation 3.19 is used.

$$P = \frac{Q\rho g H}{\eta} \tag{3.19}$$

Where
Q = flow rate m^3/s
ρ = specific density = 997 kg/m^3
g = specific gravity = 9.81 m/s^2
H = total dynamic head m
η = total pump efficiency

Total dynamic head is the total equivalent height that the fluid is to be pumped, including friction losses in the pipe. It combines the static discharge, suction head and friction losses. The static head includes all head losses from the tank outlet to inlet. Main contributions are shown in table 7. The head loss of the degasser is included in its operation, see section 3.4.2.

Table 7: Static head losses.

Unit	Head loss	Reference
Fish tank	3.2 m	see appendix A.9
Drum filter	0.2 m	[90]
MBBR	Insignificant	[49]

Friction losses are expressed as major and minor losses. Major losses are friction losses within the pipe, and depends on the roughness of the pipe and flow pattern (f). Minor losses are friction losses due to geometrical shapes, valves, expansions etc. The equation for total friction losses is expressed as

$$H_{loss} = f\frac{l}{D}\frac{v^2}{2g} + \sum K_L \frac{v^2}{2g} \tag{3.20}$$

The friction losses are determined based on an assumption about pipe length, diameters, material and path (see appendix A.9 for calculations). The total head loss due to friction losses is 0.53 m. Adding this to the static head, a total dynamic head of 4.03 m is used for calculations of pump power. η is assumed to equal 0.8 [91]. Flow rate Q is the total water flow for all water treatment loops. The calculated required power for the recirculation pump is 67.8 kW. No frequency regulation is included for calculations of the total energy demand for the pump, and it is assumed that the pump constantly operates at 67.8 kW.

Oxygenation

Energy requirements for three different types of oxygenation units are considered: LHO unit, high pressure oxygenation cone (partial loop) or low pressure oxygenation cone (total flow).

Energy required for production of oxygen is 0.2 kWh/kg O_2 as it is assumed bought from an industrial supplier. The O_2 demand in each week is calculated by consumption of oxygen minus the oxygen content in make-up water. The consumption of oxygen is determined as described in section 3.2. The oxygen use by different units compared is varying, as they have different oxygen transfer efficiencies as displayed in table 8.

Table 8: Oxygen transfer efficiency for the three units considered

Unit	Start	End	Reference
LHO	95%	85%	[92]
Cone, partial	90%	90%	assumption
Cone, total	80%	80%	[57]

Energy required for oxygen production is found by multiplication of the energy intensity (kWh/kg O_2 produced) and the O_2 demand in each week divided by oxygen transfer efficiency. Pump power is estimated from flow rate through the O_2 addition unit and the required pressure.

Low head oxygenation unit - OxyStream

The low head oxygenation unit is placed within each tank, and operates at significant lower pressure than the two other units. A pressure of 1.11 mWC is estimated. Energy requirement to operate the unit is 1.77 kW given the O_2 demand and other system specifications. Calculations are performed by AGA [57].

Oxygenation cone - total loop

The power consumption for a low pressure oxygenation cone, adding oxygen to the total water treatment flow is estimated by AGA [57] based on the specific case. One oxygenation cone is assumed for each loop. The cone pressure is about 7 mWC. Power consumption for each cone is estimated to 11.22 kW.

Oxygenation cone - partial loop

To determine pump power required to increase the pressure, data points from a supplier was plotted and a linear curve fitted. One oxygenation cone is assumed for each tank, and only 15% of the water treatment flow rate is pumped through the cone. A power consumption of 7 kW is estimated for each cone. See appendix A.7 for further details.

The power requirements are then multiplied by total hours to obtain overall energy demand for the pump during production, as a constant power consumption is assumed. Energy for oxygen production is summed over the 10 weeks.

3.4.3 Intake water

Mechanical filtration

The power demand for the small drum filter is estimated in the similar way as for the drum filter within the water treatment loop (section 3.4.2). A constant backwash frequency of 20% is assumed.

Ozone treatment of freshwater

The freshwater inlet flow is treated with ozone added through a cone. Multiplication of the dose (3 mg/L), energy requirement for ozone production (10 kWh/kg O_3) and the flow rate of freshwater yields the average energy consumption. The transfer efficiency is assumed to be 100%, as ozone is 13 times more soluble than oxygen. As freshwater only constitutes 66 % of the intake water (see section 3.4.5), the flow rate is so small that ozone addition requires minimal energy and is negligible.

UV disinfection

Theoretical UV-dose can be estimated according to equation 3.21 [61].

$$Dose = I * \frac{V_{UV}}{Q} * a * exp^{b\%T} \tag{3.21}$$

Where
I = UV intensity, mW/cm^2
V_{UV} = volume of UV vessel
a,b = parameters depending on specific unit
$\%T$ = transmittance factor
Q = flow rate of make-up water

The volume of the UV vessel divided by flow rate yields the exposure time. This is typically 10-30 sec in UV-systems for aquaculture [61]. The correction factors, including transmittance, is essential, as UV intensity drops off with a square of the distance between the bulb and target organisms [61]. Transmittance factor is varying, depending among other factors, on content of particulate matter. Typical values for filtered freshwater is 80-95 % and for seawater 70-90% [93]. The flow rate of make-up water assumed constant, together with applied dose. In reality many UV-systems measure transmittance and flow rate, and adjust the power output accordingly [94]. This is called dose-pacing, and contribute to energy savings. The electric power input does not equal power output from the UV-lamp, as most of the energy input is converted to heat. A low pressure lamp typically has an efficiency of 30-40% [95], [61].

As a,b is unknown and the effective irritated area is difficult to estimate, the output power of the UV device (I times effective irritated area) is estimated based on technical specifications from three different UV suppliers. The maximum flow rate given in data sheets are calculated based on an applied dose of 150 mJ/cm^2, and $\%T$ of about 95% at end of life. To calculate input power an efficiency of 35% is assumed. Power to operate the control system is also included. The estimated power input for a given flow rate is presented in appendix A.6. The power requirement increases linearly with flow rate, and the three different devices yields approximately the same result.

The flow rate of make-up water equals 98 m^3/h, yielding a power input of 2 kW. This is quite similar to the UV power installed in a study of a RAS with flow rate of the same order of magnitude [94]. If a safety factor of about 5 is applied (equal to a UV-dose of 150 mJ/cm^2), the resulting power input is 8.6 kW. As no dose pacing is accounted for, the UV is assumed to have a continuous power consumption equal to the rated capacity. The input power is multiplied with the total number of operating hours to estimate energy demand.

Sea water pump

The equation used to determine the pump's power requirement is presented in section 3.4.2. The inlet is assumed to be situated at a depth of 60 m, so the static head equals 60 m. The share of intake salt water is 34%, as described in section 3.4.5. This yields a flow rate Q of 34 m^3/h. As the diameter of intake pipes often are 500 mm [33] and flow rate is low, friction losses are negligible compared to the static head. The other parameters used for calculations are equal to the ones in section 3.4.2. Theoretical installed pumping power equals 7 kW.

3.4.4 Sludge treatment

It is assumed that the DM content is about 3% in the effluent water from the mechanical filter. Two different options are considered:

- Option 1: sludge water is untreated and released into sea. This requires energy for pumping.
- Option 2: sludge water is dewatered to a dry matter content of 10-20%. This requires energy for filtering and dewatering processes.

Option 1

The sludge water from the backwashing process in the drum filter is typically 0.1-0.5% of the treated water flow, when intermittent backwashing is applied [96], [97]. Hognes & Rosten [97] looked at a similar case, and report a required head of 40 m. Using the equation for theoretical pump power (see appendix A.8), the estimated power consumption is 3.4 kW.

Option 2

Hognes & Rosten [97] report a yearly electricity consumption of 51684 kWh for filtering and dewatering of 1500 tonne sludge at DM10%. Using this, an energy factor of 0.035 $kWh/kg_{DM10\%}$ is assumed. The amount of sludge at DM10% produced is 1.5 kilo per kilo feed [98]. See appendix A.8 for calculations.

3.4.5 Cooling and heating

The power consumed by the heat pump is calculated according to equation 3.22.

$$E = \frac{Q}{COP} \tag{3.22}$$

Where
COP = coefficient of performance, calculated by equation 3.23
Q = heating demand, calculated by equation 3.24

$$COP = \frac{T_c}{T_c - T_e}\eta_c \tag{3.23}$$

Where
T_c = outlet temperature of condenser
T_e = inlet temperature in evaporator
η_c = Carnot efficiency

The heat demand is estimated from the temperature lift/decrease required to meet the system temperature of 12°C minus the heat gain from internal loads. It is assumed that all energy input to the pumps (recirculation and degasser), light, MBBR blower, O_2 pump and UV is dissipated as heat. This adds to the internal load. The net heating demand is estimated as:

$$Q_{net} = \dot{m} * c_p * \triangle T - Q_{internal} \tag{3.24}$$

Where
$\triangle T$ = temperature difference between source and system temperature
$\dot{m}$ = mass flow rate, calculated according to 3.25
c_p = specific heat capacity

$$\dot{m} = \dot{V}\rho \tag{3.25}$$

Where
ρ = specific density
$\dot{V}$ = volumetric flow rate of make-up water, known from $\dot{V}_m$ equation 3.10

The salinity in the system is defined as 12 ‰. Calculating the share of fresh- and saltwater mass flow rates, yields 66 % and 34 % respectively (see appendix A.3 for further details). Since the share of freshwater is larger than saltwater, the monthly temperature profile is based on a freshwater source to simplify calculations. Temperature profiles are taken from Marine Harvest's facility at Slørdal in Snillfjord, Trøndelag (appendix A.10). Temperatures were reported in the time period from 2003 to 2013, and monthly average is used [66].

The outlet temperature of the condenser is assumed to be 20 °C. This water is then led to a heat exchanger, with the make-up water on the cold side. The outlet temperature of 12 °C is met by a controller adjusting the flow rate on the hot side of the heat exchanger.

Parameters used for calculations are shown in table 9.

Table 9: Parameters for calculation of heat pump power consumption

Parameter	**Value**	**Reference**
η_c	55 %	[99]
c_p	4127 J/kgK	[100], [101]
ρ	1009 kg/m^3	[100], [101]
T_c	20 °C	assumption

3.4.6 Building requirements

Power consumption by the ventilation system is determined as described in equation 3.17. The Norwegian building code states that the total SFP for the ventilation system should be less than 1.5 [89]. SFP varies depending on several factors as described in section 3.4.2, and an average of 1.3 is assumed for calculations [89]. The flow rate of air $\dot{V}_{air}$ is determined based on the air exchange rate and is described as

$$\dot{V}_{air} = V_{building} e_{air} \tag{3.26}$$

Where
$V_{building}$ = volume of building $m3$
e_{air} = air exchange rate per hour h^{-1}

As the building consist of several divisions and the post-smolt only constitute a part of it, the volume of the building here only refer to the post-smolt division. This volume is found by computing the tank area and adding 40 % of its area for the treatment system [77]. The height is assumed to equal 4 m. The air exchange rate e_{air} is recommended to be between 1-3 according to [102], 1.5 h^{-1} is used for calculations [64].

The heat demand can shown in equation 3.27 [103].

$$Q = Q_t + Q_v - Q_g = (H_T + H_V)(T_{int} - T_e) - Q_g \tag{3.27}$$

Where
Q_t = transmission losses through building construction
Q_v = heat loss through ventilation and infiltration
Q_g = internal heat load
T_{int} = temperature within the building
T_e = temperature outside
H_T = heat transfer coefficient transmission losses [W/K]
H_V = heat transfer coefficient ventilation [W/K]

The internal load is estimated assuming that all energy input is dissipated as heat, and that the ventilation fans, degasser fans, mechanical filter motors and auto feeder add heat to the air. Other internal gains such as lights, control systems, computers, as well as heat transfer between air and water, are not included. The estimated specific energy demand is 157 kWh/m2 year, and is covered by direct electric heating.

4 Results and discussion

4.1 Main system characteristics

The production of post-smolt with an initial weight of 150 g to 500 g takes ten weeks. Only this batch is considered in this case study. The maximum specific density is 60 kg/m^3, while the specific density in the beginning of the production period is only 21 $kg/m3$, as no size grading occurs. The total production equals 196 297 kg, and the total volume of the system is 3300 m^3. The results from the production planning model, along with waste generation and O_2 demand are shown in figure 6. Maximum daily feed load is 2040 kg/day.

The waste generation of TSS, TAN and CO_2 scales with feed load, while O_2 demand scales with body mass.

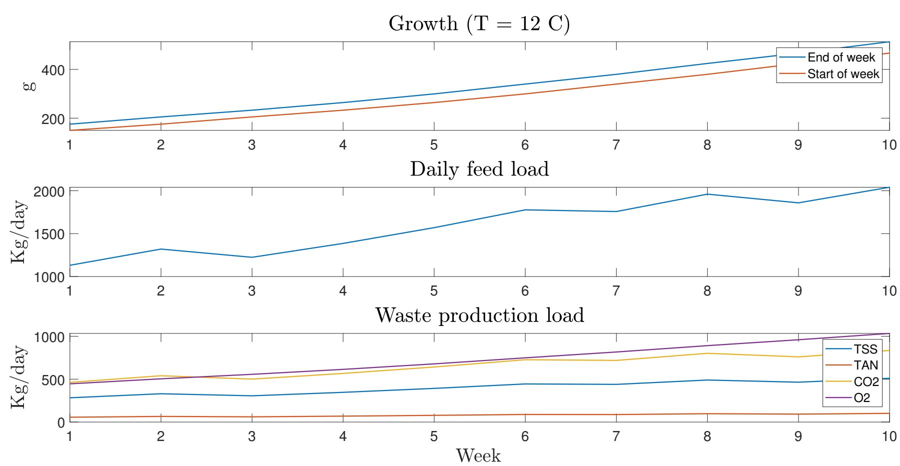

Figure 6: Weekly growth, feed load, oxygen demand and waste generation calculated by the production planning model.

A HRT of 40 min for the base case yields a flow rate of 82 467 L/min in the recirculating loop. The intake water flow equals 1649 L/min. If the production loads of TSS, TAN and CO_2 are uniformly distributed the respective concentrations in the last week are 4.3 mg/L, 0.85 mg/L and 7 mg/L. Hence, a HRT of 40 min is low enough to meet the water quality requirements presented in table 2 with good margin. This indicates that the HRT used here may be lower than required. With a HRT of 60 min and the assumption that substances are uniformly distributed, concentrations are still below the water quality requirements in the last production week. From a biological perspective there is however no point in operating close to the water quality limits. The water quality needs to be well within tolerance limits and as stable as possible [54]. Furthermore, assuming that waste is uniformly distributed is a simplification and a proper mass balance model should be used to establish the relation between HRT and water quality. Moreover, the relations for estimation of waste load is based on general factors, and may not be representative.

Summerfelt et. al [76] did an survey of Norwegian RAS facilities for smolt and post-smolt. They find that tank flow in newer systems is in the range of 33 to 40 m^3 water per kilo feed. The system described here operates at 58 m^3 water per kilo feed. Different stocking densities can explain some of the reason behind the divergent results. However, it may also indicate that the feed load estimated here is too low and/or that the HRT used is lower than needed. The bFCR used is 0.8, which is based on data from the feed supplier Aker Biomarine [67]. This may be too low, and an other study presents 0.9-1 as an average range for bFCR in closed-containment systems [68]. How important this is for the final result is further discussed in the section on sensitivity analysis (section 4.5).

4.2 Total and weekly energy use

In the base case oxygenation is done by a low-head oxygenation unit, sludge is treated to a dry matter content of 10% and HRT equals 40 min. The production of 196 ton post-smolt from 150 to 500 g over ten weeks results in an energy demand of 505 068 kWh, which is the same as the yearly energy consumption of 31 Norwegian households [104]. The review of energy use in RAS by Badiola et al. [16] presents energy use per live-weight kilo at farm gate. By dividing total energy use by 196 ton, the energy consumption is 2.57 kWh per live-weight kilo of fish. This energy use considers production of fish from 150 to 500 g and energy use required for production up to 150 g is not added. Comparing this to the energy use reported in table 1, this value lies in the middle of the range considered relevant for energy use in the Norwegian context.

It should be underlined that comparing energy use per kilo fish produced would have to take into account the stocking density and feed load of each system. If two different systems have the same energy consumption and volume, but different stocking densities, the system with higher stocking density will have a lower energy use per kilo fish. One can not conclude that one of the systems is more energy effective than the other based on kWh/kg fish produced. Variation in stocking densities and feed loads, as well as different system boundaries, may explain the variation in reported energy use for smolt and post-smolt in the Norwegian context.

More importantly, the final weight of smolt is different in the studies. The case here considers production of post-smolt from 150 to 500 g, and the energy use for production up to 150 g is not considered. Today, the most common size of smolt is considerable smaller than 500 g, typically around 80-150 g [54]. Colt et al. [34] find an energy use of 1.56 kWh/kg fish for salmon smolt of 80 g produced in RAS in the US (Pacific Northwest). The value of 2 kWh/kg fish reported by AKVAgroup [39] probably refers to smolt of 80-150 g. On the other hand, the study by Hilmarsen et al. [13] (3-5 kWh/kg fish) refers to post-smolt of 500 g. Including the energy for production of smolt up to 100-150 g will increase the total energy use, while the final production in kilo will still be the same. Adding the 2 kWh/kg fish required to produce fish of about 150 g to the energy use to grow fish from 150 to 500 g found in this study, yields a total energy use of 4.57 kWh/kg. This is in the same range as the energy use reported for post-smolt of 500 g in the study by Hilmarsen et al. [13].

The energy consumption in each production weeks is shown in figure 7. Processes related to treatment of recirculating water and intake water contribute 54% and 21% respectively to the total energy use. Building operations and fish tanks contribute 14% and 10%, while sludge treatment represents 1% of the total use. d'Orbcastel et al. [29] allocates 67% of the energy use to treatment of recirculating water. The higher share is most likely a consequence of airlifts being used instead of centrifugal pumps for recirculation. Colt et al. [34] allocates 58% to water treatment in the recycling loop. The same study allocated 26% to internal processes, such as heating/cooling and lightning. Hence, the aggregated distribution presented here is in agreement with earlier results.

Energy demand varies from 48 765 kWh in the first to 51 265 kWh in the last week, yielding a change of only 5%. Energy demand of the processes linked to tank, intake water and building operations stays constant, while energy use of water and sludge treatment processes increases as feed load increases. The flow rate in the water treatment loop is assumed to stay constant, which is the reason why energy use is fairly constant. If the flow rate is adjusted with respect to stocking density, the increase in energy use towards the end of the production period will be more significant. In addition to flow rate, the study by Badiola et al. [7] identifies temperatures and system maintenance as drivers for fluctuations in energy use. No studies published earlier report weekly or monthly energy consumption, so the evolution of weekly energy use can not be compared to earlier results.

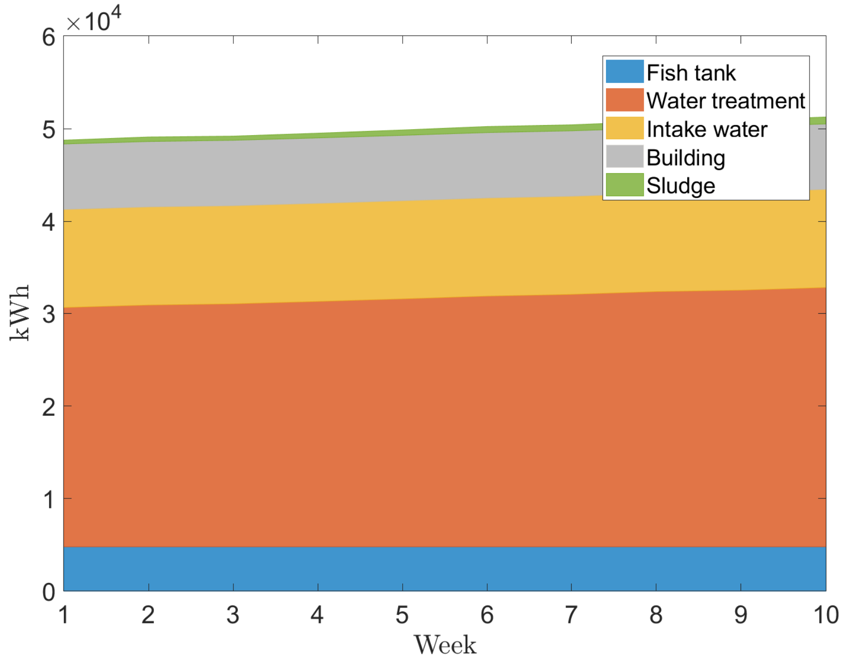

Figure 7: Weekly energy consumption of the main subsystems.

While most of the processes have a constant energy demand during the year, energy for building operations and the heat pump heating or cooling the intake water depends on external temperatures. For building operations the average yearly energy consumption is used, while in reality the weekly energy consumption is obviously related to outside temperature. The yearly average energy demand for space heating during a week is 3 kWh/m^2. This increases to 7 kWh/m^2 during winter, while no heating is required in summer.

The energy use of the heat pump depends on water source temperatures, which yields seasonal variations. The yearly average of 48 kW is used when results are presented. No temperature lift is required during summer, as the system temperature is assumed to be increased to around 14°C in these months. However, cooling is required due to heat gain from the system. Minimum power consumption is 4 kW, while maximum power consumption is 84 kW. This implies that which season the production period occurs will greatly influence the result, as the heat pump contributes significantly to overall energy use. A batch of post-smolt produced during autumn/winter will lead to a higher kWh/kg fish, than a batch produced in spring/summer. It should be underlined that the heating demand for the intake water is estimated as the heat required to lift the water temperature minus the heat gain from some of the components in the system. In practice, the heat gain is probably larger, as fish metabolism and bacterial activity in the biofilter are not accounted for. In addition, some of the heat from the discharge water is usually recovered. Together this will reduce energy consumption of the heat pump and decrease the importance of water source temperature. So, the seasonal variation in energy use may be smaller in reality than estimated by the model.

The stable energy use presented here is a result of the modeling choices made, and is not necessarily reflecting the actual energy consumption pattern of a post-smolt facility. Pumps are usually frequency controlled, meaning that pressure is controlled to the actual demand. This will lower the actual energy consumption of the pumps. UV devices can also be operated in a similar fashion using dose-pacing, which measures flow and transmittance to adjust the applied dose to the demand. Various feedback controls are also used, for instance for adjustment of oxygen addition with respect to the actual concentration. This may lead to errors in the weekly energy use estimated here. It is a weakness of the modeling that control systems, and thereby fluctuations in energy use, is not taken into account. An energy audit of an existing RAS highlights hourly fluctuations in energy use and argues that identifying energy consumption peaks is essential for energy efficiency [7]. This is certainly true, but developing a model with an hourly resolution and feedback controllers, would require detailed knowledge about system configuration. Such a model may be useful in the design phase of a specific system. To identify main energy consumption units and measures for energy efficiency on a more general basis a weekly resolution is however sufficient.

4.3 Distribution and drivers for energy use

The distribution of energy use in the different processes is displayed in figure 8. The recirculation pump is the main energy consuming unit, accounting for 23% of the total. This is inline with earlier studies. Summerfelt et al. [37] identify the recirculation pump as the main energy consuming unit in a partial-reuse system for smolt. Aubin et al. [30] find pumping and temperature control of water to be the most energy intensive processes in a RAS for turbot. Furthermore, a study of a RAS in Spain by Badiola et al.[7] find that the heat pump stands for the largest share of energy use, as there is a large cooling demand. When cooling is excluded , the pumps are the main energy consuming units, representing 42% of the total. Water flow is driving the energy use of the pump, but head and efficiency influence energy use to the same degree. As mentioned, variable frequency drive is often applied to pumps, which may lead to a lower energy demand than found in this study. On the other hand, friction losses estimated here may be lower than in reality, as few bends and geometrical shapes are considered. As a result, minor head losses may in reality be higher than estimated and increase the pumps energy use. In addition to the recirculation pump, a pump is used in the degasser. Taken together, the pumps account for 31% of the total energy use.

The heat pump and building operations represent about 15% of the total energy use each. The electrical energy demand for space heating is assumed to equal the heating demand, but this can be lowered if a heat pump is used. This is further described in section 4.6.

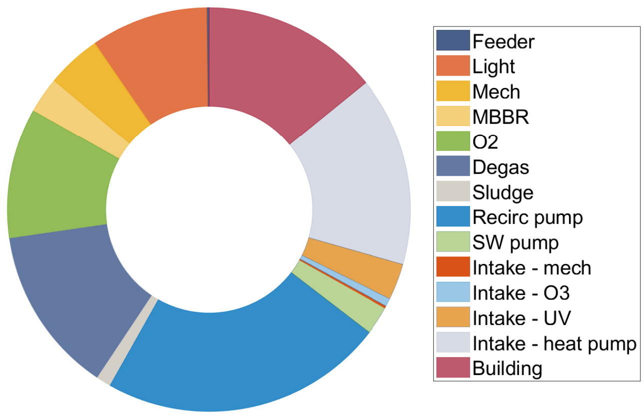

Figure 8: Distribution of energy use across different processes.

Water temperature, intake water flow rate (recirculation degree), COP and power consumption of other units determine the heat pumps energy consumption. Changing the degree of recirculation implies a large change in intake water flow, so energy use of the heat pump is sensitive to the chosen recirculation degree. The assumed COP is high, in average 10. Including an heat exchanger, recovering heat from the outflow, could however increase the overall efficiency of the heating unit to 20 [105]. Heat recovery is not included in the base case, which lead to a high energy demand of the heat pump. This is further discussed in the section on energy efficiency. Furthermore, excluding heat dissipated from fish metabolism and bacterial activity and heat transfer from air, may lead to an overestimation of the actual heat demand. Several suppliers of RAS in Norway point out the low demand for heating and significant demand for cooling [40]. The results here does not show this, which indicates that the internal heat gain may be underestimated.

Water temperature is also an essential driver for energy use of the heat pump, as heating or cooling water is very energy intensive [7]. As a consequence, the location of the RAS and the associated water source temperature will greatly influence energy use. As optimal growth for salmon smolt occurs at 15°C [40], the water temperatures in the Norwegian fjords are likely to reduce the energy consumption of the heat pump compared to many other production locations. Badiola et al. [7] for instance finds that the heat pump constitutes 73% of the total energy consumption in a RAS located in Spain. Energy use in different locations is analysed by using the same input data as for the base case, but changing the water source temperatures. Sea water temperature in Gibraltar, Chile and

Shanghai was used. The result is shown in table 10. Average power consumption of the heat pump is doubled if the RAS is located in Gibraltar, while average power consumption is reduced if the location is Chile.

Table 10: The influence of location and water source temperature on final energy consumption.

Location	Min/max temp.	Average power of heat pump	Total energy use
	°C	kW	kWh/kg
Gibraltar	15/22	87	2.9
Chile	12/16	31	2.4
Shanghai	5/25	65	2.7
Norway	3/14	48	2.6

The degassing unit stands for 13% of final energy use. The pump and blower has a constant energy use due to constant water flow, while the ventilation unit has an increasing power consumption as CO_2 concentration increases due to rising feed loads. The pump is most important for energy use of the unit, accounting for 85%. The necessary height of the degassing unit is 1.7 m, while the height used for calculations is 2 m, as done in a study describing the design of a RAS [75]. If the unit installed is 1.7 m instead of 2 m the energy consumption of the pump increases by 15%. Despite the increased height, there is only a minor improvement in treatment efficiency as seen from figure 5. This indicate that operating with a "safe margin" for the height of the degasser will not improve CO_2 removal significantly, but have important impact on energy use.
The ventilation unit ensuring that CO_2 does not accumulate is more important than the high capacity air blower. The power of the ventilation unit is driven by the recirculating water flow, as well as CO_2 concentration. The ventilation system is assumed to operate continuously, independent of the measured concentration in the room. If this is measured, the ventilation rate can be adjusted according to the actual demand.
The power of the blower is very sensitive to the inlet and outlet pressure of the degasser, while its efficiency is less important. This indicates that controlling the pressure is more important in terms of energy savings than investing in a blower with higher efficiency. Additionally, water flow rate is important, as the blower power scales linearly with the gas-to-liquid ratio and water flow. Reducing the water flow will reduce energy use, but as water quality is more important than energy use this is not a suitable energy efficiency measure.

The oxygenation process contribute 10% to total energy use. This is based on a system with one LHO unit in each tank using 1.77 kW. In this case, 20% of the energy use for oxygenation is attributed to oxygen production. This solution was also compared to a oxygenation cone operating with higher pressures adding oxygen to a partial loop and a cone adding oxygen to the total water flow. The results show that energy use increases by a factor of three in the first case and five in the latter. This increases the relative contribution of the oxygenation process to 26% and 36%.

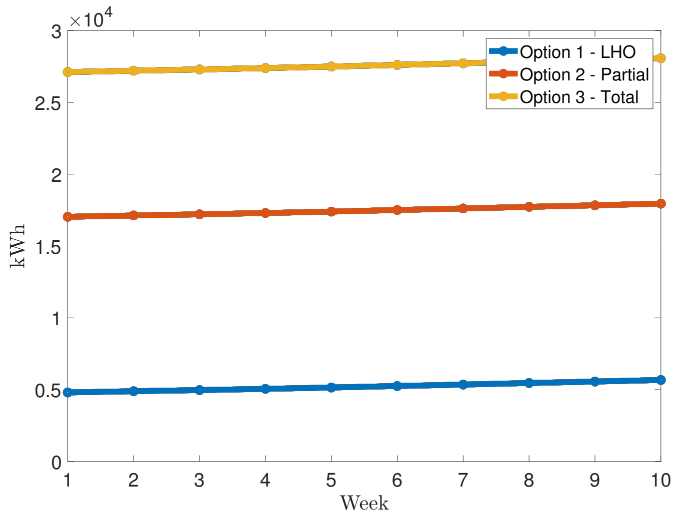

Figure 9: Weekly energy consumption of the different oxygenation options considered in the base case

The difference in weekly energy use for the different options is shown in figure 9. The slight increase in weekly energy demand is due to the increasing O_2 demand as the fish body mass increases. The energy for O_2 production is fairly similar for the three options, with only small differences due to different transfer efficiencies. The energy required for addition is however drastically different. Based on this one can conclude that the choice of oxygenation system and pressure levels is highly important for overall energy use. In larger saline systems with high water flows, a LHO unit is the preferred option considered here. In freshwater the oxygen transfer efficiency of these units are low, and a cone is typically used. U-tubes are another solution used in RAS, which as low head solutions requires minimal pressure [51].

A part from the aforementioned processes, lighting within the fish tanks is important for final energy use, representing 9% of the total. The data is taken from a RAS supplier and refers to energy efficient LED lights. The energy use depends on the dimensions of the tanks, but may be reduced if the water is clearer, i.e. through better mechanical filtration [62]. The mechanical and biological filtration, as well as treatment of intake water, is of less importance to total energy use. The latter is due to the low flow rate of intake water, as recirculation degree is high. The power factor used for the biofilter is 15 W/m^3 and may be a low estimate [67]. If the factor is doubled, the relative importance of the MBBR in terms of energy use remains little.

Energy use for sludge treatment is presented based on the option of treating the sludge to a dry matter content of 10%. This results in a total energy use of 5889 kWh and a relative contribution of only 1%. The other option, pumping the water directly to the fjord, has a total energy use of 5646 kWh. So, there is no significant differences in the energy demand of the two considered options. The two options considered reflect the common practice at many RAS and flow-through facilities today [62], [67]. However, primary treatment, meaning the filtration of particles from effluent water, has become the new standard for an increasing number of facilities. This has lead to an increased focus on sludge treatment and solutions for further use. The significant volumes of sludge with low dry matter content and the subsequent large need for transport has increased the focus on rising the dry matter content. This requires energy demanding drying processes [63], [62]. A study by Rosten et al. [63] on solutions for sludge treatment point to a significant increase in energy use for treatment if the dry matter content is increased from 30% to 90%. A rough estimate is 1 GWh for treatment of all sludge in Nordland county [63]. Using the same numbers, the sludge produced in this case implies an energy use of 23842 kWh. If this is added to the energy required to dewater and filter the sludge to DM10%, the contribution of sludge treatment increases to 6%. This highlights the need to focus on energy use when developing solutions for sludge treatment to higher dry matter contents.

The total energy use and relative contribution of each unit is shown in table 11. The power refer to the maximum/minimum hourly power consumption. The most significant drivers and parameters influencing the result are also presented.

4.4 Uncertainty

The color in the last column in table 11 indicates the anticipated uncertainty of the results. The units assigned green colour is based on well-established equations and available data for parameters is fairly good. In addition, through contact with RAS technology suppliers the values obtained have been validated to some degree.

Yellow indicates medium uncertainty. For mechanical filtration the installed power for both rotation of the drum and the backwashing unit is probably correct. The hour of operations of the backwashing motor is however uncertain, as limited data is found on the relation between TSS concentration, particle distribution and backwashing frequency. The wide range of reported treatment efficiencies found in literature makes a reasonable estimate difficult. In case of the air blower for degassing the uncertainty is related to the pressure levels in and out of the degasser, which the power consumption is sensitive to. The power consumption for UV is regarded uncertain even though data from three different suppliers are used for estimation. The low accuracy is due to limited documentation of the data, and the fact that data is adjusted to correct for the higher dose applied. Energy for ozone addition and production is assigned medium uncertainty as limited data is found for the ozone dose typically used. The relative contribution of all units assigned medium uncertainty is fairly small. Even if the accuracy of the estimated energy use for these units is low, a change is not likely to change the final result to a significant degree.

Energy demand for the heat pump and space heating is assigned a high uncertainty, and show large seasonal variations. The space heating demand is found by subtracting heat gains from heat losses. Heat losses is estimated based on heat transfer through the building envelope and ventilation system. Relevant heat transfer coefficients are easily found, and the heat loss has low uncertainty. Contrary, the estimated heat gain has high uncertainty. Heat gain from system components is taken into account, but other heat gains such as heat from lightning, electrical components and computers are left out. This is due to data limitation. In addition, the heat transfer between air and water is not considered. Taking this into consideration requires a more detailed modeling of the building heat transfer, and appropriate values relevant for land-based aquaculture systems are needed. As mentioned earlier, the estimation of heat gain leads to uncertainty in the energy use of the heat pump as well. Heat dissipated from fish, bacterial activity and air is excluded. Moreover, certain estimates for the outlet temperature out of the condenser would reduce the uncertainty of the COP. Lack of complete data on the configuration of the heating system and operation of heat exchangers leads to uncertainty.

Table 11: Total energy use, variation in power demand and drivers for each unit.

Unit	Share	Power min/max	Total	Main drivers/parameters	Uncertainty
		kWh	kWh		
Feeder	0.2%	0.6/0.6	941	Tank dimension	
Lightning	9.3%	28/28	47 040	Tank dimension	
Mechanical filtration	4.3%	10.3/15.5	21 759	Water flow rate TSS conc. and distribution	
Biological filtration	2.9%	8.7/8.7	14 559	Volume of biofilter Flux through filter	
O_2 addition	8.2%	24.8/24.8	41 630	Water flow rate O_2 demand Operating pressure	
O_2 production	2.1%	3.8/9	10 551	O_2 demand Oxygen transfer efficiency Production process	
Sludge	1.2%	2.5/4.5	5889	Feed load DM%	
Recirculation pump	22.5%	67.7/67.7	113 767	Water flow rate Total dynamic head Efficiency	
Sea water pump	2.3%	6.9/6.9	11 518	Intake water rate Total dynamic head Efficiency	
Intake - mechanical filtration	0.2%	0.5/0.5	840	Intake water rate TSS conc. and distribution	
Intake - UV	2.9%	8.6/8.6	14 497	Intake water rate UV dose Water transmittance	
Intake water - O_3	0.7%	1.9/1.9	3292	Intake water rate Ozone dose	
Intake - heat pump	16%	4/84	81 179	Water source temperature Internal heat gain COP	
Degassing pump	11.2%	34/34	56 460	Water flow rate Height of unit Efficiency	
Degassing ventilation	1.5%	3/5.7	7561	Water flow rate CO_2 concentration Specific fan power	
Degassing air blower	0.6%	1.7/1.7	2820	Water flow rate Gas to liquid ratio Pressure	
Space heating	12.6%	35/82	63 634	Building heat loss Ventilation heat loss Internal/external temp.	
Ventilation	1.4%	4.2/4.2	7134	Air exchange rate Specific fan power	

4.5 Sensitivity analysis

Sensitivity analysis is performed for some parameters to analyse how total energy use changes with respect to a change in input parameters. Sensitivity is assessed for head, bFCR, recirculation degree and HRT, as these are important drivers of the total energy use.

4.5.1 Head

As the recirculation pump is the most important contributor to overall energy use, the change with respect to head is presented. Figure 10 shows the variation in energy use due to a change in head from -30% to 30% with respect to the base case value of 4.03 m. If head is increased by 1%, and all other parameters kept constant, the total energy use increases by 0.21%. This shows the importance of reducing friction losses and lifting height to reduce energy use in RAS, especially as it does not worsen water quality and biological conditions.

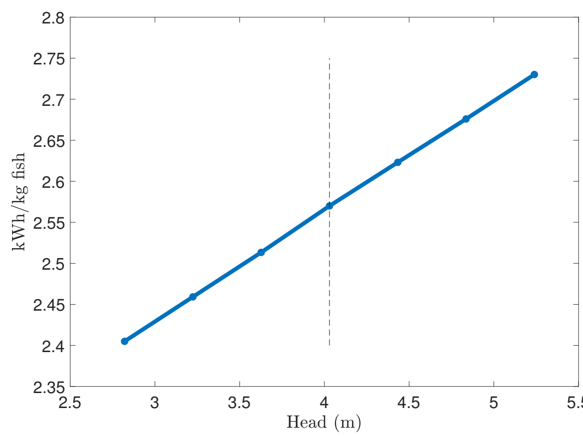

Figure 10: Sensitivity of energy use to the total dynamic head of the recirculation pump.

4.5.2 Feed factor

The variation in energy use due to a variation in bFCR was also analysed, as the bFCR applied in the base case is lower than values reported by other studies. The result is shown in figure 11. Increasing bFCR by 1% increases total energy use by 0.04%. Hence, the use of a low bFCR in this study does not influence the final results greatly. Energy use increases if bFCR is increased, as the process for biological filtration, oxygenation and degasser ventilation depend on feed load. The low sensitivity of energy use to a change in bFCR is to some degree explained by the modeling choices made. As an example, energy use for sludge treatment is increased if bFCR is changed from 0.8 to 0.9. However, energy use of the mechanical filter is not, even though backwashing frequency should increase with higher feed load and particle concentration. The reason for this is the assumption that backwashing frequency is increased each week, independent of the actual concentration. Lack of a valid relation

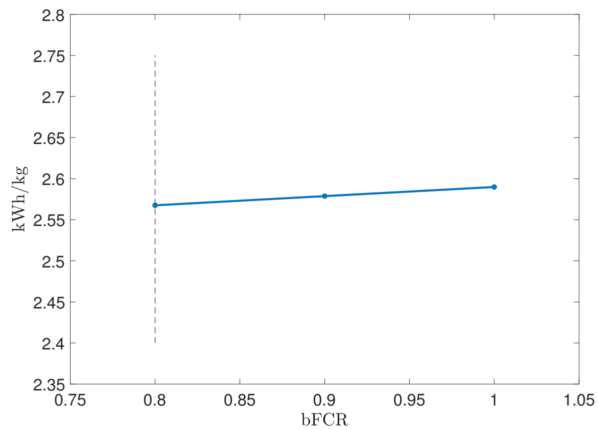

Figure 11: Sensitivity of energy use to bFCR.

between concentration and backwashing frequency is the reason for this simplifying assumption.

The limitations of a sensitivity analysis changing only one parameter at a time should be pointed out. By changing only one factor at a time, simultaneous variation in input parameters are not taken into account. In this case, an increase in feed factor will increase the waste produced and concentrations. This may cause a reduction in HRT, which will increase the energy use of the other units in the water treatment loop as well. Hence, when bFCR is increased the actual increase in energy use may be higher than predicted by a simple sensitivity analysis.

4.5.3 Recirculation degree

Only a minor change in the recirculation degree cause a large change in the water flow of intake water. The result of the base case was compared to a high recirculation degree of 99.3%, and a lower of 97%. HRT stays constant, while in reality it could potentially be increased as more clean intake water dilutes some of the waste load.

As the intake water flow rate changes, the energy use of the sea water pump, UV, ozone and mechanical filtration, as well as the heat pump and space heating changes. For a recirculation degree of 99.3% the relative contribution of intake water treatment is reduced to 7% compared to 21% in the base case. This is mainly due to the reduction in energy use of the heat pump, which is reduced from 81 179 kWh to 16 483 kWh. Total energy use is 2.17 kWh/kg fish. A recirculation degree of 97% increases the relative contribution of intake water treatment to 30%. The heat pump energy use is increased to 123 250 kWh, and overall energy use is 2.86 kWh/kg fish. The heat pump is the main contributor to overall energy use in this case.

4.5.4 Water treatment flow rate

The variation in energy use with respect to HRT is shown in figure 12. Increasing the HRT, decreases the water flow rate and vice versa. The red line refers to a constant intake water flow, while recirculation degree is allowed to vary as a consequence of increased flow rate in the water treatment loop (see equation 3.10). The blue line refers to a constant recirculation degree, while the intake water flow is allowed to vary as the water treatment flow rate is changed. Increasing HRT, i.e. reducing water treatment flow rate, lead to a larger reduction in energy use if the intake water flow is kept constant (red). If the recirculation degree is constant (blue), increasing HRT will increase the intake water flow rate. Hence, the energy use of the intake water treatment is increased and the overall energy use reduction is smaller (blue). Increasing HRT by 1% leads to a change in total energy use of -0.56% (red) and -0.34% (blue).

Summerfelt et al. [76] finds that water flow per feed load is lower in systems built earlier than in newly built systems, meaning that newer systems operate at lower HRT. The study points out that this change had improved the water quality in RAS. The sensitivity analysis shows that this increases energy consumption. There is a trade-off between biological conditions and energy use. However, one can also argue that the improved biological conditions increase fish growth and reduce mortality, which could reduce energy per kilo fish produced.

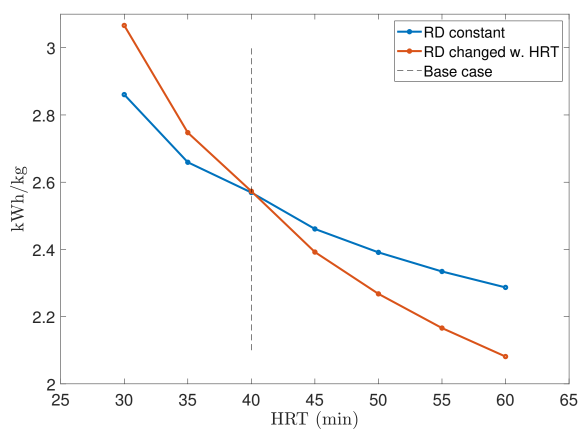

Figure 12: Sensitivity of energy use to HRT. RD constant refers to a constant recirculation degree of 98%. The red line refer to a changed recirculation degree due to changes in HRT. The dashed lined indicate HRT of the base case.

4.6 Energy efficiency in RAS

Some of the main energy efficiency measures relevant for RAS are summarized in table 12. The symbols to the right indicate the potential effect on water quality and conditions for the fish: (∗)

indicates a neutral effect on water quality, (+) indicates better water quality, while (-) indicates a worsening. The measures and savings potentials are described in further detail in this section.

Table 12: Identified energy efficiency measures and the potential effect on water quality.

Unit	**Energy efficiency measure**	**Effect on water quality/fish**
Pumps	• Frequency control • Piping dimensioning • Correct pump dimensioning • Parallel pumps	$*$ $*$ $*$ $*$
Water treatment loop	• Increase HRT	-/$*$
Building operations	• Heat pump • Heat recovery ventilation • Demand controlled ventilation • Heat integration • LED lightning and sensors	$*$ $*$ $*$ $*$ $*$
Heat pump	• Heat recovery • Deep intake	$*$ +/-
Lightning	• Replacement of halogen by LED	+
Oxygenation	• LHO in saline water • Oxygenation of partial loop	+/$*$ +/$*$
Feed	• Special feed reducing soluble particles	+
Energy management	• Monitoring and analysis of energy use • Better decision-making for energy efficiency	$*$ $*$

4.6.1 Adjustment of water flow rate

As shown earlier, most of the processes within the water treatment loop depend on the water flow rate. As seen by the sensitivity analysis, an increase in HRT of 10% can reduce the total energy use by 5.6%. d'Orbcastel et al. [35] also identified the potential for reducing energy use by decreasing water flow rate. By reducing the water flow rate by 25%, energy use was reduced by 20% in a RAS for rainbow trout, without a significant effect on fish performance. The energy reduction potential is determined by the decrease in water flow rate which is possible without compromising water quality. In addition to water quality, potential reduction in water flow is subject to other requirements. Firstly, sufficient flow velocity is required for trimming the fish and settling of faeces and feed spill. Second, increasing the water flow rate is found to be beneficial for the growth rate of smolt [106]. In total, this implies that the water flow rate is often not reduced to the level predicted by the water quality parameters alone [51].

Summerfelt et al. [76] note that newer systems operate with shorter HRT, which tend to produce better water quality at the expense of higher energy use. In this study, the sensitivity analysis shows that a change in HRT below 45 minutes increases energy use more rapidly than a change in HRT above 45 minutes. Energy use seems less sensitive to a change in HRT if the HRT is higher. This indicates that reducing HRT below 40 minutes will have important impacts on energy use. This result should however be validated at an operating RAS, as it may be an artifact of the modelling. If possible with respect to water quality, operating with a higher HRT will reduce energy demand.

4.6.2 Pumps

Pumps are designed based on the maximum water flow rate and pressure, but this usually occur for only limited periods of the operation time. Frequency controllers are used to control speed and provide energy savings of 5-20% ([107], [7]) or even 30-50% [108]. The focus on variable frequency drive for energy efficiency of centrifugal pumps is large both in literature and industry [108]. In this regard, one can expect that many systems operated today already has this implemented. Component selection and system dimensioning are other factors affecting energy efficiency. By increasing the diameter of the piping system and reducing bends, friction losses are reduced and energy savings of 5-20% and 5-10% can respectively be achieved. For this specific system, the sensitivity analysis for head shows a reduction in total energy consumption by 2.1% if head is reduced by 10%.

In total, correct dimensioning of pumps and piping system can reduce energy demand by 15-20% [108]. In many cases pumps are over dimensioned to ensure safety capacity, which is disadvantageous in terms of energy use. Installing pumps in parallel, which each is able to deliver half of the flow rate at the total designed head, is a better option. By installing a parallel pumping system savings of 10-30% and a wider range of desired flow rate with increased efficiency is obtained [108]. The installation of a new motor with higher efficiency contribute less to energy savings, typically only 1-3% [108]. To summarize, (1) variable frequency drive, (2) correct dimensioning of pumps and piping systems and (3) parallel pumps are the most effective measures to reduce energy consumption of the recirculating pump.

4.6.3 Building operations

Space heating is in this case study assumed done by direct electric heating. This means that the estimated electrical energy demand for heating equals the heating demand. By using either an air-to-air or water-to-water heat pump for space heating, the energy demand can be reduced significantly. Assuming that the heat pump installed is designed to cover 90% of the yearly heating demand, while an electric boiler (95% efficiency) covers the peak load the yearly energy savings can be calculated as below [99]. 3.5 refers to the seasonal COP.

$$\triangle E = 1 - \left(0.9 * \frac{1}{3.5} + 0.1 * \frac{1}{0.95}\right) = 64\% \tag{4.1}$$

This reduces yearly energy demand for space heating to 22 908 kWh, and reduces the relative contribution of building operations from 14% to 6.5 % when energy demand of all other units is kept constant. The total energy use is reduced from 2.57 to 2.37 kWh/kg fish.

A large share of the heat loss from the building occurs due to the ventilation system. Reducing ventilation air rate is beneficial to minimize heat loss and power consumption, but an acceptable facility climate must be met at the same time. Gehlert et al. [64] analysed the potential for energy savings of ventilation units in RAS, and argued that this part of the system is a bit out of focus as it does not affect fish growth directly. They find that dynamic facility ventilation can provide significant energy savings. Dynamic facility ventilation means that frequency controllers are installed on all blowers, which adjust the air flow rate based on measurements of temperature, relative humidity and pressure differences. The facility investigated in their study is designed to operate with an air residence time of 0.5 h, meaning that the total building volume is replaced twice an hour. The air residence time applied in this study is 0.67 h. They find that the air residence time can be increased to 1.1 h, and still keep the relative humidity within acceptable limits. This reduces energy consumption of the blowers in the ventilation unit by 85%, but will also reduce heat loss. Savings can thus be obtained by optimizing the control of the ventilation system without substantial modification.

A study by Enova on general measures for energy efficiency in the food processing industry states that control of ventilation air rates can reduce ventilation power consumption by 40% and heat demand by 20% [107]. Heat recovery of ventilation air is another energy efficiency measure to reduce heat losses from the ventilation unit. This can be applicable both for the ventilation air from the degassing unit and the rest of the room. In general the potential for heat integration is large, for instance by recovering the heat from drying processes for sludge treatment or oxygen generators if they are located on-site. As facilities become larger the potential for this is increasing, as the return on investment is higher.

4.6.4 Temperature control

Using an heat pump for temperature control of the make-up water is essential for energy efficiency, and reduces energy use significantly compared to oil furnaces or electric heating. This study did not include heat transfer from effluent treatment water to the make-up water. This is typically done by installing a plate heat exchanger, as seen in figure 13.

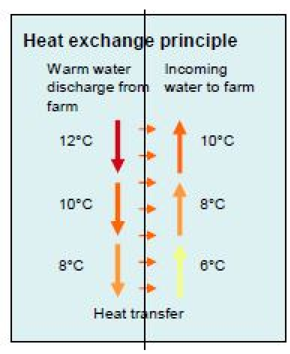

Figure 13: Principle of a plate heat exchanger for recovery of heat from waste water. Figure taken from [54]

The saving potential of installing an heat exchanger can be calculated by adding the recovered heat to the internal heat gain. Temperature efficiency of the heat exchanger is dependent on in- and outgoing temperatures. Assuming an average efficiency of 0.75 (ϵ), the heat recovered is calculated as:

$$Q_{recovered} = \epsilon * \dot{m} * C_p * \triangle T \tag{4.2}$$

Using the same temperatures as indicated in the figure 13, and the same water source temperatures as earlier, the average yearly heat recovery is 330 kW. This reduces the contribution of the heat pump from 16 to 9% and reduces total energy use from 2.57 kWh/kg fish to 2.37 kWh/kg fish.

Reducing the water temperature of the system can also be beneficial, if this does not increase the cooling demand. Reducing the temperature decreases the heating demand for the heat pump, but will also extend the production period due to slower growth. The reduction in heat demand must be weighed against the longer operating time.

The depth of water intake also influences the heat demand for make-up water. By using a deep intake water temperatures are higher and more stable. Along the Norwegian coast stable temperatures of 7 +- 1.5 °C is found, contrary to the variable temperatures of surface water used in this study [19]. The pumping costs are however increased, but is likely to have less of a contribution to overall energy use.

4.6.5 Other measures

LED lightning

Lightning within the fish tanks is found to contribute significantly to total energy use. In this study, LED lights are used, which is 50% more efficient than halogen lamps [109]. Replacing old halogen lamps provide energy savings as well as enhanced growth rates and decreased mortality [110]. A study by Philips in cooperation with Marine Harvest [110] finds that daily growth rate increases by 42% if LED is used instead of metal halogen. Installing LED lights is also relevant for energy savings in other parts of the building.

Energy management

Badiola et al. [111] argues that rather than installing better and more complex designs, a better understanding of key factors for energy, water quality and fish requirements is necessary. RAS units are management-dependent, and optimal decision-making is crucial for efficient functioning [7]. Increasing the focus on energy management may contribute to a reduction in energy use of 5-10% [107]. This includes development of energy related goals, increasing competence, optimization of units with large energy demand and systematic analysis of energy consumption over time [107]. By the identification of key parameters for energy use an energy consumption-map can be drawn. This may aid decision-making on investments for energy efficiency and improve knowledge of the return period of those [7].

Feed

Feed spill yield suboptimal conditions for the fish and increases the load of the treatment unit. Therefore, good dispersal and precision of the feeding device is essential [107]. New feed technology has recently made faeces particles larger and less soluble. This implies increased capture of particles in the mechanical filter, which reduces the load of the biofilter [112]. This increases production capacity [112], which reduces energy use per weight of fish. Moreover, this is beneficial as control of solid particles and bio filter is identifies as the most difficult treatment processes to manage [111].

4.7 Post-smolt production and implications for energy use

The case developed in this study was chosen to illustrate the potential changes in energy use if investment in RAS for post-smolt production continue. To assess the change in energy use, it is relevant to compare this to the energy use if the smolt is placed in open-net pens at 150 g instead. The total energy use in Norway for production of 1 tonne of live-weight salmon is 4234 MJ according to a report by Bellona and ABB [113]. This yields 1.17 kWh/kg fish during the 14-24 months the fish is kept in open-net pens (smolt to slaughter weight). Growth from 150 g to 500 g is done in approximately 125 days [114]. Hence, production from 150 to 500 g in open-net pens has an energy use of 0.2-0.3 kWh/kg fish (see appendix A.13 for details). Production in RAS requires 2.57 kWh/kg fish. So, the energy use for post-smolt production in RAS is 9-13 times higher than energy required for production in open-net pens.

On the other hand, the energy use in open-net pens are diesel based in about 50% of the Norwegian facilities [113]. Energy use in RAS is nearly entirely based on electricity [107]. Comparing the emissions related to energy use in RAS and open-net pens is therefore relevant. If the facility uses diesel, the energy use of 0.2 kWh/kg fish results in emissions of 50 g CO_2eq/kg fish. An emission factor of 0.245 kg CO_2eq/kWh is assumed for diesel, which only includes emissions from combustion. The use of energy in RAS has close to no direct emissions as electricity is mainly used. If one include the emissions from production, transmission and distribution of electricity the emission factor for the Nordic electricity mix is 0.114 kgCO_2eq/kWh [13]. Using this, the emissions related to energy use in RAS is 293 g CO_2eq/kg fish. Using a Norwegian electricity mix (0.0164 kgCO_2/kWh) results in emissions of 42 g CO_2eq/kg fish. See appendix A.13 for details.

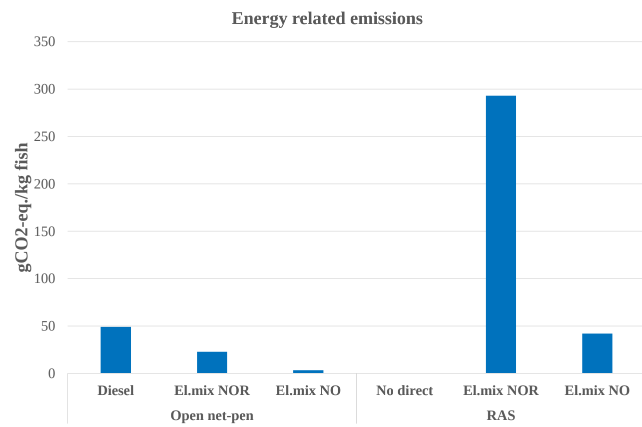

Figure 14: Energy related emissions of RAS and an open-net pen system. El.mix NOR refer to Nordic electricity mix, El.mix NO to Norwegian electricity mix.

As presented in figure 14, emissions from energy use related to production of post-smolt in RAS is very dependent on the chosen electricity mix, as highlighted by earlier life cycle assessments. If an emissions factor of the Nordic electricity mix is applied, energy related emissions in RAS is significantly higher than a diesel based open-net pen system. If a Norwegian electricity mix is applied production in RAS has lower GHG emissions than a diesel open-net pen system. It is important to underline that only emissions from diesel combustion is included, and upstream emissions are not. If the production of post-smolt in RAS replaces the production period in an open-net pen using electricity, energy related emissions will increase. To conclude, the production of post-smolt in RAS will increase energy use and may increase associated emissions in the industry.

4.8 Recommendations and future work

The model developed for power consumption in this study is a first draft towards developing a general model for energy use in RAS. Such a model is useful as carrying out experiment at full or pilot scale is expensive. RAS is highly complex systems due to system feedbacks, as well as interactions between fish grow-out on one hand and water treatment and energy use on the other [115]. Developing a simulation model for RAS including energy use allow for identification of energy-efficient solutions in the design phase. This is relevant for the Norwegian industry, due to large investments in RAS and increased interest for post-smolt.

The model developed in this study is useful for a first identification of main energy consuming units in the system, and associated energy efficiency measures. The results of this study should however be compared to energy use of each unit in an operating RAS. The source data used is scarce for several parameters and values are taken from a range of different sources with varying quality. In several cases assumptions are made. This implies that a validation beyond the sensitivity analysis and comparison with earlier studies done here is vital. Moreover, some units found in operating RAS today are not included, such as UV within the treatment loop and ozone/protein skimmers. Additionally, energy use for transport of fish within the system, feed distribution and control systems are not included.

The modeling of heating/cooling demand in this study is regarded uncertain. Improving the modeling of energy use in these units is highly relevant as they contribute largely to overall energy use. Additionally, the identified potential for heat integration is large, and smart management of waste heat can reduce heating/cooling demand. It is argued that this has been a bit out of focus in the industry, as it is not directly related to fish performance [64]. The quantities of sludge is anticipated to increase significantly, as facilities with larger capacities are built. The potential for heat integration of drying treatment processes and even biogas production locally, provides opportunities for local energy production and effective treatment of effluent water [116]. Despite a low carbon intensity of the Norwegian electricity mix, local production of energy and reduced energy demand is important to avoid increased CO_2emissions if larger fish is produced on land instead of in sea.

The study here is limited to one production of post-smolt from 150 g to 500 g. A more complete picture of energy use in RAS should include several sections, and will to a larger degree reflect the actual energy use. No size grading is assumed in the case developed here. Despite a low stocking density in the first week compared to the last production week, HRT is kept constant. This was done based on feedback from RAS suppliers saying that many facilities operate with HRT being more or less constant. As this is found to be an essential parameter for energy use, the practices on HRT adjustment among RAS operators should be further examined. The energy use was also found to be more sensitive to a change in HRT if HRT is low. The results here indicate that a change in HRT below 40 min will increase energy use more significantly, than a change in an high HRT. Whether this is only an artifact of the modeling, should be validated against HRT and energy use of operating systems.

Further work should also link the water treatment flow rate to water quality and flow requirements. As the flow rate in this study is not adjusted according to water quality parameters, many of the units have a constant energy use. Understanding how flow rate are adjusted and how energy use change as a function of water quality are important next steps. This can be done by integrating mass balance models into the work done here, or incorporate energy use into an existing simulation model for RAS, such as the work by Wik et al. [115].

In this study several energy efficiency measures with no negative impact on water quality are identified, yet the actual saving potentials are not quantified. To which degree these measures are already implemented in Norwegian recirculating facilities today is unknown. A study by Enova [107] indicated that some of these measures provide significant saving potential, but this study was done before RAS technology was commonly used. An overview of the current energy use and actual potential for energy savings within the industry is thus essential.

5 Conclusion

This study provides insight to the energy use of post-smolt production in RAS in Norway. The literature review identifies the lower environmental impacts compared to flow-through systems, with energy related impacts as an exception. Production of larger smolt in RAS is also found to reduce the problem of lice and escapes, which are main limiting factors for future growth in the Norwegian salmon industry. There is a need to develop new technical solutions to lower energy use of recirculating systems, but little research is done yet. There is a wide range of reported values for energy use in literature, and few of them are relevant for the Norwegian production of post-smolt. Furthermore, only a few studies are found to report energy use on a unit basis and most of them are older, pilot scale RAS.

In this study, drivers for energy demand in a typical Norwegian RAS for post-smolt production are identified. The head, water treatment flow rate, recirculating degree and configuration of the heating system are identified as key drivers for energy use. Knowing what drives energy use allow for identification of energy efficiency measures and development of energy management strategies. A case was developed to estimate the distribution of energy use. The production of 196 ton fish from 150 g to 500 g results in an energy demand of 505 068 kWh, equalling the yearly energy consumption of 31 Norwegian households. The energy use is 2.57 kWh per kilo fish produced, which is comparable to earlier estimates. The recirculation pump is identified as the main energy consuming unit. Heating of make-up water, space heating, oxygenation and degassing are other units with high energy use. The energy use for heating/cooling of make-up water and space heating is however uncertain, and a more detailed modeling is required. A comparison of different options for oxygenation finds that a low head oxygenation unit is the most energy efficient choice.

Energy use is sensitive to the choice of location and associated water source temperatures. The comparison of various locations revealed that average power consumption of the sea water heat pump is doubled and total energy use increased by 11% if the facility is located in Gibraltar instead of Norway. This, as well as the low carbon intensity of the electricity mix in Norway, can make salmon production in RAS a more sustainable technology in Norway than in many other locations. The sensitivity analysis shows that estimated energy use is sensitive to head and water treatment flow rate. The recirculation degree also greatly affect the result and increases energy use of the heat pump and UV. Finally, more extensive sludge treatment and an increase of dry matter content will increase the relative contribution of this process. Focus on energy use is thus essential when developing new solutions for sludge treatment and further use of this resource.

Several measures for energy efficiency are identified, especially with regard to pumps and heat recovery. Many of these would not decrease water quality, which makes promotion of these energy efficiency measures possible. To which degree these are already implemented at Norwegian facilities is unknown, as no recent studies are done.

There is obviously a large focus on water quality in RAS, while little research has been conducted on energy use and efficiency. Previous research on overall environmental impact of RAS technology indicate however that energy use may hamper its sustainability. This study indicates that a displacement of a part of salmon production from open-net pens to RAS will increase energy use, and related emissions may rise. To avoid the case of problem shifting, where emission of nutrients, lice and escapes are reduced, while energy related emissions increase, increased efforts for lowering energy use is necessary. The reduction in energy use will however always have to be balanced to the increased biological risk.

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A

A.1 Appendix 1

Table 13: Life cycle assessments of recirculating aquaculture systems.

Species	Technology	Location	Main result	Energy use kWh/kg	Reference
Atlantic salmon	Open net-pen Conceptual RAS	Norway USA	Carbon footprint (CF) only. Salmon produced in RAS 50% lower CF.	5.46	Liu et al. [14]
Atlantic cod 1 kg.	RAS	Spain	High energy demand and associated impacts.	29.4	Badiola et al. [7]
Turbot	RAS	France	High impacts due to pumping and heating of water	-	Aubin et al. [30]
Atlantic salmon Artic char	Marine pen and bag FTS RAS	Canada	Results sensitive to el-mic RAS worst in 6 of 7 impact categories	22.6	Ayer & Tyedmers [27]
Trout	FTS RAS (low head)	France Denmark	RAS more favourable at local and regional level, except energy	16	d'Orbcastel et al. [29]
Rainbow trout	FTS RAS	Germany Denmark	RAS high impact for GWP, acidification, land use. Low eutrophication and water use.	19.6	Samuel-Fitwi et al. [28]

A.2 Appendix 2

Table 14: Studies considering energy use in recirculating aquaculture systems.

Species	Harvest weight	Technology	Location	Main result	Energy use	Reference
		g			kWh/kg	
Atlantic salmon smolt	80	FTS Partial reuse RAS	USA	Energy use of water supply, internal hatchery, water treatment.	1.56	Colt et al. [34]
Rainbow trout	up to 700	FTS RAS	Denmark	Energy use of water treatment and global	3.56	d'Orbcastel et al. [35]
Trout	-	FTS RAS	Denmark	Energy use of water treatment, pumping, oxygenation feed distribution, fish handling	16	d'Orbcastel et al. [29]
Rainbow trout	103	Partial reuse	USA	Energy use of pumps, aeration, drum filter	2.9	Summerfelt et al. [36]
Atlantic salmon smolt	137	Partial reuse	USA	Energy use of pumps, stripping tower, drum filter	19-26	Summerfelt et al. [37]
Atlantic salmon smolt	-	RAS	Norway Canada	Total energy use	4.1 20	Bergheim et al. [38]
Several	-	RAS	Several	Review article. Energy efficiency and integration of renewables	2.9-81.5	Badiola et al. [16]

A.3 Appendix 3

The two equations A.1 and A.2 are then solved for freshwater and saltwater mass flow rates. This results in the share of each.

$$S_{fw}\dot{m}_{fw} + S_{sw}\dot{m}_{sw} = S_{tot}\dot{m}_{tot} \tag{A.1}$$

$$\dot{m}_{fw} + \dot{m}_{sw} = \dot{m}_{tot} \tag{A.2}$$

Where
S_{fw} = salinity in freshwater = assumed to equal 0 ‰
S_{sw} = salinity in salt water = 35 ‰
S_{tot} = salinity in system = 12 ‰
m_{fw} = mass flow rate of freshwater
m_{sw} = mass flow rate of saltwater
m_{tot} = total mass flow rate, calculated from **??** and 3.25

A.4 Appendix 4

Pump

$$P = \frac{(\rho * g * H) * \dot{V}}{\eta} * \frac{1}{3.6 * 10^6} \tag{A.3}$$

Where
ρ = 1000 kg/m^3
g = 9.81 m/s^2
η = 80% [91]
$\dot{V}$ = 82467 L/min = 4989 m^3/h
P = 33.61 kW

Air blower

$$P = \frac{\frac{G}{L}\dot{V}P_1}{17.4\eta}\left[\left(\frac{P_2}{P_1}\right)^{0.283} - 1\right] \tag{A.4}$$

$$P = \frac{5 * 1.37m3/h * 101kPa}{17.4 * 0.7}\left[\left(\frac{111.91kPa}{101kPa}\right)^{0.283} - 1\right] \tag{A.5}$$

P = 1.68 kW

Ventilation rate for degasser

$$\dot{V}_{air} = \dot{V}_{\mathrm{CO_2}}\frac{T_s}{T_i}\frac{10^6}{(C_i - C_s) * 60} \tag{A.6}$$

taken from [103], with unit $\frac{L}{min}$
Where
T_s = outdoor temperature = 7 °C = 280.15 K, assumed yearly average
T_i = indoor temperature = 16 °C = 286.16 K, assumption
C_i = allowed concentration of CO_2 = 1000 ppm [103]
C_s = outdoor concentration of CO_2 = 400 ppm [103]
$\dot{V}_{\mathrm{CO}_2}$ = production of CO_2 in L/min

Production of CO_2 refers here to the amount of CO_2 transferred to the air passed through the degasser in L/min.
Production of CO_2 in L/min, led out by air in the degasser is estimated using the following equation:

$$\dot{V}_{\mathrm{CO}_2} = \frac{\eta * P_{\mathrm{CO}_2}}{1000 * \rho} \tag{A.7}$$

Where
η = removal efficiency, 72%, estimated from 3.4.2
ρ = density of CO_2 = 1.98 g/L
P_{CO_2} = production of CO_2, g/min
Calculations are shown in figure 15.

Week	CO2 conc (mg/L)	Vent CO2 (L/min)	Vair (m3/sek)	P (kW)
1	3,9	116,8	3,18	3,18
2	4,5	136,3	3,71	3,71
3	4,2	126,4	3,44	3,44
4	4,8	143,2	3,89	3,89
5	5,4	162,1	4,41	4,41
6	6,1	183,5	4,99	4,99
7	6,1	181,5	4,94	4,94
8	6,7	202,4	5,50	5,50
9	6,4	192,0	5,22	5,22
10	7,0	210,7	5,73	5,73

Figure 15: Estimation of CO_2 production rate from degasser and required power to vent this out to meet the limit of 1000 ppm

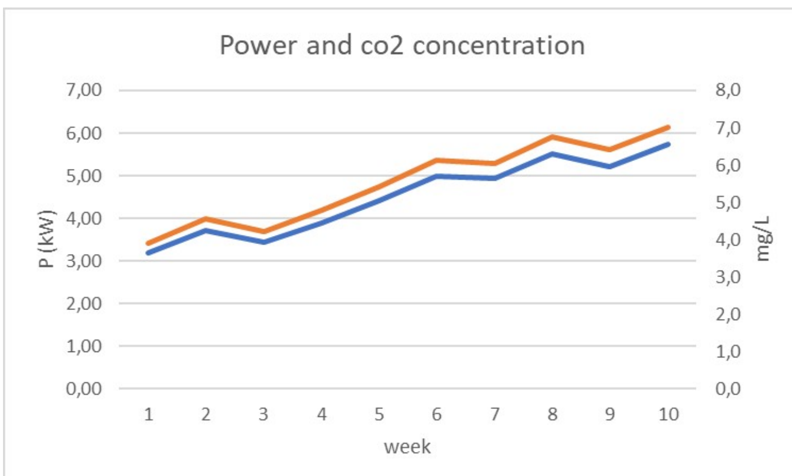

Figure 16: Power requirement of exhaust ventilation fan (left axis) and concentration of CO_2 (right axis) in each week

A.5 Appendix 5

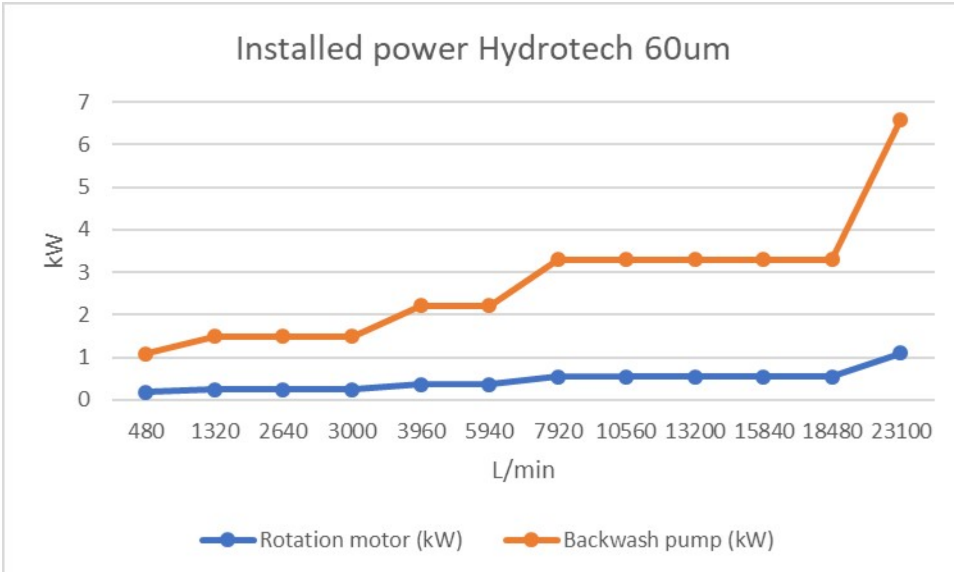

Figure 17: Data taken from https://teknor.no/produkter/filter/hydrotech_filter/content_1/filelist_be5c42ad-65cf-4a6c-858d-1c2713e64e84/1313417170061/hydrotechfilter.pdf

A.6 Appendix 6

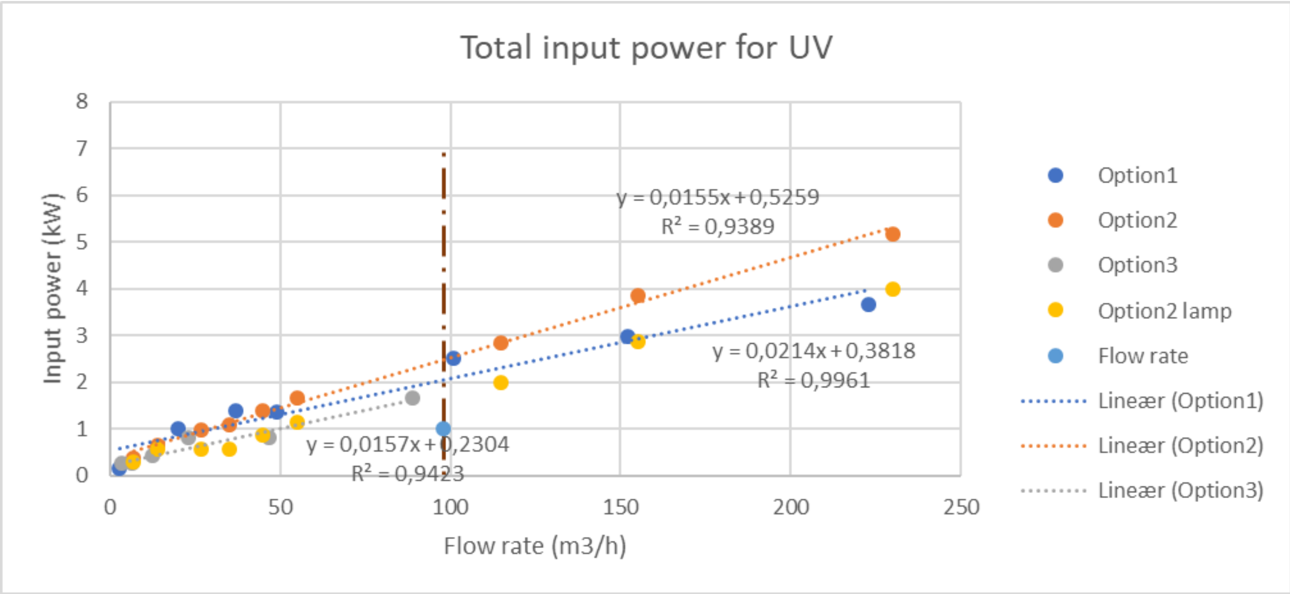

Figure 18: Input power for UV device in relation to flow rate

Data series are taken from:
Option 1: Sterner AS, `http://www.sterneras.no/wp-content/uploads/2018/05/Spektron-brosjyre-EN.pdf`
Option 2: UltraAqua, `https://www.ultraaqua.com/uv-systems/uv-systems-for-corrosive-environments/`
Option 3: Kaldnes, `http://www.krugerkaldnes.no/kruger-kaldnes/ressources/files/1/54240-Standard-Product pdf`

All data series has a linear relationship between flow and power input.
98 m3/h yields:
Option 1: y =0,0214*98+0,3818 = 2.04 kW
Option 2: y =0.0155*98+0.5259 = 2.48 kW
Option 3: y =0.0157*98+0.2304 = 2.10 kW
Average power input equals 2.21 kW

98 m3/h yields:
Option 1: y =0,058*98+1,7386 = 9.69 kW
Option 2: y =0,0889*98+0,9823 = 7.42 kW
Average power input equals 8.56 kW

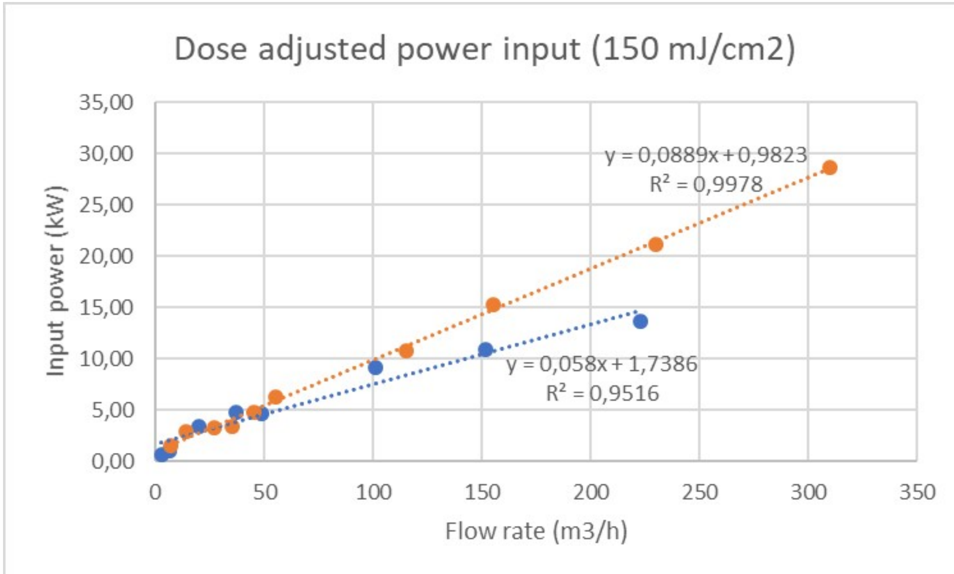

Figure 19: Power given a dose of 150 mJ/cm^2 instead of 30 mJ/cm^2. Found by multiplying the power input by 5.

A.7 Appendix 7

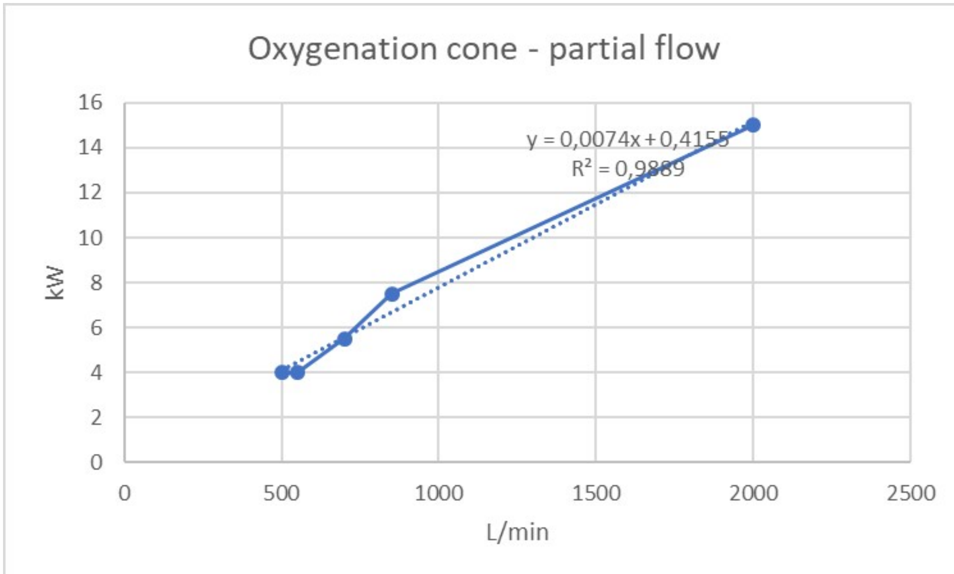

Figure 20: Relation between installed power capacity and flow rate. Data from `http://www.sterneras.no/wp-content/uploads/2018/10/Ny-Oxytech.pdf`

The resulting formula given in kW is

$$P = 0.0074x + 0.4155 \tag{A.8}$$

$$x = 15\% * \frac{\dot{V}}{14} \tag{A.9}$$

Where
$\dot{V}$ = flow rate in water treatment loop, L/min
Division by 14 since this is the number of tanks, and one oxygenation cone is installed for each tank.
$\dot{V}$ = 82467 L/min
x = 884 L/min
P = 7 kW

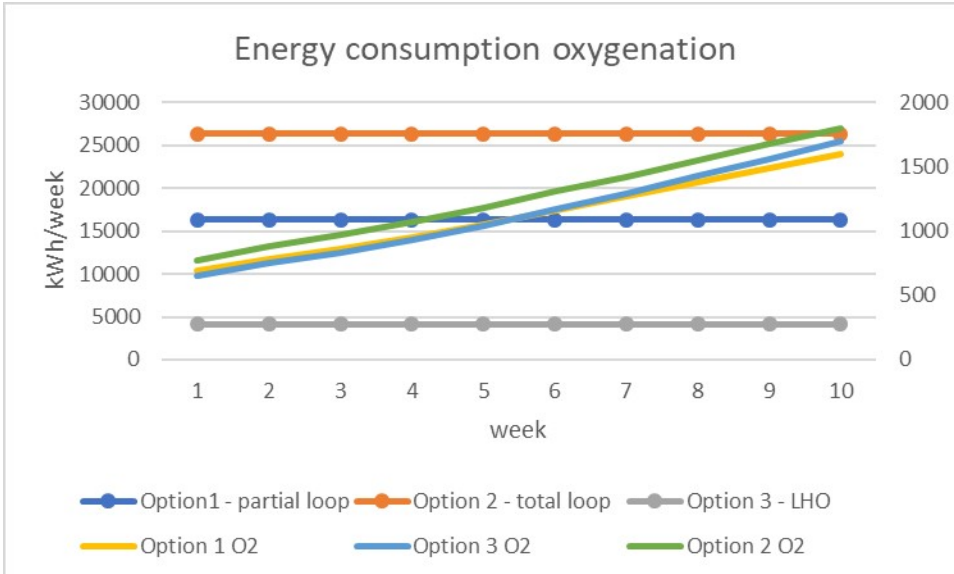

Figure 21: Energy consumption for oxygen addition and oxygen production for each of the options considered. Calculations as explained in methods. Oxygen addition (left axis) and production (right axis)

A.8 Appendix 8

Option 1 Pump power required to pump sludge from the RAS facility out in the fjord is estimated as:

$$P = \frac{\rho * g * H * Q}{(3.6 * 10^6) * \eta} \tag{A.10}$$

Where
ρ = specific density of sludge water, assumed equal to water = 997 kg/m^3
g = 9.81 m/s^2
H = 40 m, see methods
η = 0.8, assumption
Q = sludge water flow, see methods. Unit m^3/h

$$Q = 0.5\% * \dot{V} \tag{A.11}$$

This gives P = 3.396 kW.
Option 2

$$Energyfactor = \frac{51684kWh}{1500 * 1000kgsludge} = 0.035kWh/kgsludge \tag{A.12}$$

Calculations shown in figure below.

Week	Feed(kg/h)	Slugde 10% (kg/h)	Energy (kWh/week)
1	47	71	416
2	55	82	485
3	51	77	450
4	58	87	509
5	65	98	577
6	74	111	653
7	73	110	646
8	82	122	720
9	77	116	683
10	85	128	750

Figure 22: Calculations for energy consumption for filtering and dewatering to DM10%

A.9 Appendix 9

Height of fish tank

The design of the fish tank is shown in the figure below. From this the lift needed to return the water from the level after the water treatment loop back to the fish tank is determined to 3.3 m.

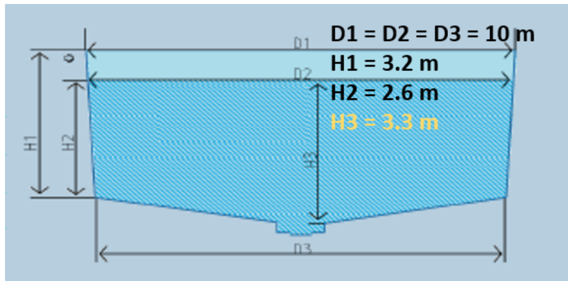

Figure 23: Fish tank design. Figure provided by[57]

Friction losses

The major friction losses are found using the figure below, which is a graphical representation of equation 3.20. PE pipes are assumed, with a diameter of 300 mm.

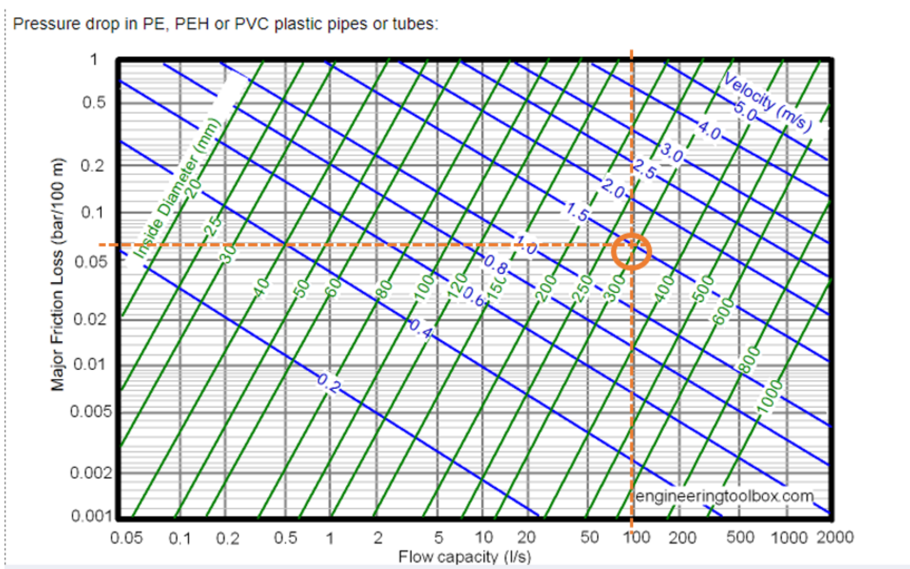

Figure 24: Chart friction losses in PE pipes. Figure provided by[57]

This yields a friction loss 0.06 m/ 100m. Pipe length is assumed to equal 200 m. This is based

on that the length from the water treatment units to the water treatment unit is approximately 40 m. In addition, pipes are needed within the water treatment area. It should be pointed out that the number is highly uncertain, and more of a guess in this case.
H_{major} **= 0.12 m**.

For the minor losses, K_L is taken from [117] (table 15). Velocity is determined by the chart above to 1.5 m/s. Using equation 3.20 this yields:
H_{minor} = 0.41 m
In total H_{loss} = 0.53 m

Shape	K_L	Number
90°bend	0.3	8
Intake	0.2	1
Outlet	1	1

Table 15: Coefficients for minor losses

A.10 Appendix 10

Month	Shanghai	Norge	Gibraltar	Chile
1	5,0	3,8	16,0	15,9
2	5,0	3,4	15,0	15,8
3	7,0	3,3	16,0	15,2
4	10,0	3,6	16,0	13,6
5	12,0	6,2	17,0	12,9
6	19,0	9,9	20,0	12,0
7	24,0	13,6	22,0	11,9
8	25,0	13,9	22,0	11,8
9	21,0	11,2	22,0	12,1
10	17,0	7,2	20,0	12,3
11	13,0	4,5	18,0	13,2
12	7,0	3,6	17,0	14,7

Figure 25: Sea water temperatures of different locations.

A.11 Appendix 11

Values used for calculation of heat transfer coefficient for transmission losses are shown in table 26. Values are taken according to TEK17 [118]. Areas are estimated based on the assumption that the post-smolt area is an enclosed squared building, 4 m high. For ventilation heat transfer coefficient

	U-values (W/m2K)	A (m2)	H (W/K)
Walls	0,18	704	127
Roof	0,13	1960	255
Floor	0,1	1960	196
Glas/doors	0,8	58,8	47
Thermal bridges	0,06	1960	118
			742

Figure 26: Heat transfer coefficient for transmission losses

equations and parameter values are taken from [103].

$$H_v = 0.34 * \dot{V}_i \tag{A.13}$$

$$\dot{V}_i = \dot{V}_{inf} + \dot{V}_{vent} = 2 * V_i n_{50} e\epsilon + \dot{V}_{vent} \tag{A.14}$$

Where
n_{50} = 2
e = 1
ϵ = 0.025
V_i = volume of building
$\dot{V}_{vent}$ = ventilation rate, estimated as described in methods.

Using this H_T = 742 W/K and H_v = 4265 W/K.

To estimate the heat demand the degree-day-method can be used, when exact outdoor temperature is unknown. It is the number of degrees the outdoor temperature is below 17 °C, which is assumed to be the indoor temperature. The average degree-days in Trøndelag in 2017 was 4202 [119]. This is adjusted down to 4000 to account for the fact that the indoor temperature is lower in this case.

$$Q = (4265W/K + 742W/K) * \frac{4000 * 24}{1000} kWh - 173010kWh = 307673kWh \tag{A.15}$$

A.12 Appendix 12

Sludge treatment from 30%DM to 90%DM:
$1 * 10^6$ kWh/7 056 640 L sludge = 0.14 kWh/L at DM10%
Sludge produced = 168244 L in this case
0.14 kWh/L*168244 L = 23842 kWh

A.13 Appendix 13

Energy use in open-net pens
Total diesel use in aquaculture industry 2017/winter 2018: 143514 m^3 [113]
Total production volume salmon 2017: 1308487 ton [120]
Energy density diesel: 38.6 MJ/L [121]

Calculation of energy intensity per kg live-weight salmon:

$$Energy = \frac{38.6MJ/L * 143514m^3 * 1000L/m^3}{1308487ton}\frac{1ton}{1000kg} = 4.23MJ/kg = \mathbf{1.17}kWh/kg \quad \text{(A.16)}$$

If production period is 24 months, the energy use in the 125 days is:

$$Energy for post-smolt in sea = \frac{125days}{24 * 30days} * 1.17kWh/kg = 0.2kWh/kg \quad \text{(A.17)}$$

If the production period is 14 months, the energy use in 125 days is 0.3 kWh/kg.

Emissions from energy use
Emission factor diesel: 3.17 kgCO_2/kg diesel [122]

Diesel fuel: 0.832 kg/L (source `https://en.wikipedia.org/wiki/Diesel_fuel`)

Using 0.832 kg/L and 38.7 MJ/L and multiplying with 3.17 kg CO_2-eq./kg diesel yields an emission factor of 68 kg CO_2eq./MJ and 0.245 kg/ CO_2eq./kWh.

Emission factor electricity mix:
Norwegian el-mix: 0.0164 kg CO_2eq./kWh [123]
Nordic el-mix: 0.114 kg CO_2eq./kWh [13]

Emissions open-net pen diesel:
0.245 kgCO_2eq./kWH* 0.2 kWh/kg fish = 49 g CO_2eq./kg fish
Emissions open-net pen electricity, Norwegian el.mix:
0.0164 CO_2-eq/kWh* 0.2 kWh/kg fish = 3.3 g CO_2eq./kg fish

Emissions open-net pen electricity, Nordic el.mix:
0.114 kg CO_2eq./kWh*0.2 kWh/kg fish = 22.8 g CO_2eq./kg fish Emissions in RAS - Nordic el.mix:
0.114 kg CO_2eq./kWh*2.57 kWh/kg fish = 293 g CO_2eq./kg fish Emissions in RAS - Norwegian el.mix:
0.0164 kg CO_2eq./kWh*2.57 kWh/kg fish = 42 g CO_2eq./kg fish

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