Department of Mechanical and Aerospace Engineering

Sustainable Growth of The Scottish Aquaculture Industry: Investigation of the Capability of Recirculating Aquaculture Systems vs. Open Net Pens for the Transition Towards a Circular Economy

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Copyright Declaration

Abstract

The Scottish fishing industry is set to double in size by 2030, expanding from £1.8bn to £3.6bn. Scotland makes up approximately 10% of the population in the UK however, it is responsible for approximately 60% of aquaculture production making it an industry of significant value to both Scotland and the UK. While the targeted growth have substantial benefits for the country economically, it may result in various ramifications for the environment on both a local and global scale.

The aquaculture industry is reported to be one of the least compliant sectors that is regulated by SEPA, the Scottish Environmental Protection Agency (McNaught, 2018). This is largely due to lack of appropriate measures being put in place to deal effectively with the effluent leaving the farms resulting in approximately 21% of marine finfish farms and 7% finfish having unsatisfactory seabed surveys and effluent quality failures in 2015 (McNaught, 2018). Uncontrolled release of effluent is not the only problem, last year in 2017, there was a considerable spike in Salmon mortalities due to sea lice (BBC News, 2018).

In addressing these factors of concern facing the aquaculture industry in Scotland, the purpose of this report is to investigate and support the quantification of how the industry can realise growth in a more sustainable manner. Sustainability of aquaculture in Scotland is comprised of economic, environmental and social factors and these are what this thesis aims to address however the main focus is predominantly on reducing environmental impacts. Sustainable development in food resources implies that current production systems should reach maximum efficiency to ensure the current population does not hinder the ability of generations to come to meet their own needs (Colt et al., 2008).

Scotland is not the only nation facing issues with aquaculture; other key producers such as Norway and Canada are also suffering from increased disease, mortalities, fish escaping and wild stock depletion. Due to this, the industry worldwide has seen an increase in research and development of recirculating aquaculture systems (RAS), altering the horizon for the sector. RAS which is on-land closed containment has the capability of reducing or eliminating the farm emissions that are associated with traditional open net pen farming. The closed system prevents harmful substances in the waste generated on farms entering the local environment and contributing to the depletion of wild species (McGrath, 2015). RAS technology allows for greater control

of the fish rearing environment, which may also reduce concern for animal welfare that is increasingly prevalent on Scottish farms (Allen, 2018).

The aquaculture industry can often be complex and incorporate many stages from raw material extraction to product. The holistic approach of a life-cycle assessment (LCA) allows for quantifying and addressing key impacts whether they be on a local or global. A review was carried out of current available literature, focusing specifically on the impacts of Atlantic Salmon farming to identify the hotspots in the product value chain that may have scope for increase in efficiency. An LCA of the Scottish Salmon industry found that sometimes the product often depicted as “local” is in fact supporting a product with an extensive value chain (Newton and Little, 2017). Approximately 80% of all impacts assessed in this study were due to the requirement of feed, as less than 25% of the raw material feed resources were procured in Scotland. Recirculating aquaculture systems, if run efficiently can allow for a lower feed conversion ratio (kg feed per kg fish), reducing the dependency on raw materials hence, increasing the environmental integrity of the supply chain. The potential for eutrophication due to the on farm emissions for open net pens had the second greatest impact.

With recirculating aquaculture systems comes a greater energy demand which raises concern for this technology exacerbating global scale challenges such as climate change and increasing costs incurred in production (McGrath, 2015). However, Scotland is a country that is at the forefront of renewables and continues to strive for innovation and progress in the field; the Scottish Government has set a target of generating the equivalent of 100% of its gross annual electricity consumption by 2020 (Gov.scot, 2018). Further to this, the government released their circular economy strategy in 2016, ‘Making Things Last’. A circular economy supports systems and designs that are inherently regenerative and restorative. Recirculating Aquaculture systems allow for the collection of waste that can be transformed into useful products.

Based on the knowledge gained from the literature review of this report, a tool (RAq) was created to quantify the sustainability of recirculating aquaculture systems replacing the more traditional and dominating method of farming in Scotland, open net pens. The tool was created for comparisons to be drawn mainly at smolt and salmon grow-out production stages, quantifying the resources and energy required.

Acknowledgements

I would like to thank my supervisor Paul Tuohy who was incredibly encouraging in my pursuit of choosing a topic for this thesis that suited my personal interests whilst being relevant to industry in Scotland. Despite my very limited knowledge of the aquaculture industry before embarking on this thesis, the environment created at the University of Strathclyde enables students to be self-starters in dealing with and tackling current issues related to sustainability in industry. Also, thanks to Jack Byre and Fergus Ross at Wood Group for their input along the way and to Jon Clarke from Community Energy Scotland.

Abbreviations

AP	acidification potential
BRU	biotic resource use
CEU	cumulative energy use
GHG	greenhouse gases
GWP	global warming potential
kg	kilogram
kWh	kilowatt- hours
LCA	life cycle assessment
MJ	mega joule
N	nitrogen
ONP	open net pen
P	phosphorous
RAS	recirculating aquaculture system
SS	suspended solids

List of figures

Table of Contents

1. Introduction

1.1. Background and Motivation

Providing food for the growing population is a key driver of anthropogenic environmental change (Pelletier at el., 2009). As the Scottish Aquaculture industry is set to experience heavy growth, it is becoming increasingly important to have available and accurate information on the impacts this industry has and could potentially have on the environment both locally and globally.

The Scottish Aquaculture industry is one that is worth £1.8billion a year with the desire to double in size by 2030. Approximately 95% of the Aquaculture industry in Scotland consists of Atlantic salmon production whereby it is the third largest producer in the world after Norway and Chile. It underpins the Scottish economy as its second largest export after whisky, exporting to more than 60 countries. The industry has laid out goals for 'sustainable intensification', with equal weight on economic, social and environmental factors.

So why in this period of 'sustainable intensification' is the industry suffering from the greatest rate of mortalities yet? In 2017, approximately 22, 476 tonnes of both salmon and trout died; considering 162,817 tonnes of Salmon were produced, this resulted in approximately 13% loss in production. The industry has pinned such losses on the sea lice 'crisis' spiralling out of control, resulting in increasing chemicals being pumped into the natural environment to deal with the increasingly resistant lice (BBC New, 2018). The number of infected sites went from 28% in 2014 to 49% in 2015.

Not only are fish dying at a devastating rate, a recent life cycle assessment investigating the impacts of farmed Scottish salmon (Newton and Little, 2017) revealed that less than 25% of aquaculture feed ingredients were procured from the UK. Statistics released by the Scottish Government showed that in the past 10 years Scotland has come to rely heavily on Ova exports particularly from Norway which reportedly reached approximately 78.2% in 2016 (Marine Scotland Science, 2017).

The open net pen (ONP) culture system that accounts for almost all salmon production in Scotland is heavily damaging to the natural environment and evidently doesn't protect the salmon from various problems such as sea lice, predator attacks, climate change etc. This puts into question not only the efficiency and stability of the sector but causes grave concern for animal welfare as we see the proliferation of salmon.

The LCA conducted found that over 90% of the impact to farm-gate was due to the feed for all factors apart from eutrophication potential which was due to the effluent release on the farms polluting the local environment. Recirculating Aquaculture Systems (RAS) were investigated for comparison with the current ONP as they do not result in eutrophication potential and require a lower feed consumption ratio (FCR) hence reducing feed requirement. They are closed cage systems whereby rearing environment is controlled to allow for optimum conditions for the fish growth and waste streams with the potential to be utilised instead falling to the benthic floor.

A key concern with closed cage systems is the increased energy requirement, mainly for water pumping, hence the pressure that should be put on increasing the presence of renewable energy sources utilised in the industry. This is in line with goals set by the Scottish Government in its Energy Strategy for meeting targets in generating renewable energy. Opportunity is also to be sought in utilising the waste streams from the farm in generating energy by anaerobic digestion.

With current growth being led by industry, with presumably economical gain at the forefront, attempting to intensify at a rate that has been proven to not be achievable, it is necessary that scientific based decision making tools are available to allow for more sustainable decision making and to increase transparency and accountability in the industry. Investigation must be carried out to determine ways to yield maximum output whilst incurring minimum environmental impact in production.

1.2. Aim and Objectives

The objectives of this thesis were to provide an overall view of the stance of the aquaculture industry in Scotland and to understand and quantify the capability of RAS in aiding in reducing the environmental impacts of the industry. As Salmon accounts for approximately 95% of finfish production in Scotland, this species was the focus of this investigation. A model/ methodology will be developed that can support understanding of the impact from aquaculture from a life cycle perspective. The model allows for the comparison of open net pen and recirculating aquaculture systems for production.

The key aims of this thesis are to investigate and support research in the following:

- The lack of scientific-based decision making tools available to industry particularly regarding the potential for a sustainable transition to recirculating aquaculture systems (RAS)

- More holistic approach to understanding and analysing true environmental impacts from fish farms in Scotland
- Helping to reduce marine and freshwater pollution from the aquaculture industry
- Enable increased transparency and accountability in Aquaculture
- Ensuring sustainable investment that considers socio-economic factors as well as environmental factors

1.3. Overview of Methodology

Literature Review

Chapter 2: The Global Aquaculture Industry

Chapter 2 briefly addresses the aquaculture industry globally, with a focus on Atlantic Salmon; its history, its current status and its importance. It addresses the key environmental issues and discusses the two methods of fish farming that will be compared in this thesis; the current approach in Scotland, open net pens (ONP) and the more modern recirculating aquaculture systems (RAS). The two types of farms can be seen below in figures 1 and 2.

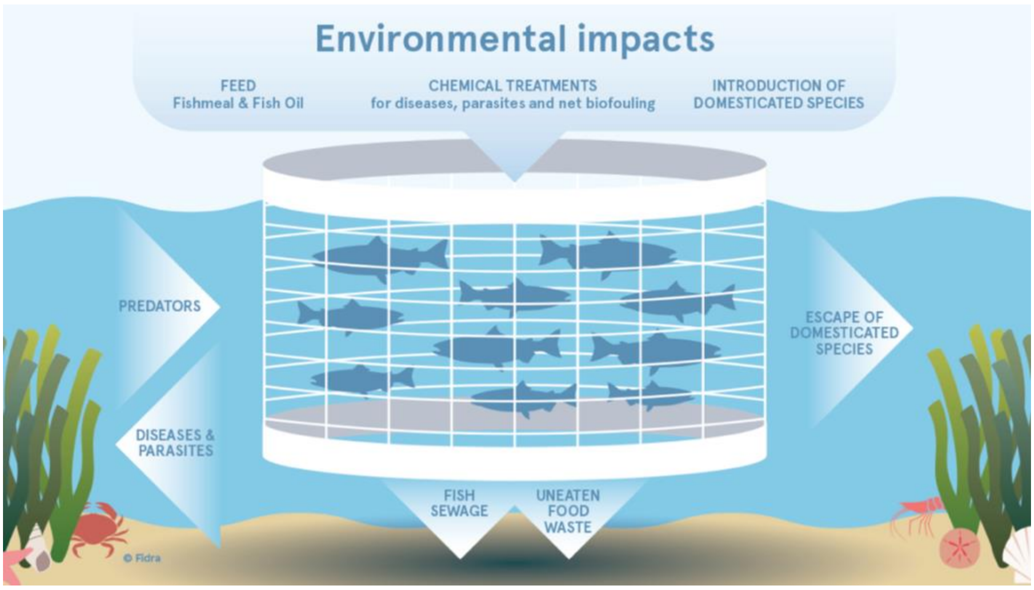


Figure 1: Impacts from Salmon Farming in Open Net Cages (Best Fishes, 2018)

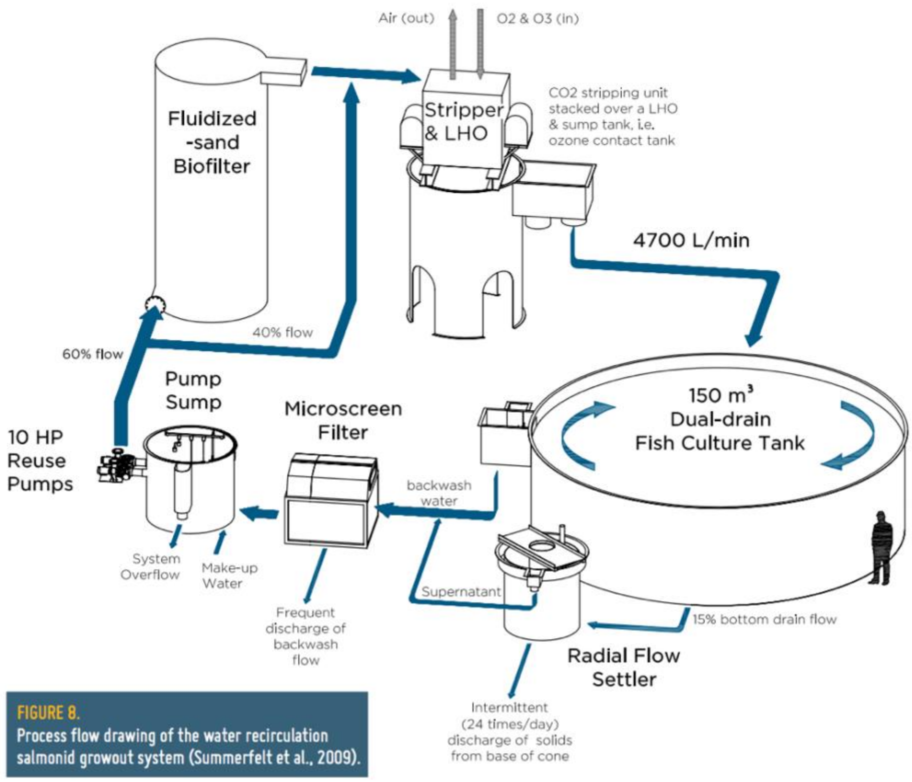


Figure 2: Diagram of a recirculating aquaculture system (RAS) (Summerfelt et al., 2013)

Chapter 3: Aquaculture in Scotland

Chapter 3 looks at the aquaculture industry within a Scottish context. It addresses the current state of the industry and its targets for growth. It discusses policy and regulation relevant to the Scottish aquaculture industry, sustainability within the industry and industry decision-making.

Chapter 4: Circular Economy

Chapter 4 investigates the circular economy potential within the industry particularly relating to methods of dealing with waste from farms and how it can be harnessed into a value product. Current examples of implementations of the circular economy concept in aquaculture are presented.

Chapter 5: Life Cycle Assessment Review

In conducting the initial stages of the literature review, it became evident that the Life Cycle Assessment (LCA) methodology was an appropriate method in analysing the true impacts of the aquaculture industry. It has been utilised globally to analyse various species with various examples in literature focusing on Atlantic Salmon. Key examples that have been discussed in this thesis are Newton and Little (2017), Pelletier et al. (2009), Ayed and Tyedmers (2009) and Badiola et al. (2015).

Figure 3 shows the results of an LCA carried out on the Scottish salmon industry. Firstly, it found that approximately 80% of environmental impacts in the life-cycle were related to the feed. The second largest impact was eutrophication potential due to the farming stage.

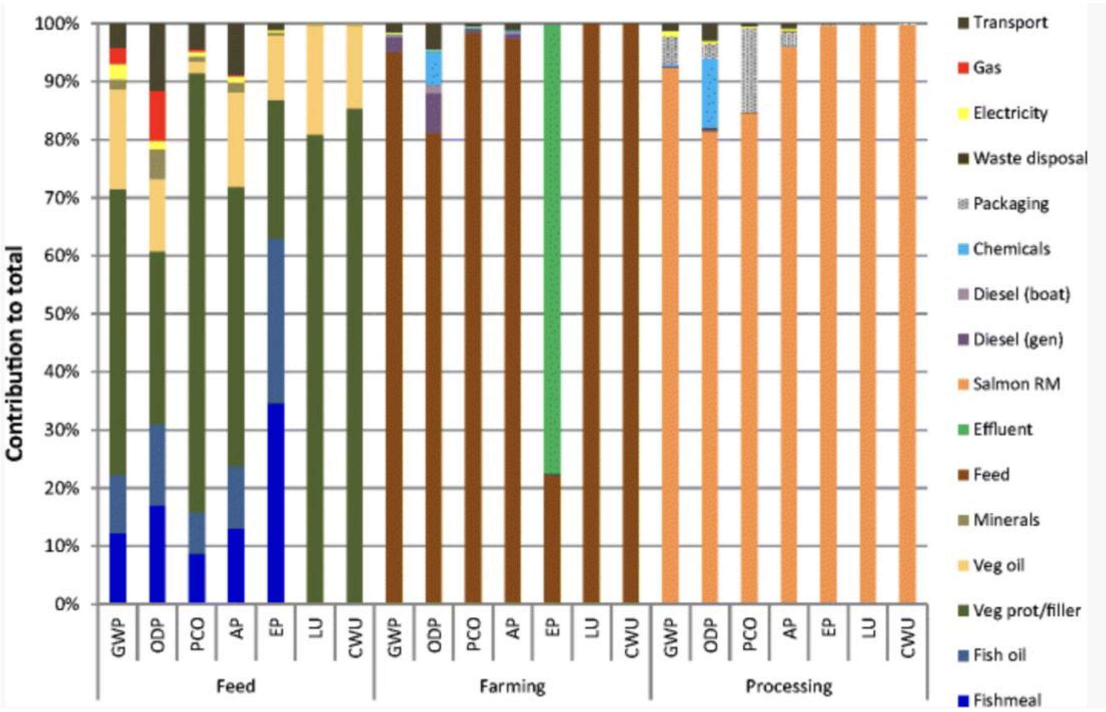


Figure 3: Split contribution analysis for producing HOG salmon at the primary processor (Newton and Little, 2017)

Chapter 7: Pre-Farm

Chapter 7 addresses the pre-farm stage of the life-cycle consisting of raw material procurement, feed production, smolt production and transportation.

Chapter 8: On-Farm

Chapter 8 discusses the on-farm stage of the life-cycle, detailing the open net pens and recirculating aquaculture system technology.

RAq Tool

Chapter 9: Tool Creation

Based on the literature review conducted and the gaps identified in research, a tool was created to support the further development of the following:

- Comparing current open net pen production with recirculating aquaculture systems and their potential for enabling sustainable growth of the industry
- Investigating farming methods that, based on a LCA approach, can reduce environmental impacts
- Quantifying waste outputs from farm production and potential waste utilization
- Comparing the economic viability of systems with a high-level cost comparison

The tool applies a linear temperature dependant growth model for the salmon based on values from literature to calculate the key resources and energy required by either an open net pen (ONP) and recirculating aquaculture system (RAS) to meet a certain production demand. While the tool has limitations and various assumptions as detailed in this chapter, it provides a framework or basis for future research.

RAq Tool Application

Chapter 10: Results

Three scenarios were chosen for analysis using the tool based on motivations from literature and industry. Scenario 1 is the current practice in Scotland whereby both Smolt and Salmon Production occur in freshwater and seawater open net cages respectively. Scenario 2 is the production of Smolt in freshwater tanks whereby they are kept in the tanks till they reach greater weight than typically reached in cages before being transferred to seawater cages for a shorter period of Salmon production. Scenario

3 is the production of both smolt production and salmon production in recirculating aquaculture systems.

Table 1: Scenarios for analysis using RAq tool created for this thesis

Scenario	Smolt Production	Salmon Production
1. Current Practice (70g smolt)	Open Net Pen (ONP)	Open Net Pen (ONP)
2. Smolt in RAS to 70g	Recirculating Aquaculture System (RAS)	Open Net Pen (ONP)
3. Smolt in RAS to 200g	Recirculating Aquaculture System (RAS)	Open Net Pen (ONP)
4. Smolt & Salmon in RAS (200g Smolt)	Recirculating Aquaculture System (RAS)	Recirculating Aquaculture System (RAS)

Final Section

Chapter 11: Discussion

Chapter 11 discusses the findings from this thesis report and the results provided by the tool created for this thesis.

Chapter 12: Conclusions

Chapter 12 outlines the key findings from this report, providing the final conclusions for this project.

Chapter 13: Future Work

Chapter 13 details opportunity for future work based on the findings of this thesis for the Atlantic salmon industry in Scotland and the development of the tool created in this thesis.

1.4. Scope and Limitations

In conducting a literature review on the industry and the impact and energy requirements of the industry in Scotland, it became evident that lack of transparency and accountability in the industry is hindering the development in technology and efficiency of production that could lead to reductions in costs and minimising environmental impact. Thus, this hindered the ability to confidently create the RAq tool with reliable data however the tool presents a basis for decision-making tools that may support current and future decisions for the sustainable growth of the Scottish aquaculture industry. The findings of this study focus on how recirculating aquaculture systems can reduce the impacts pre-farm and on-farm that are prevalent in using open net systems.

2. The Global Aquaculture Industry

The following section gives a global overview of the aquaculture industry and more specifically in the context of Atlantic Salmon (Salmo Salar). It addresses the importance of aquaculture for global food security, the key issues with the industry and introduces the two key methods of farming addressed by this thesis; open net pens and recirculating aquaculture systems.

2.1. Global Overview

Brief History of Aquaculture

Aquaculture dates to the Neolithic age, around 4000 B.C. in Europe whereby humans began to harness natural resources (Fisheries –European Commission, 2018). Aquaculture in this age was very minimalistic, carried out in lagoons, ponds or small shallow lakes whereby humans would trap the aquatic animals. More recently, capture fisheries are the method by which humans have obtained a supply of fish and shellfish. However, this method of production has not expanded at the same rate, remaining stagnant in the past 20-30 years, whereas aquaculture has seen increases year on year (Ellis et al., 2016) as can be seen in figure 4.

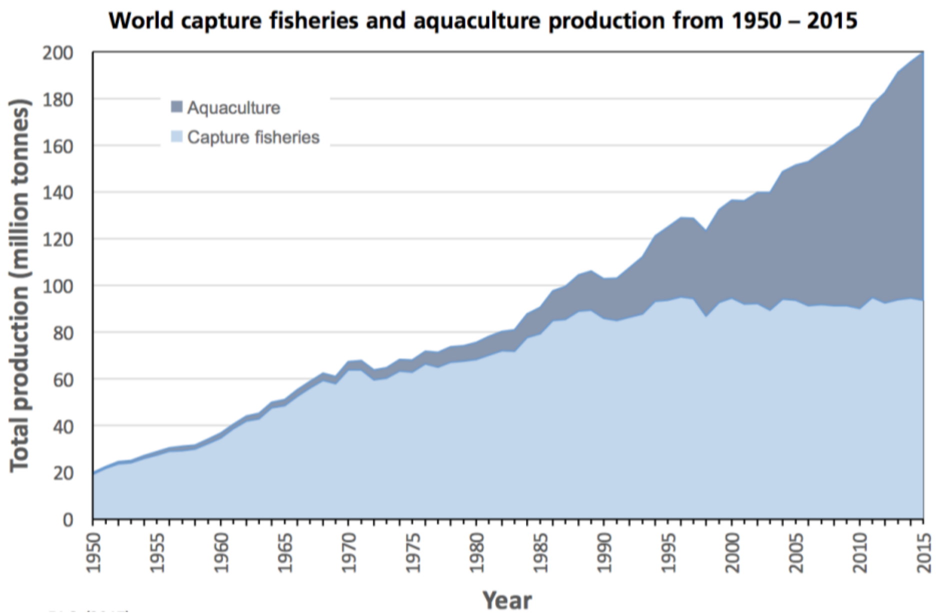


Figure 4: World Capture Fisheries and Aquaculture Production from 1950-2015

Aquaculture is currently defined as the rearing of aquatic animals or the cultivation of aquatic plants in either seawater or freshwater for human consumption (SEPA, 2018). It consists of intensive practice that is normally carried out in tanks, ponds or open-water cages whereby there is a high stocking density, high water exchange and often oxygen and feed management (FAO, 2015).

From a global perspective, looking at the overall aquaculture industry, Scotland does not have a major presence. China is the biggest fish producer and exporter of fish and fishery products, remaining a major importer also due to increased demand for produce not grown locally. Norway is the second biggest and then Vietnam which took over Thailand due to expected problems with disease control in their shrimp production. However, the EU was the largest market for global imports with the UK importing \$2.7billion of the \$44.5billion imported by that market in 2017 (Worldsrichestcountries.com, 2018). The EU is reportedly increasing its dependence on seafood imports due to their inability to meet the growing demand in European fisheries, against the growing consumer interest in locally sourced food (Newton and Little, 2017)

Brief History of Atlantic Salmon

The culture of Atlantic Salmon was first present in the UK in the 19th century when they began stocking freshwaters with Parr to maintain a flow of salmon returning from the wild for fishermen (Fao.org, 2018). However, it was in Norway in 1960 that sea cage farming flourished when they focused on raising the Atlantic salmon to a more marketable size. This was so successful that sea cage farming expanded to Scotland, and followed in Ireland, the Faroe Islands, Canada, the North-Eastern seaboard of the USA, Chile and Australia (Tasmania) as can be seen in figure 5, present across 11 countries. Atlantic salmon production has seen growth as fast as the aquaculture industry itself, perhaps underpinning the success of the industry (Ellis et al., 2016).

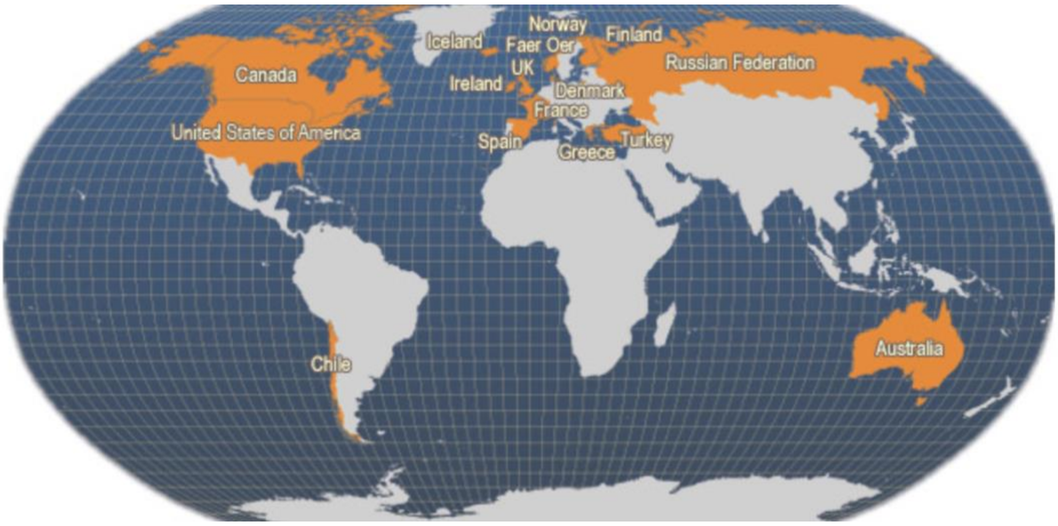


Figure 5: Map Showing Global Salmon Production (FAO, 2015)

In the early 1980s, Salmon from both Scotland and Norway were taken to Chile which has resulted in them becoming a major producer. Chile can take advantage of low production costs while having easy access to cheap feed, this allowed them to have a significant impact on the market in recent years as can be seen in figure 6 although Norway remains the biggest producer with Scotland being the third.

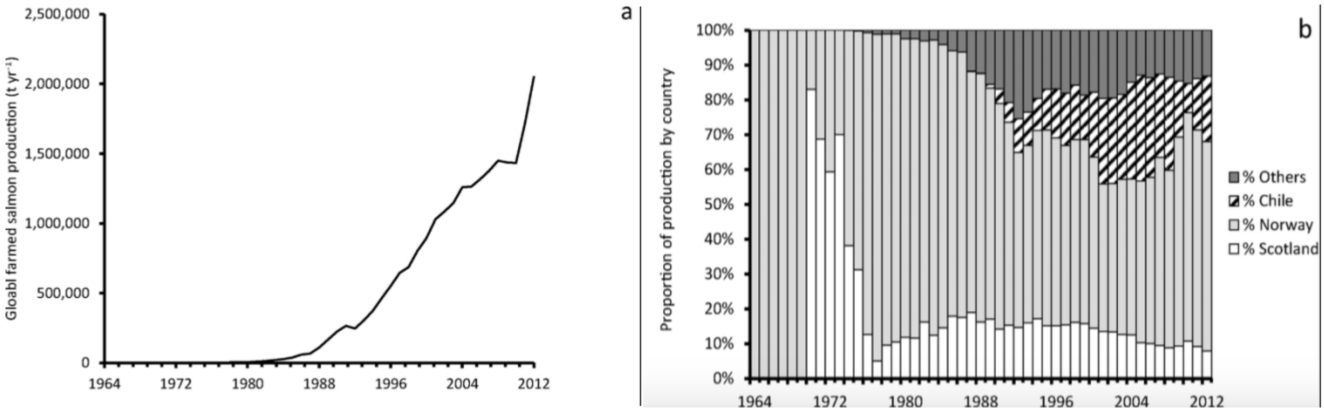


Figure 6: (a) Global Farmed Salmon Production (t/yr) (b) Proportion of Production by Country

Atlantic salmon is a fed aquaculture species meaning that it is reliant on external sources of feed as opposed to non-fed species that feed on-site depending where they are. Atlantic salmon accounts for 21.32% of the intra communitarian economic value of fishing products in Europe, making it the species of highest value (Badiola et al., 2017).

2.2. Global Food Security

The aquaculture industry has an essential part to play in the future of global food security. As the global population continues to rise along with the requirement of nutrition and increase in consumption rates, the aquaculture industry continues to experience considerable rates of growth to meet that demand. Interestingly, the global supply of fish for human consumption overtook the 3.2% rate of population increase by approximately double during 1961-2013; this has resulted in an increase in the average per capita available for consumption which has been encouraged by many factors including increased international trade (FAO, 2016).

WORLD FISH UTILIZATION AND SUPPLY

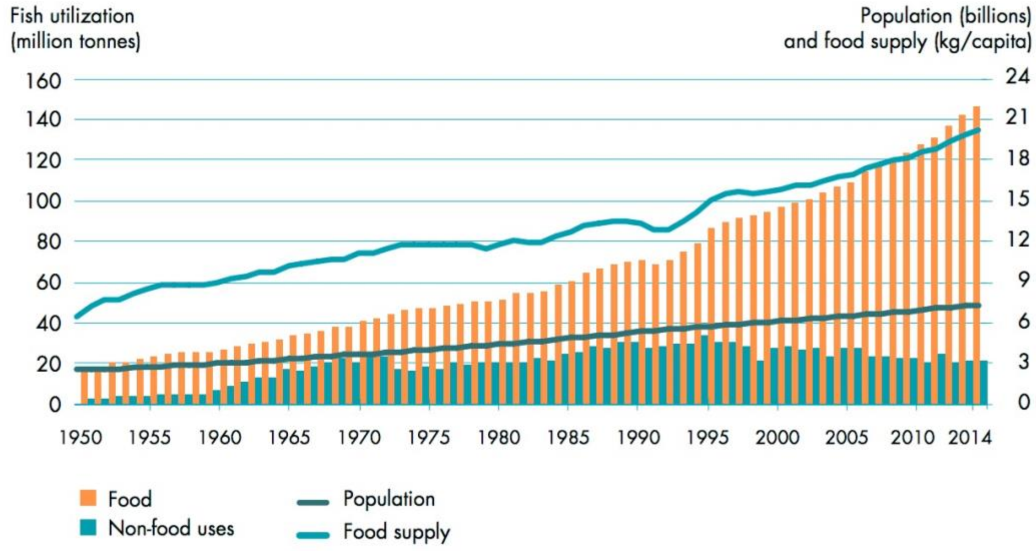


Figure 7: World Fish Utilization and Supply (FAO, 2016)

Figures project population growth by almost 50% from 2000 to 2050, reaching 9.5billion people worldwide (Henchion et al., 2018). Therefore, it is imperative that aquaculture practices increasingly improve their environmental performance by conducting research that allows and supports decision-making along aquaculture supply chains (FAO, 2015).

The UK Rural Economy Secretary Fergus Ewing acknowledged the important role to be played by aquaculture saying:

> *"Aquaculture's contribution to the global food production challenge is increasingly significant and has great potential as our Oceans cover 70% of the planet, but yield only 2% of our global food requirement."*

More than 3 billion people currently depend on the oceans to obtain their source of protein as protein consumption per capita continues to increase in both developed and developing countries as can be seen in figure 8.

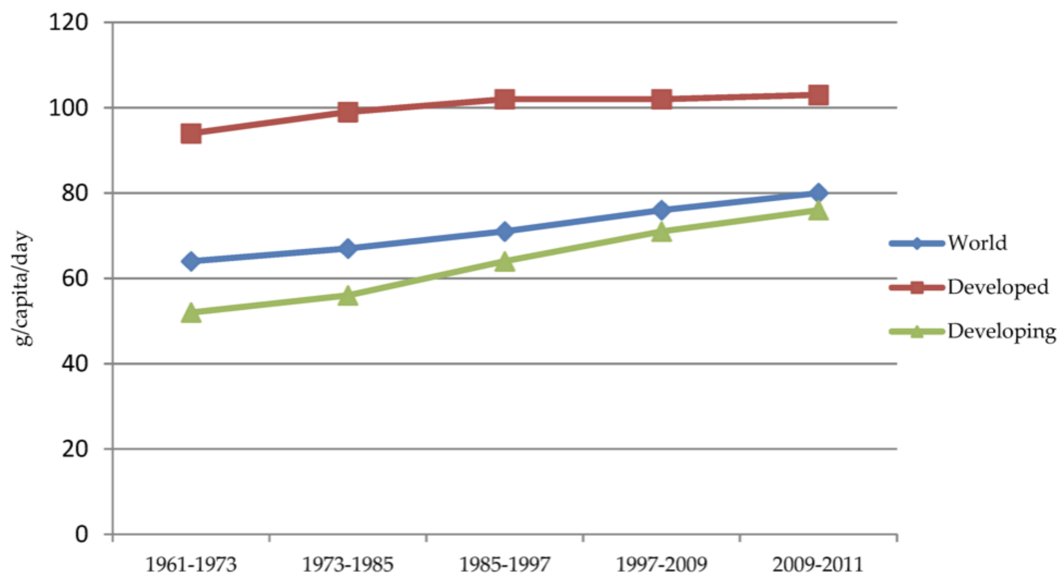


Figure 8: Evolution in protein consumption (g/capita/day) (Henchion et al., 2017)

Goal 2 of the UN Sustainable Development Goals (SDGs) sets out targets to achieve zero hunger, food security and improved nutrition and promote sustainable agriculture (Sustainabledevelopment.un.org, 2018). It underlines the potential of fisheries to provide a percentage of this as well as generating reasonable incomes for people globally; making it central to eradicating hunger and poverty worldwide. UN research finds that 815 million people worldwide are undernourished, the majority residing in developing countries. To achieve their 2030 goals, they have set out targets such as ensuring food production systems are sustainable and that agricultural practices are resilient to adapt to increased productivity and production. They outline that the systems should maintain ecosystems and strengthen capacity for adaptation to climate change.

2.3. Atlantic Salmon Production Cycle

As this thesis focuses on the production of Atlantic Salmon, the production cycle has been summarised; the typical cycle can be seen in figure 9, taken from the Marine Harvest handbook (2014). The salmon production cycle consists of 6 main stages, the first two in freshwater, the second two in seawater and the final stages being slaughtering and processing the fish.

They are an anadromous species meaning that they spend the first stages of their life in freshwater (smolt production) and have their main ‘grow-out’ phase in seawater (salmon production), after which the adults return to freshwater to reproduce. In the case of Salmon production, broodstock are selected before salmon are harvested and are typically moved back to freshwater before undergoing stripping and then ova (egg) production.

After being 'laid down' for approximately 12 weeks, the stripped ova are fertilized and grow into Parr. The parr then develop into smolts in the process of smoltification that includes physiological, morphological and behavioural changes to prepare them for seawater survival. They typically respond to seasonal changes in temperature and light, making them ready in Spring after 1 or 2 years according to the natural cycle. However, due to developments in photoperiod control, it has enabled smolt to be grown outside of this period as detailed later in the report. The smolt are then transferred to sea to pursue the main 'grow-out' period that typically lasts from approximately 18 months to 2 years.

This thesis focuses on the quantification of resources for the smolt production (3) and salmon grow-out stages (4).

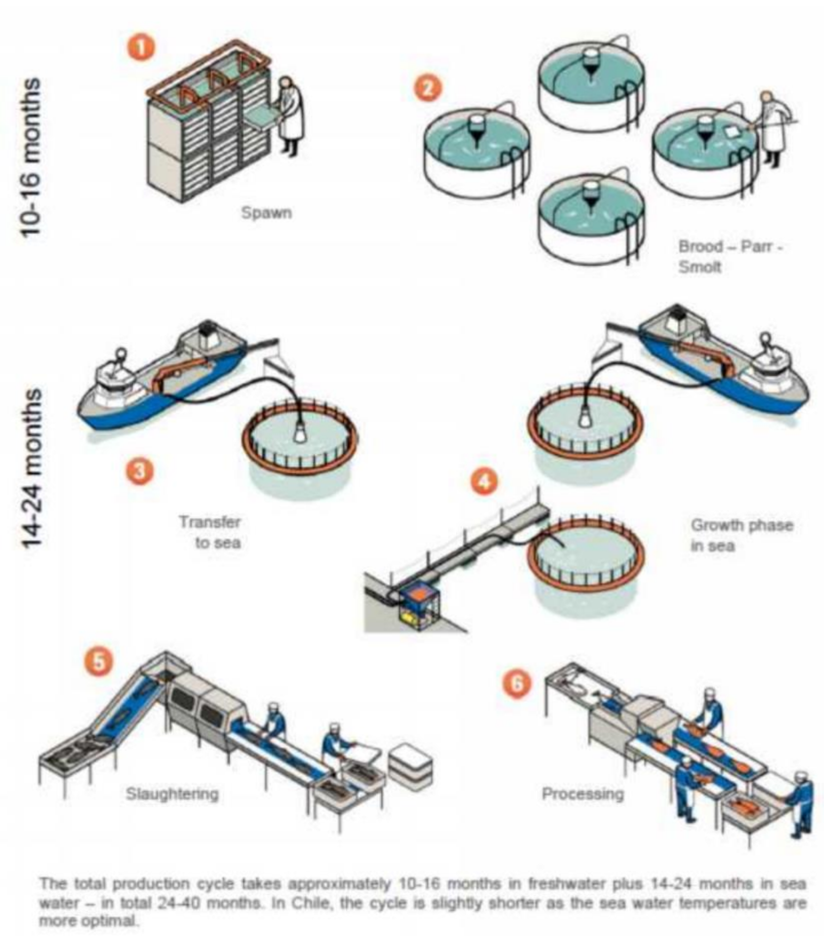


Figure 9: Marine Harvest Handbook 2014

2.4. Key Issues

Goal 14 of the United Nations Sustainable Development Goals highlights the need to 'conserve and sustainably use the oceans, seas and marine resources' (Sustainabledevelopment.un.org, 2018). Marine and coastal biodiversity is the source of 3 billion people's livelihoods worldwide and such resources account for about 5% of global GDP. Marine fisheries alone are the source of over 200 million people's jobs both directly and indirectly. However, current issues arising in aquaculture worldwide are hindering the prospect of achieving this goal as detailed in this section.

The salmon farming industry and aquaculture industry in general, has attracted many critics as the sustainability of the industry is being subject to scrutiny. Key issues that have arisen, which concern the public, researchers, industry and other stakeholders are greenhouse gas emissions, ecological impacts, culling of predators, fish escaping which impacts or depletes wild fish stocks and mass cases of mortalities due to disease. The vast increase in disease also leads to concern regarding poor animal welfare along with human health as the fish receive higher levels of drugs to combat the diseases. The following diagram show the key environmental impacts from Salmon Farming by the predominant method of Atlantic salmon farming, open net cages.

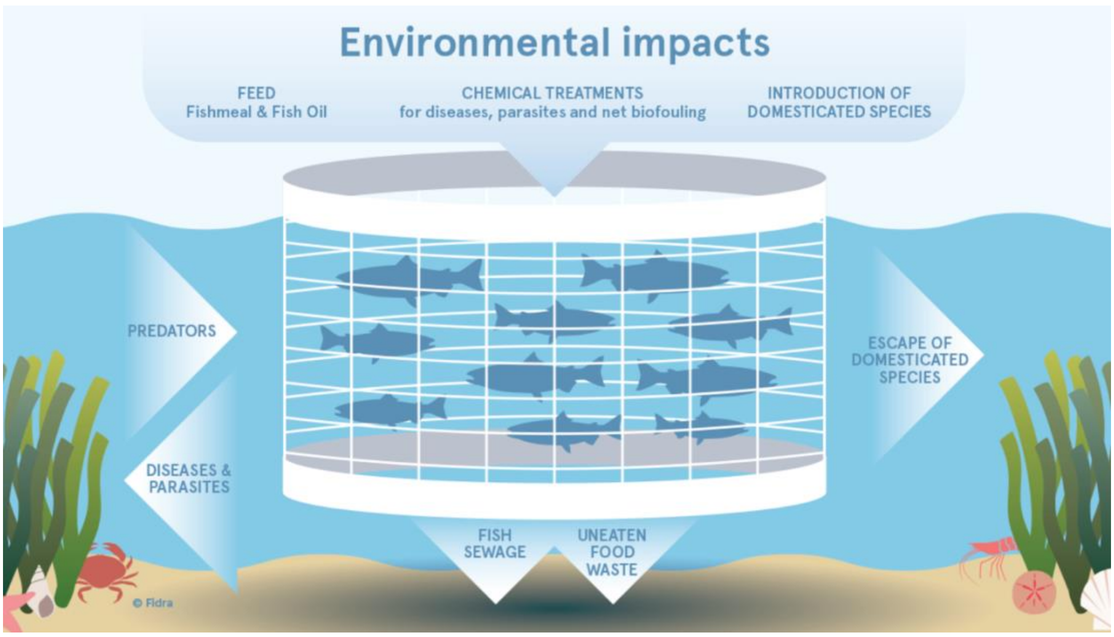


Figure 10: Impacts from Salmon Farming in Open Net Cages (Best Fishes, 2018)

Greenhouse Gas Emissions

The environmental consequences of aquaculture are often overshadowed by the huge environmental burden of the meat industry despite it being the most rapidly growing food sector. This has resulted in less research being carried out to understand the penalties felt by the environment due to aquaculture leading to insufficient investment of resources to tighten up processes and adapt them to be more environmentally benign. One study estimated that between 1990-2011, the greenhouse gas emissions from the global fishing industry increased by approximately 28% (Parker et al., 2018).

It is true that fish offer a protein that is much less greenhouse gas intensive compared to beef and pork however this does not minimise the impact as the industry worldwide is set to expand to meet increasing populations.

Ecological Destruction

The oceans currently absorb approximately 30% of the CO_2 emissions generated by humans worldwide acting as a buffer for global warming impacts. Aquaculture causes destruction of natural sites such as wetlands and mangroves and untreated effluent discharge is accountable for polluting ground and surface waters (Van Rijn, 2013).

Disease and Parasites

A major issue in salmon farming is the salmon contracting sea lice. They attach themselves to the skin of the fish and cause lesions by feeding on its flesh. Sea lice breed rapidly particularly in the case of concentrated open net pens. Sea lice originate from wild salmon however they may also be transferred to wild populations of salmon and sea trout if the pen is in a migratory route. The lice have effects on the salmon's health such as decreasing swimming ability, off-setting the water and salt balance and increase stress levels. The sea lice make the salmon more susceptible to disease and result in poor growth and prevailing death (Best Fishes, 2018).

Fish Escaping and Wild Stock Decline

Aquaculture is contributing to decreased biodiversity of natural fish populations in respective farming areas which is largely due to the escaping of non-native species (Van Rijn, 2013). For Atlantic Salmon, it has been reported to be up to 2 million escape each year which makes up half the population of wild salmon (Commence et al., 2018).

Animal Welfare

Concerns have been raised over the welfare of the fish. As intensification of the industry proceeds, yielding higher percentages of mortalities than before, current practice puts into question whether the industry is as ethically sound as it should be for the fish. Changing environmental conditions can cause stress for the salmon such as low oxygen, toxic algae blooms, pathogens, sea lice etc. (Allen, 2018).

Climate Change

Salmon begin their life in rivers where they and various other aquatic river species depend on certain temperature and discharge regimes. Climate change is anticipated to alter these, likely to impact the growth and survival of Atlantic Salmon. Research has been conducted to further understand the impact that may occur, predicting that negative effects of climate change may be mitigated by releasing water from reservoirs during critical points in salmon life-cycle (GOV.UK, 2018).

2.5. LCA Key Impacts in Atlantic Salmon Farming

An LCA carried out, assessing farmed salmon across Norway, the UK, British Columbia and Chile, found differences in material and energy use and hence environmental impacts across the countries. This identified the scope for better performance across the industry globally, finding Norway to be the least impacting and salmon in the UK incurring the highest impacts (Pelletier et al., 2009). As can be seen in figure 11, the study reported on cumulative energy use (CEU), biotic resource use (BRU), greenhouse gas emissions (GHG Em.), acidifying emissions (Acd.Em.) and eutrophying emissions (Eut. Em.) finding feed to be the source of the largest amount of emissions except for the farm's N/P eutrophying emissions.

This was persistently the case across aquaculture LCA, with the feed and farm emissions being of greatest environmental impact (Pelletier et al., 2009) (McGrath, 2015) (Newton and Little, 2017); this will be discussed in greater detail in the LCA section of this report. However, it became evident that to fulfil a route of sustainable growth, developments or methods that would directly reduce these two factors should be assessed.

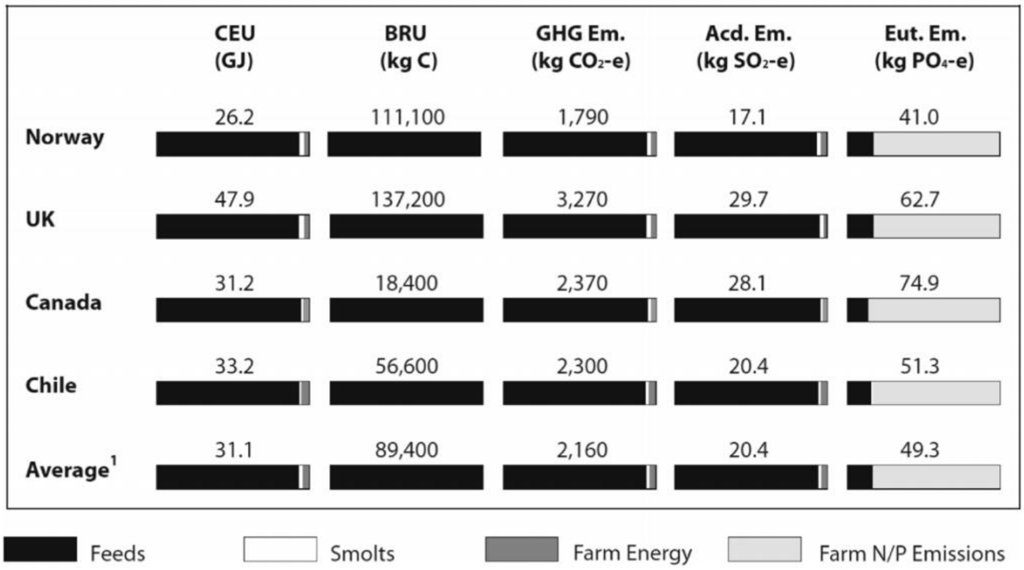


Figure 11: LCA for the Production of 1 Live-weight Tonne of Salmon in Norway, UK, Chile and Canada in 2007 (Pelletier et al., 2009)

2.6. Feed Conversion Ratio

The Food and Agriculture Organization of the United Nations (FAO), carried out a study into the greenhouse gas emissions from aquaculture by conducting an LCA of three Asian systems; Nile tilapia, Indian major carps and striped catfish. The study found that the greatest source of GHG emissions was generated in the production of the feed (Robb et al., 2017). It highlighted the importance of the economic feed conversion ratio eFCR:

$$eFCR = \frac{weight\ of\ feed}{tonne\ of\ live\ fish\ at\ harvest\ including\ mortalities}.$$

eq.1

The ratio measures the efficiency of the system; by maintaining a lower eFCR, environmental impacts can be minimised along with reducing losses economically. Minimised rates of mortality can improve environmental performance, particularly if the mortalities tend to happen later in the cycle. Due to the high dependence on raw material imports, costs of feed are highly dependent on trade conditions hence a further reason to reduce the feed requirement from an economic perspective.

2.7. Aquaculture Systems

In developing countries, where cheap labour is available, the majority of aquaculture is carried out in ponds and fish-pots due to their simplicity and low energy consumption (Mongirdas, Žibiené and Žibas, 2017). Nowadays, in more developed countries, the majority of aquaculture is carried out in open net pens however there are other methods such as flow-through, raceways and the more novel technologies such as recirculating aquaculture systems.

For Atlantic salmon aquaculture, farming is generally carried out in two stages due to the natural production cycle of salmon. The first stage is smolt production whereby the salmon spends the first part of its life in freshwater before transitioning to seawater for the main grow-out stage. Both stages are typically carried out in open net pens however smolt production is now often carried out in single-pass flow-through farms with evidence of transitions to recirculating aquaculture systems (Bergheim et al., 2009); the flowthrough system was not prioritised in quantification for this study based on this. The flow-through salmon hatchery, land-based recirculating aquaculture system and open net pen (sea net pen) can be seen in the following diagram.

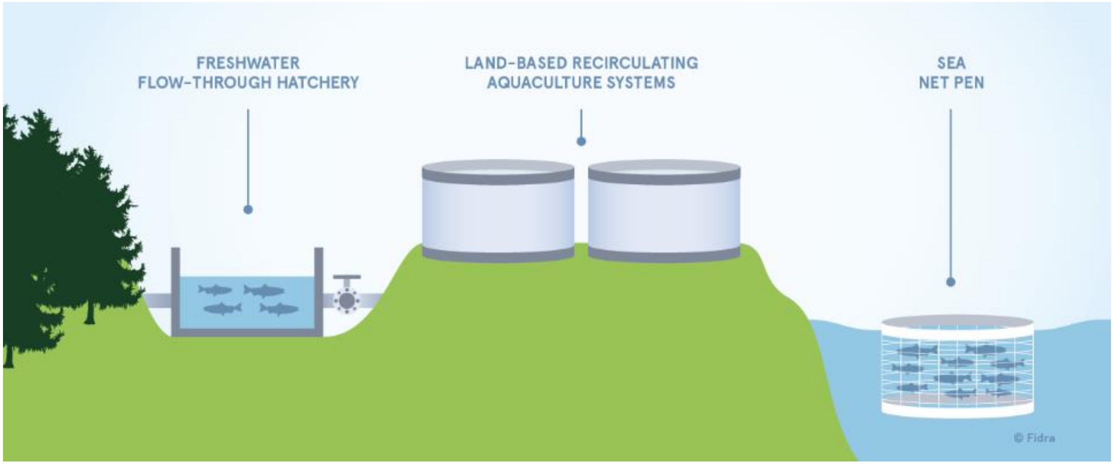


Figure 12: Salmon Farm Structures (Best Fishes, 2018)

Open net pens make up the majority of salmon grow-out, particularly for seawater operations. As it stands, it is still the most widely used method of farming worldwide; it is particularly attractive to farmers and companies as it typically incurs the lowest capital and operating costs. However, as can be seen in figure 13, there is lack of control in this system whereby the water quality cannot be strictly managed resulting in fish being susceptible to poor health due to changes and incidents occurring in the local environment. Further to this, the open net containment doesn't allow for collection of waste effluent which may include uneaten food, fish sewage and chemicals used to treat diseases.

The farming methods currently used can be split into different levels of control in how they operate in respect to restricting undesirable outflows to the local environment and protecting the rearing environment of the fish:

	Level of Control	**Examples**
1	Uncontrollable	Net pens in open bodies of water
2	Limited Control	Pond production and flow-through basins
3	Full Control	Recirculating Aquaculture System

Figure 13: Levels of control for various aquaculture systems (FAO, 2015)

Closed containment is becoming more appealing as farms face rises in disease and mortality due to changes in the natural environment such as rising temperatures from global warming. Further to this, farmers and companies are coming under greater pressure to ensure they are minimising their environmental impacts.

In addition, the greater level of control allows for stable conditions that can allow for relatively accurate prediction of when the fish may be ready for harvest, allowing for greater planning and so perhaps delivering a competitive edge (FAO, 2015).

2.8. Recirculating Aquaculture System (RAS)

Development

Closed cage farming began with a flow-through approach whereby the water that would be utilised in the rearing tanks would be continuously disposed, normally without treatment. However, along with growing concern of water usage and again waste disposal to the environment, the presence of the recirculating aquaculture system (RAS) has prevailed. RAS was developed in the 70s, designed for the following key purposes (Badiola et al., 2016):

1. Reducing the required water and resultant waste produced from traditional flow-through systems

2. Isolating the fish species from the surrounding ecosystems and hence reducing the ecological impacts that open systems do not

3. Eliminating pathogens, resulting in chemical-free productions and hence reduction in disease.

The presence of RAS is becoming more and more prevalent in the salmon industry, particularly in the case of smolt production whereby research suggests it is quickly becoming the preferred option over the typical operation in flow through or small freshwater cages (Badiola et al., 2017). Countries currently deploying RAS for successful Atlantic Salmon production to marketable size are Canada, China, Denmark, France, Poland and USA, interestingly ahead of the 3 biggest producers (Badiola et al., 2017).

The RAS system operates by recirculating the water; once it leaves the rearing tank it typically undergoes various water treatment processes to make it a suitable habitat for the fish to be recirculated into the rearing tank and collect waste to be utilised or disposed of. RAS presents a system that can reduce aquacultures impact on the environment; most notably by decreasing eutrophication, water usage and enabling better waste management and nutrient recycling. However, RAS systems can utilise up to 1.4-1.8 times more energy than flow-through systems (Badiola et al., 2017). Figure14 is a diagram taken from a company in Nova Scotia, Canada, that is producing both smolt and salmon in recirculating aquaculture tanks. However, this company is an example on closed containment aquaculture that is not making the most of its waste streams, still sending a portion to landfill.

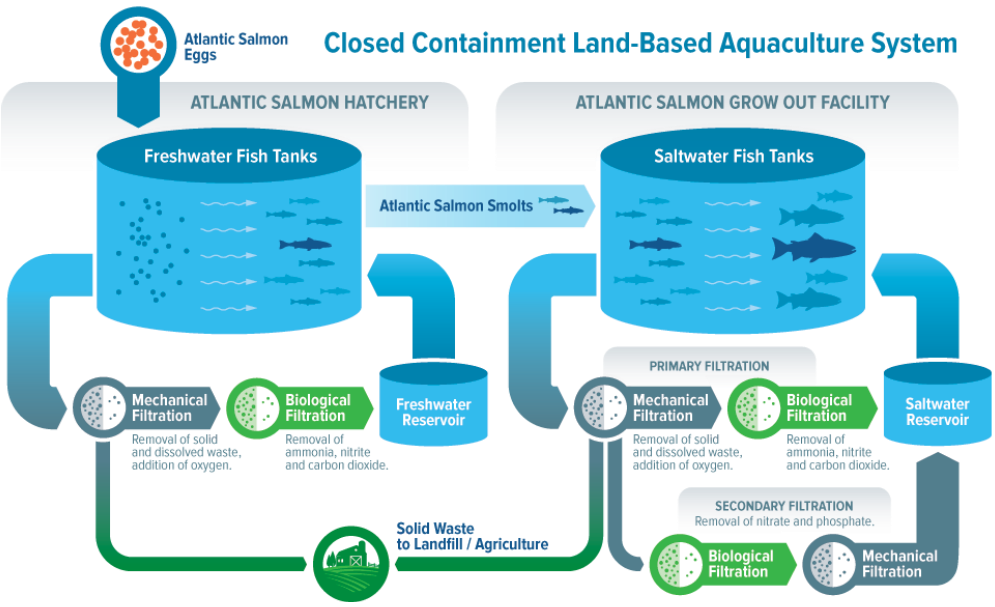


Figure 14: Closed Containment Land-Based Aquaculture System (Sustainableblue.com, 2018)

Research trends in development of RAS in Europe have shown key focus on identifying technical improvements of the recirculation loop and methods of recycling the nutrients in the waste streams (Martins et al., 2010).

Grow-Out Trail of RAS

RAS is a complex system due to the various interactions occurring between the water treatment, the feed and the fish. Experimental testing and trials alone are expensive due to the long rearing time required for the fish to be harvested. However, a trial carried out by The Conservation Fund in Canada showed the technology to be competitive with costs of data published for the open net pen industry. Below is a graph showing the rate of growth from the grow-out trial compared to that of an open net pen off the coast of Maine (Summerfelt et al., 2013).

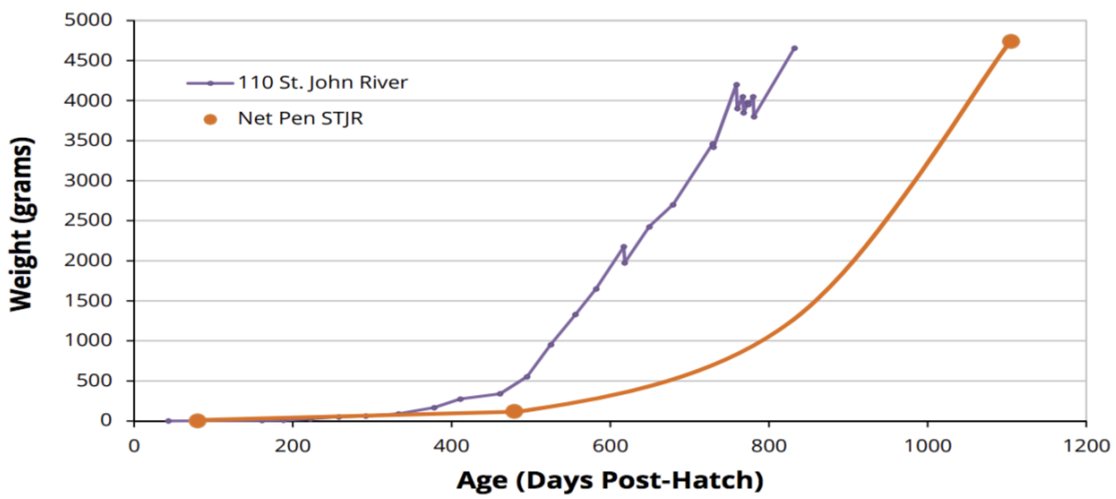


Figure 15: Overall growth curve for Atlantic Salmon in RAS grow-out trial compared with salmon grown in net pens off the coast of Maine (Summerfelt et al., 2013)

This decrease in time taken to reach harvestable weight can allow for greater production per year with structure and planning to benefit the specific farm rather than the salmon's natural growth cycle. RAS is capable of large scale production and smaller scale systems that may be used for restocking or to save endangered species and in the case of salmon may be used for all stages in its life cycle (FAO, 2015).

Research has been carried out for fish growth modelling in combination with advanced dynamic wastewater modelling to investigate how the system may be economically optimised (Wik, Lindén and Wrammer, 2009). The modelling of the growth is at the base of the tool developed in this thesis, as detailed later in the tool creation section.

2.9. Renewable Energy and Waste Treatment

As discussed, closed cage farming offers the potential to minimise the industries impact on the marine environment however, not if it is done poorly. In closed containment fish farming, despite having greater control over inputs and outputs, the waste streams are still often not dealt with correctly but instead are being disposed of in freshwater or seawater as in open net pens. This presents a huge loss in opportunity to be sought in the value chain along with harming the local environment. By releasing the sludge from the closed cage tanks, there are high levels of nutrient loss through feed residues and faeces particularly of nitrogen and phosphorous (Brod et al., 2017).

A further key issue with the less ecologically harmful RAS, is the tendency to use non-renewable sources such as fossil fuels for the more energy intensive production. A life cycle assessment of salmonid culture systems in Canada assessed various aquaculture technologies, concluding that closed-containment systems reduced the local ecological impacts that typically occur by using the more traditional open net system however, they found that the closed-containment systems presented a case for greater global concern due to their more intensive energy usage (Ayer and Tyedmers, 2009). The global warming potential was heightened due to the energy for the recirculating aquaculture system being sourced from coal. A clear solution would be increasing the presence of renewable energy sources in the industry. Integration of renewables is also an economically attractive step as fluctuating prices of energy bring uncertainty and instability in operating costs as they are susceptible to variations in the market (Muir, 2018).

The world and particularly Scotland, are pushing towards the integration of renewable energy across all areas and levels of industry hence, it is a timely opportunity to develop the presence of RAS in aquaculture. Beyond this, waste products from the farm and fish processing can be harnessed to generate energy, supporting the transition to a circular economy as detailed later in the report.

3. Aquaculture in Scotland

The following section addresses salmon farming in Scotland, specifically current issues and growth of the industry. It addresses the goals for 'sustainable intensification' of Scottish aquaculture and policy and regulation relevant to the industry. It discusses the requirement for corporate social responsibility, collaboration across industries in Scotland and support in decision making for the industry.

3.1. Overview

History and Current Situation

In 1969 in Scotland, the commercial farming of Atlantic salmon began; ten years later a government department began publishing annual statistics and information on both seawater and freshwater production to help track the development of the industry.

Scottish strains of Salmon tended to mature early before reaching marketable size however this is counteracted by the input of Norwegian strains that tend to mature later (Fao.org, 2018). As a result of this, cross-breeding has been a regular occurrence and resulted in various hybrid strains being common in the majority of production areas.

Aquaculture in Scotland mainly consists of the production of finfish in the sea, which is predominantly Atlantic Salmon and Scotland's greatest food export. Other key species farmed are Rainbow Trout, Sea Trout and marine species such as Halibut, Cod and Haddock. Aquaculture supports thousands of jobs in Scotland, particularly in coastal communities where there are typically not the same number of opportuniies hence from a social and economic perspective it's highly valuable to Scotland. However, as it stands, there is overwhelming evidence that Scotland is supporting the proliferation and intensive expansion of unsustainable aquaculture; Orri Vigusson the founder of North Atlantic Salmon Fund (NASF) has called on the Scottish Government to ensure better management of intensive farms for the sake of both farmed and wild fish (McKenna, 2018). The National Trust for Scotland has appealed to the Secretary for the Rural Economy to delay expansion of the industry until greater environmental protection is enabled with stricter regulations (Kirkaldy, 2018).

Currently, finfish farming is carried out in both seawater and freshwater fish farms, predominantly on the west coast and on the islands along the west coast. Figure X shows a map of the active seawater, freshwater and shellfish sites currently active in Scotland. The fish dominating the industry in respect to level of production are

Rainbow Trout and Atlantic salmon; Atlantic Salmon accounts for approximately 95% of production (Marine Conservation Fund, 2017). Other species that are farmed include Arctic charr, brown/sea trout, halibut, lumpsucker and several species of wrasse.

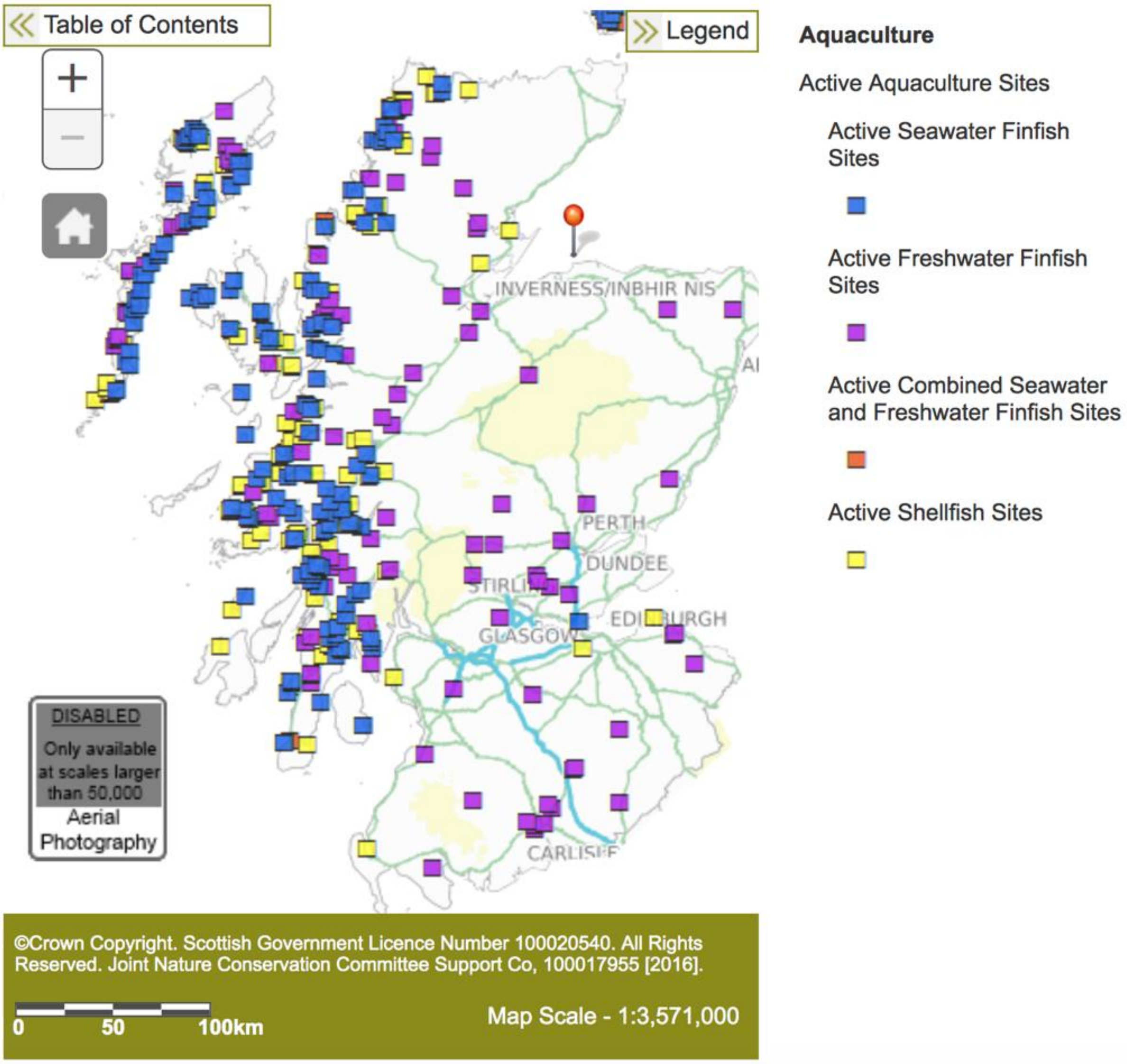


Figure 16: Map of Aquaculture in Scotland (Aquaculture.scotland.gov.uk, 2018)

Targeted Growth

Scottish salmon farmers have set out a strategic plan for enabling the growth of the industry to 2030 to bring the value of the industry from around £1.8bn annually to £3.6bn annually. This gives the potential for the number of jobs provided by the industry could reach 18,000. They have encouraged collaboration between regulators, industry, researchers and other stakeholders to develop a roadmap that supports equal efforts in economic development, social development and environmental protection.

So, ‘sustainable intensification’ is the challenge facing the industry. With the industry suffering from grave biological challenges with higher levels of mortalities in recent years than ever before, it has come under fire for unsustainable proliferation and poor ethical approaches in respect to animal welfare as detailed previously.

There is increasing concern that with the move towards closed-containment recirculating aquaculture systems, production will be more attractive for big companies in areas or countries whereby land and energy resources are cheaper. However, this may not necessarily be the case. Scottish Atlantic Salmon is a product of great history and global desirability as more than £600million of Salmon and seafood are exported annually from Scotland. Furthermore, in the UK it is the most popular fresh fish (Ellis et al., 2016) and campaigns by the government are encouraging the population to increase the presence of fish in their diets (Scotlandfoodanddrink.org, 2018). In 2014, Scottish farmed salmon was voted the best in the world by retail and foodservice buyers in 2014. Despite Beijing only allowing imports of Scottish Salmon to begin in 2011, the demand has rocketed and more than 11,000 tonnes (valued around £73million) were exported to the Far East.

With an increase in production, the value of salmon decrease and the producers are under pressure to minimise costs; the traditional open net cage is often assumed to be cheaper. However, research in Norway concluded that closed containment aquaculture could in fact be the more economical option despite the typically higher energy required for this type of farming. A thesis finds that largely due to the sea lice treatment costs of high levels of infection in Norway, closed containment aquaculture could be a more profitable solution (Pederson, 2016). Whilst there is not yet enough data from large scale testing to understand the true benefits, it is likely that Scotland too could benefit from this system shift as it suffers with similar problems such as sea lice.

In summary, Scotland is the third major producer of Atlantic Salmon in the world and a global leader in setting policy surrounding renewable energy and protecting the environment. Therefore, it is imperative that routes for sustainable growth in its leading food export industry are identified and social-environmental factors are not discarded for the sake of rapidly increasing economic growth.

3.2. Current Issues in Scotland

As of right now, fisheries in Scotland are struggling to adapt to such factors like increased production and climate change; it is anticipated that these are key reasons for the increased mortalities of the fish as the majority of salmon production occurs in open net systems, apart from smolt (juvenile) production (Newton and Little, 2017). The following section details incidents that have occurred in Scotland in recent times.

Figure 17: Open Net Pen Salmon Farm in Oban run by Scottish Sea Farms (The Independent, 2018)

Mortalities

Research found that the welfare of farmed salmon had improved as the industry had developed (Ellis et al., 2016), however since then, Scotland has experienced some of its worst cases of sea lice and rates of mortalities. In 2016, they had to dispose of a volume of 22,476 tonnes of salmon and trout which results in approximately 6-10 million (Edwards, 2018). In assessing the number of mortalities, by taking the average salmon feeding rate of 1.2kg feed/ kg salmon each day for approximately 22,476 tonnes of salmon, the economic losses and impacts on the environment without resultant food supply are severe.

Figure 18 summarises the tonnes of dead salmon thrown away by the major salmon producers in Scotland in 2013 and in 2016.

Dead salmon thrown away

fish farm company	tonnes in 2013	tonnes in 2016
Marine Harvest	2,224	7,609
Scottish Salmon Company	2,436	5,873
Wester Ross	86	3,142
Kames	51	2,854
Scottish Sea Farms	1,897	1,678
Grieg	0	611
Dawnfresh	122	200
Loch Duart	581	33
Others	3,202	479
Totals	10,599	22,479

source: aquaculture.scotland.gov.uk

Figure 18: Number of Dead Salmon Thrown Away (Edwards, 2018)

Investigations carried out by fish health inspectors into reasons for such high mortality rates have shocked animal welfare campaigners and despite industry practice being heavily criticised by a committee of MSPs at Holyrood, the Scottish Government is still encouraging the currently failing growth of the industry (Edwards, 2018). Various groups and charities including Compassion in World Farming, Animal Concern, OneKind and Scottish Salmon Watch have questioned the ethical nature of the industry, demanding increases to animal welfare (Edwards, 2018).

Sea Lice 'Crisis'

The Scottish farming industry has been facing major issues with sea lice which have led to a decrease output from production and increases in costs due to expense required to treat such diseases. Marine Harvest Scotland, Scotland's largest Salmon producer, reportedly disposed of 1,500 tonnes out of 40,000 tonne production and reportedly increased their use of antibiotics from approximately 1 gram per tonne of fish produced to 24 grams (BBC News, 2018). Devastating consequences occur in the case whereby wild salmon smolts migrate from local rivers through juvenile lice 'clouds' and even when a few mature female lice are present in cages that house thousands of farmed salmon (Salmon & Trout Conservation, 2018).

A method that has been used over the years in tackling sea lice is shock treatment whereby the fish are bathed in warm water to rid them of parasites however this has resulted in various tragedies over the years in poor practice, killing many Salmon.

Marine Harvest Scotland and Scottish Sea Farms have claimed to have had a breakthrough in tackling sea lice in Scotland by using other species such as wrasse or lumpfish that attack and eat parasitic sea lice. However, this has not been widely accepted by environmental groups such as Open Seas as the process has involved taking wrasse from the wild, damaging stocks as they are a particularly slow growing species (BBC News, 2018).

Escaped Fish

Norway, suffering from its own crisis of escaped fish, have issued a ban on importing farmed salmon from Scotland for aquaculture (Stoichevski, 2018). When farmed salmon escape and breed with wild salmon, the gene pool is changed and diluted which can impact the wild salmon's genetics and ability to adapt to localised habitats. A study funded by the Scottish Government found that along the west coast of Scotland, 369 out of 1472 (25.1%) of wild salmon were identified as hybrids meaning Norwegian genes were evident (Salmon & Trout Conservation, 2018).

Seal Attacks

In open net pen systems, farmed fish are subject to predators. In Scotland, seals present a huge issue for fish farmers for which they are able to procure a Scottish Government license to shoot the seals in the case of attack. This license is released under strict regulation whereby it must be proven that all actions to deter the seals have been put in place and shooting is a last resort. Seals are particularly vicious killers, taking individual bites from salmon which often leads to other salmon that are not under attack dying due to fear and stress. While data released by the government shows methods for deterring seals on fish farms are becoming increasingly more efficient, in the case of closed containment, this issue could be mitigated completely resulting in less economical loss and an increase in animal welfare. It was reported that in 2016/2017 the number of salmon mortalities related to seal attacks was approximately 58, 654.

3.3. Policy and Regulation

Scotland currently has various policies in place directly regarding the aquaculture industry and relevant to industry in general that should be considered.

The Farmed Fish Framework

The Farmed Fish Framework is a 10-year strategic plan put together by the aquaculture industry and the Scottish Government. Whilst the plan aims to tackle most of the industries issues including managing sea lice, ensuring better information flow and transparency, and tackling issues around climate change, it does not underline energy directly within its key plans. However, work Stream 7, addressing Climate Change and Ocean Acidification, identifies the need for determining how to measure changing climatic conditions in Scotland caused by the environmental impacts of the aquaculture industry which the tool of this thesis may help to support (The Scottish Government, 2018).

Scottish Environmental Protection Agency (SEPA)

SEPA outlines the requirement for current fish farms and future fish farms to minimise their environmental impacts by their regulatory strategy 'One Plant Prosperity'; a strategy aimed at tackling 'the challenges of the 21st century facing Scotland's environment' (SEPA, 2018). It strives to highlight and encourage companies to pursue the route of environmental protection in ways that can also result in health, social and economic benefits. Their approach for regulating the industry is based on restricting the scale of development to match the environment's capacity to bio-degrade the wastes that arise in farming. This includes the benthic floor and local surroundings capacity to cope with feed, fish faeces, chemicals and medicines input (HIE, 2017).

River Temperature Monitoring Network

Scotland has implemented River Temperature Monitoring Network (SRTMN) in the last 10 years, led by Marine Scotland Science to increase understanding of how river conditions and changes impact salmon growth and performance (Gov.scot, 2018). This is particularly relevant in protecting wild fish species that inhabit freshwater.

Renewable Energy

Scotland has been a global leader in passing ambitious climate change laws, including their reduction of greenhouse gas emissions by 42% in 2020 compared to the 1990 baseline. With further goals in sight such as a 90% reduction by 2050, it is incumbent upon the Scottish government to maximise the opportunity to clean up their greatest food export. Greater integration of renewable energy is a clear and reliable route to be pursued by the industry; increasing the sustainability of their inputs. However, there is also a lot to be done with the outputs from the processes.

Common Fisheries Policy (CFP)

The CFP was implemented on the 1st January 2014. A key element to this policy is working towards eliminating the level of discards/ waste from EU fisheries.

The Clean Growth Strategy

Pitted at the heart of the Clean Growth strategy is achieving higher industry growth however with lower carbon emissions (HM Government, 2017).

International Trade

Trade in Ova, Smolt and Salmon is well established within EU member states, enabled by the EU single market. Trade is also allowed within the European Economic Area (EEA) between the EU and member states of the European Free Trade Association (EFTA); namely Iceland and Norway. Trade of Salmon and Ova in Scotland has changed considerably over the past 10 years, in part to be explained by the percentage it produces in the global market as it strives to remain a key player.

3.4. Socio-Economic Impact

With Salmon being Scotland's top food export, it is the source of thousands of jobs and helps coastal communities to thrive. Figure 19 shows the economic multiplier in Scotland of Salmon production, demonstrating the importance of the industry's success to the livelihood of many.

The value chain in salmon production is long, from feed production to farm-gate there are many opportunities for jobs requiring skills, training and education. It also provides opportunities for innovation and research; a prime example being the Scottish Aquaculture Innovation Centre (SAIC).

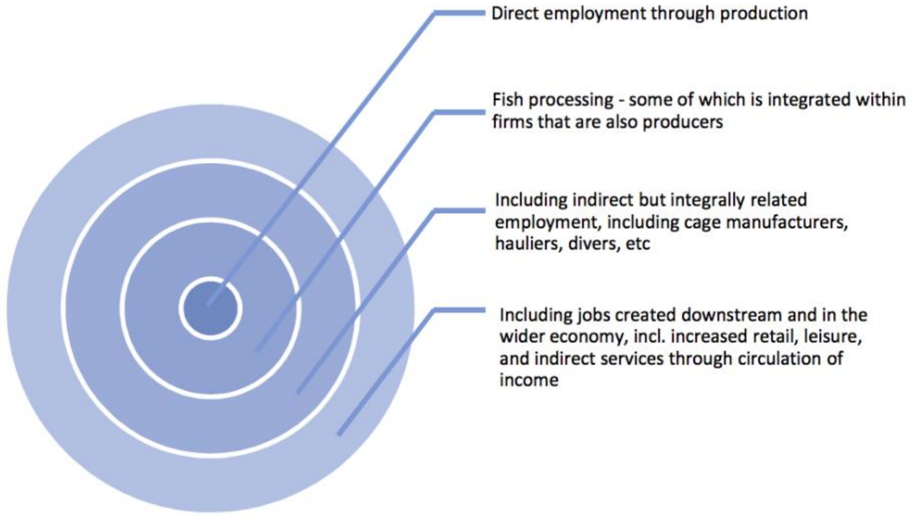


Figure 19: The Economic Multiplier in Scotland of Salmon Production (HIE, 2017)

3.5. Sustainability

Sustainable development in food resources implies that current production systems should reach maximum efficiency to ensure the current population is not hindering the ability of generations to come in meeting their own needs (Colt et al., 2008).

In a report released by Scotland Food and Drink, they have defined sustainability of the fishing industry in Scotland as being made up of Environmental, Social and Economic Considerations and should aim to thrive in all aspects, as defined by at the World Summit on Social Development (2005) (Scotland Food and Drink, 2016). The following diagram demonstrates their priorities as defined by a working group of leading aquaculture businesses and organisations in Scotland.

To enable sustainable growth of the industry, better understanding is required throughout the whole value chain of the product so that companies operating in aquaculture can identify hotspots whereby they can make decisions and developments that are not only beneficial to the environment but to them economically. A tool that is becoming increasingly important across the globe to determine the sustainability of agriculture and other production processes is the life cycle assessment.

The term of 'sustainable intensification' is used for increases in yield for agricultural food production in respect to various resource inputs such as space, water, feed, energy and other materials along with various outputs such as greenhouse gases, eutrophication emissions and biodiversity (Ellis et al., 2016). Other key aspects that have been recognised as being fundamental to sustainable intensification are animal welfare, nutritional value of products and rural economies; these will be briefly addressed in this report however environmental impact is the key focus.

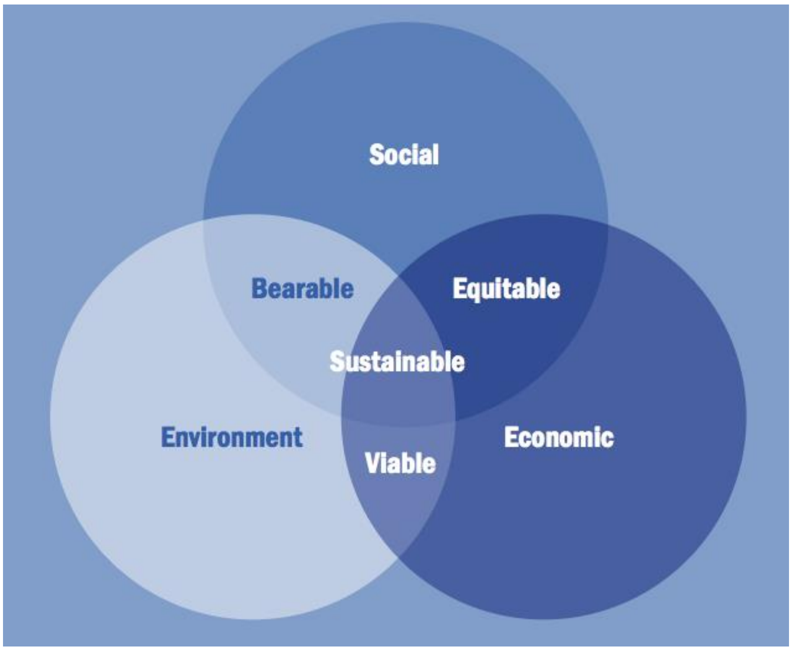


Figure 20: Balancing the three pillars of sustainability (Food and Drink Scotland, 2016)

3.6. RAS Enabling Sustainable Growth in Scotland

As detailed in the previous subsection, Scottish Salmon does not consist of a local value chain therefore in considering the growth of the industry it is imperative that it is done with the goal of ensuring production that minimises damage to its value chain. A key initiative is reducing the feeding conversion ratio which is enabled by the use of RAS and its ability to optimise the rearing conditions.

Expanding the Scottish Aquaculture Industry using the current framework with the knowledge of the impact that open net farms have on the environment is arguably negligent. Salmon & Trout Conservation Scotland state in their Salmon Farming Campaign that the industry must create a biological barrier between farms and surrounding sea areas by encouraging a shift to closed containment farming whether it be land-based or floating tanks, replacing open nets (Salmon & Trout Conservation, 2018).

A study carried out by Stirling Aquaculture at The University of Stirling for Highlands and Islands Enterprise recommended the following (HIE, 2017): “There should be no presumption against RAS technology as it is likely to play an important role in the future development of the Scottish salmon industry”. Proceeding to encourage support for research and trial projects, whilst ensuring that a mechanism be put in place to ensure public collaboration on lessons learnt to strengthen the industry in Scotland (HIE, 2017).

3.7. Collaboration and Industry Decision-Making

There are currently 26 companies operating in the freshwater production of Atlantic salmon, operating across 87 active sites and 12 companies operating in the seawater production of Atlantic salmon, farming across 253 active sites. In addition to this, there are various feed production, fish processing sites and farms of other fish species. Collaboration along the value chain could be of benefit both environmentally and economically. Zero Waste Scotland (ZWS) released a report in June 2015, highlighting opportunity for collaboration between three sectors: Beer, Whisky and Aquaculture. The opportunities highlight ways in which Scotland can become more of a circular economy, turning its waste into value products. The report found that the Scottish economy could benefit by up to £800million by utilising by-products from the fish, beer and whisky industry (Zero Waste Scotland, 2015). The study identified hotspots for anaerobic digesters as seen in appendix. It is evident that to increase the sustainability of the aquaculture industry will not only require looking at the opportunities for improvements in aquaculture across industry in Scotland.

There is a lack of scientific based decision-making tools available in the aquaculture industry. As this push towards RAS ensues, it would be beneficial for fish farms to undergo regular energy audits to obtain real data that can record and account for energy flows, highlighting areas of inefficiencies. In addition, holistic understanding of fish product impact is required as the fish supply chain consists of multiple stages.

It is important for the aquaculture industry and Scottish Government to understand where to be making sustainable investment. This aim of this thesis is to provide an overview as well as support the development of a framework for the assessment of current and future farms.

4. Circular Economy

The following section addresses the circular economy concept and how it may be applicable to the aquaculture industry. It details current examples of farm adaptations that show progress towards aquaculture designs that have demonstrated the capability for application of the circular economy concept.

4.1. The Concept

The concept of the circular economy is restorative and regenerative by design. It has a key focus in design that mitigates waste and minimises negative impacts such as pollution that are incurred in the activity. It strives to decouple economic activity from the consumption of non-renewable sources; it is driven to build economic, natural and

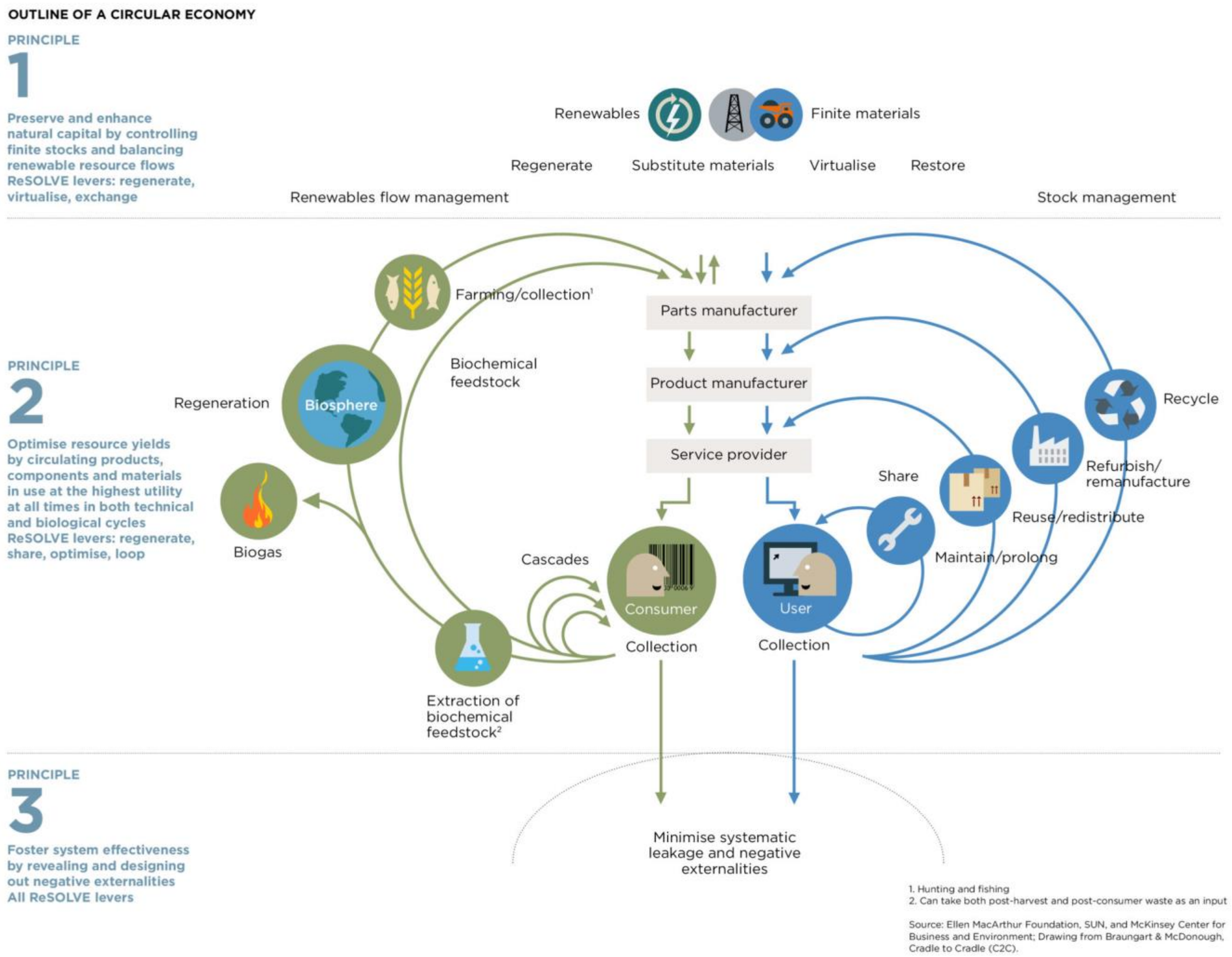


Figure 21: Circular Economy System Diagram (Ellenmacarthurfoundation.org, 2018).

social capital (Ellenmacarthurfoundation.org, 2018). In the face of the intensification of the aquaculture industry in Scotland, sustainable growth would be achievable if the concept of circular economy was given appropriate consideration. Under the Resource Efficient Circular Economy Accelerator Programme, small and medium sized businesses or organizations in Scotland can apply to receive the Circular Economy Investment Fund administered by Zero Waste Scotland (Zero Waste Scotland, 2016).

This section details areas or generation of waste within the value chain that can be harnessed to make the process more profitable and less environmentally damaging with the concept of the circular economy at the forefront. Most of the following concepts require waste collection enabled by RAS however Integrated Multi-Trophic Aquaculture may be implemented to improve the environmental impact of open net farms as detailed. It is acknowledged in literature that utilising nutrients in the waste generated in aquaculture is intrinsic to the effectiveness of the future 'circular economy' (Brod et al., 2017). There is huge opportunity considering approximately 301,037 tonnes of fish waste are produced at the fish processing stage in the UK every year with a further 45,762 tonnes dumped in the sea (Ward and Slater, 2002). A study quantified the release of nutrients from Norwegian fish farms and concluded that of the total feed input, 70% of the carbon, 62% of the nitrogen and 70% of phosphorous were being released into the environment (Wang et al., 2012).

4.2. Animal By-Product Regulations

Waste that falls under the category of animal by-products comes with very tight regulations in both Scotland and the EU. The waste cannot be utilised in human food production; it is divided into 3 categories that limit the way waste can be treated due to the circumstances under which it has arisen (Zero Waste Scotland, 2015):

Category	**Status**	**Description**
1	Very High Risk Material	e.g. animals suspected of having infectious disease that can be spread to humans or animals
2	High Risk Material	e.g. mortalities; animals that have died for reason other than slaughter
3	Low Risk Material	e.g. parts of slaughtered fish that are suitable for human consumption however

		aren't intended for consumption such as food rejected for commercial reasons like packaging faults

Figure 22: Table showing categories of animal by-products (Zero Waste Scotland, 2015)

4.3. Fertilisers

The two main methods currently utilised and under research for waste treatment from fish farms are fertilisers and anaerobic digestion (Brod et al., 2017). Fish wastes offer many benefits to agriculture, particularly in their high nitrogen content (Zero Waste Scotland, 2016). In a recirculating aquaculture system, after mechanical filtering, the sludge is dried to increase the dry content of the waste sludge (up to around 90%) which is then transformed into pellets which can be used to produce fertilisers for agricultural land. In Scotland, they must be proofed to determine that they are going to have agricultural benefit however fish sludge has been cited as an appropriate method for closing nutrient cycles in aquaculture (Brod et al., 2017).

4.4. Anaerobic Digestion

Anaerobic digestion (AD) can be used to treat the waste to generate energy which can then be recycled into the energy demand of the plant; it can be economically viable if the AD unit is designed suitably for the content (Ward and Slater, 2002). Biogas production allows for increased efficiency of the agricultural sector along with aiding in energy supply and reducing the environmental impact of the process. Anaerobic digestion may be used for waste generated on the farm and at the fish processing stage. Agricultural waste may be co-composted with high carbon content material such as garden or wood wastes. Fish waste tends to have a high level of ammonia when digested which can result in technical difficulties however these have been overcome and the system can be designed to cope with this issue (Ward and Slater, 2002).

Generation of electricity by use of dead salmon has caused outrage amongst animal welfare campaigners, as the biogas is burnt to feed into the National Grid; the by-product is reportedly used as fertiliser (Macaskill, 2018). It is acknowledged that it is an efficient way of utilising the waste and is in line with Scotland's targets for zero waste however an advance on this would be for energy suppliers to be transparent with their customers who may want their energy to be procured by other means.

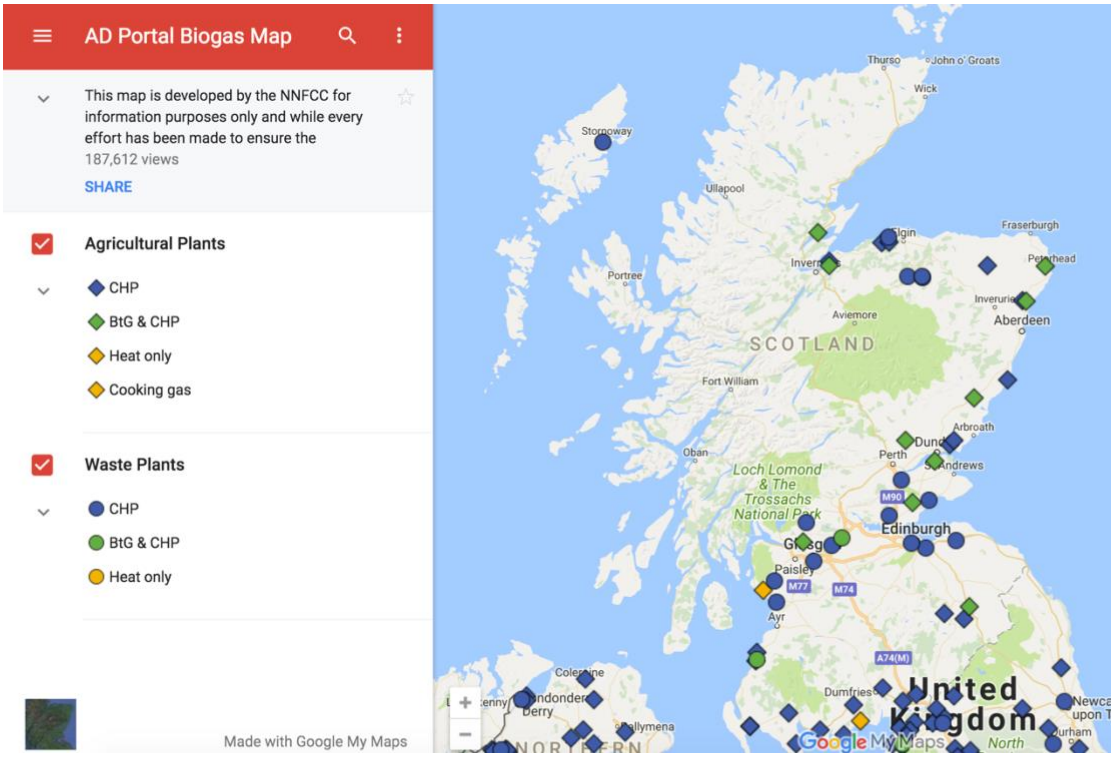


Figure 23: Biogas Map Scotland (Biogas-info.co.uk, 2018)

4.5. Algae Production

Organic digestate generated as a by-product of anaerobic digestion may be utilised in algae production, as it includes salts, minerals and bio-processing wastes that can be turned into useful products that have a wide range of purposes such as biofuel, health supplements and fish feed production (Wong, Hung and Chiu, 1996).

Algae has been cited as the most sustainable raw material available for production of salmon feed, enabling the future growth of aquaculture. Hence, the value in producing algae from by-product. It could allow for maintaining the omega-3 required in feed as microalgae contains almost all the nutrients fish require (Phys.org, 2018); a project from the National Food Institute has predicted its potential.

A recent start-up company in Edinburgh, Scotland developed a process capable of turning whisky by-products into fish food microalgae products, using the circular economy to enable viable operating costs (Mialgae.com, 2018).

4.6. Aquaponics

Aquaponics is an innovative approach to aquaculture that combines aquaculture with the production of vegetables by hydroponics (Palma Lampreia Dos Santos, 2018). By integration of plants to an RAS system, a system can become more profitable whilst minimising the requirement for filtration. It is typically facilitated by a recirculating system; the water received by the plants is the small percentage (usually less than 3%) of nutrient rich water that is discarded from the system (Harmon, 2005).

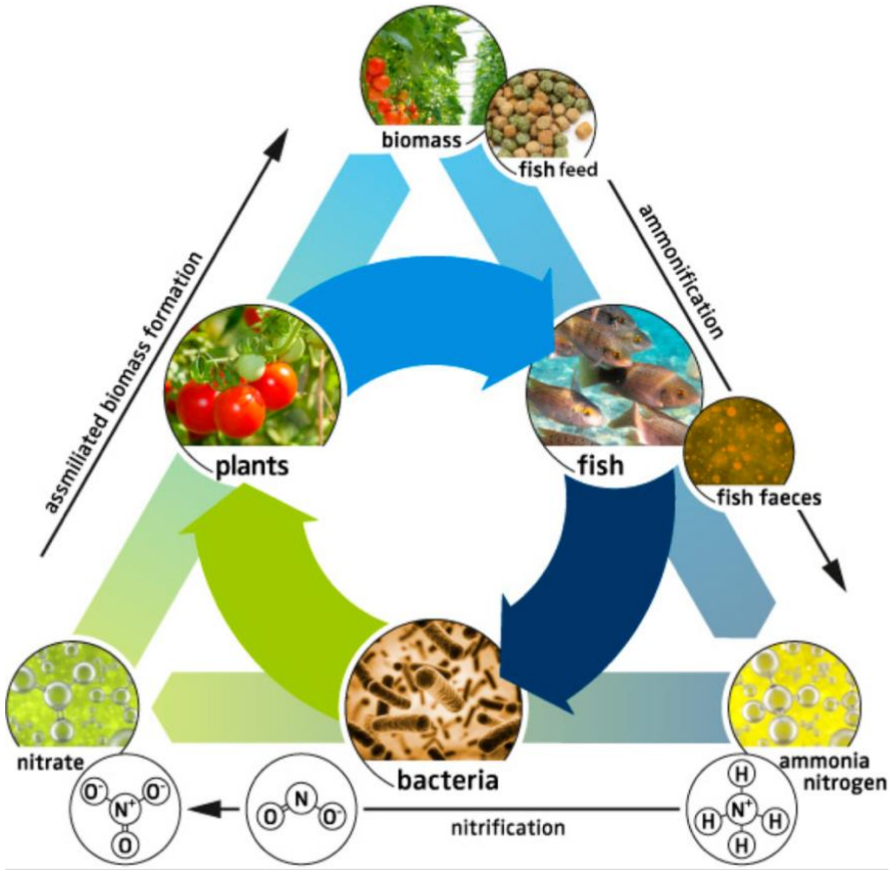


Figure 24: Symbiotic Aquaponic Cycle (Goddek et al., 2015)

Ratios for plant growing area to fish growing area can vary from 2:1 to 10:1 depending on the system; if the system is well designed then a small volume of fish can result in a large amount of plants (source). It was found that depending on the system, the rate of plant growth based on the grams of feed input varied from 1.3g/plant/day to 2.4g/plant/day (Harmon, 2005). A pH as close to 7 is required as a typically hydroponic nutrient solution ranges in approximately 5.0-7.0 in pH (Harmon, 2005).

A study showed using Google Trends data and a quantitative methodology, multivariate analysis and econometric models that there was an increasing interest in aquaponics, particularly in European countries whereby the Aquaponics Hub operated (Palma

Lampreia Dos Santos, 2018). The Aquaponics Hub was funded by the European Cooperation in Science and Technology (COST) to promote innovation by researchers and industry in this field from 2014-2018 (EU Aquaponics Hub, 2018).

Whilst studies have mainly been carried out to address the scientific aspects of aquaponics, research is now being carried out to help realise commercial aquaponics systems. Research has concluded that aquaponics as an integrated food production system has vast potential at this scale, determining that areas whereby there are water shortages may benefit largely from this system however research is still required in this area (Goddek et al., 2015). The general system design for aquaponics can be seen in the diagram below.

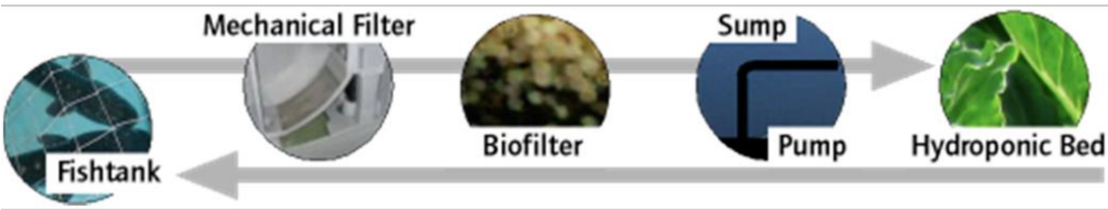


Figure 25: Basic aquaponic system layout (Goddek et al., 2015)

4.7. Integrated Multi-Trophic Aquaculture

Integrated Multi-Trophic Aquaculture (IMTA), allows for combining species to complement each other – certain species eat the uneaten feed and faeces of the salmon for example. It is a traditional technique carried out in China in the case of small scale aquaculture however nowadays, various countries are investigating and implementing IMTA. As approximately 60% of nitrogen is lost to the local area when conducting open net farming, it is important to harness this resource and limit negative ecological impacts. In Canada, research is being carried out to model and predict dispersion of farm waste to ensure a balance of organic and inorganic species (Dfo-mpo.gc.ca, 2018). Effective systems can be designed by optimising the position of species collecting waste, considering the direction of water flow.

4.8. Example 1: OHLEH

The Outer Hebrides Local Energy Hub (OHLEH) is an effective example of integrating various renewable energy technologies that supports the concept of a ‘circular economy’. The innovative project allows for energy from renewable sources whilst utilising its waste stream for anaerobic digestion. The project is underway however isn't expected to be fully functional until Autumn 2018 hence data could not be collected to analyse its efficiency and effectiveness.

The project was identified as having potential as the Isle of Lewis implemented the anaerobic digestion plant for dealing with domestic waste however it was not being utilised well due to lack of domestic waste on the island. Further to this, the island is host to a wind farm that was experiencing a high level of grid curtailment (Communityenergyscotland, 2018).

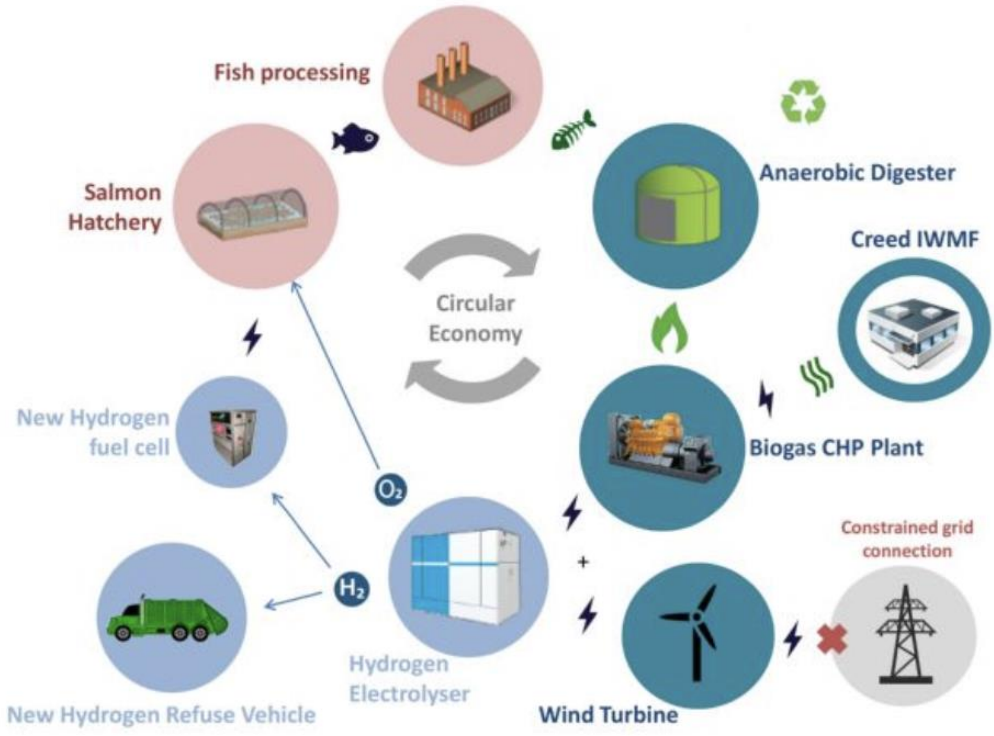


Figure 26: OHLEH Circular Economy System (Communityenergyscotland, 2018)

This system also incorporates a method of storage to allow for managing the stochastic nature of the renewables to ensure supply meets demand. The choice of hydrogen storage is advantageous as the electrolyser generating the hydrogen has a by-product of oxygen which is required by the fish. Thermal energy supplied by CHP may also be useful in temperature control for the salmon growth however it is unsure if this is implemented at the OHLEH site.

4.9. Example 2: Niri

Niri is an RAS technology company that has been developed over the past 10 years, established by engineers and marine biologists. Whilst there are other companies that have focused on deploying RAS technology, the are few that integrate horticulture and aquaculture production with anaerobic digestion into their model.

The system harnesses the waste stream including feed and faeces from the fish and potential waste after the fish have been processed to generate electricity. The biofuel can be used in combined heat and power which is of use in the case as heat is often required in RAS temperature control (Niri.com, 2018).

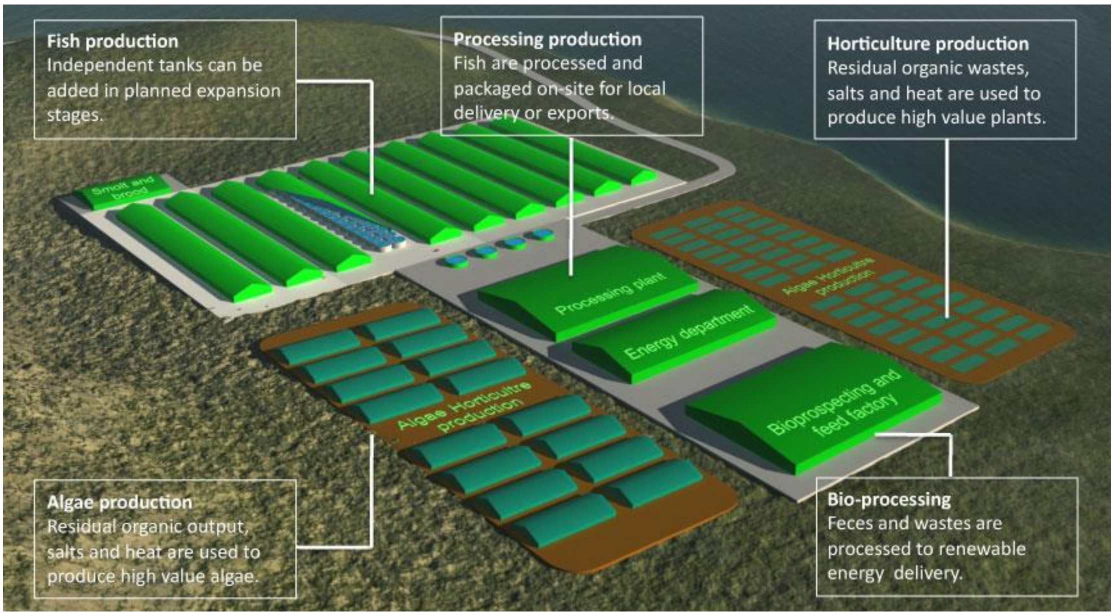


Figure 27: Niri Aquaculture Plant (Niri.com, 2018)

4.10. Example 3: Grow Up Urban Farm

Grow Up Urban Farms is a company based in the South of England operating in Aquaponics. They operated a commercial-scale aquaponics farm that produced 4,000kg of fish per year and 20,000kg of salad and herbs over 8,200 square feet growing space.

Figure 28: Pictures taken of Unit 84 (GrowUp Urban Farms, 2018)

They also designed units capable of a smaller community scale level of production with 150kg of fish and 435kg of sustainable salads. The company farmed the species Tilapia which is the second most farmed fish in the world whilst maintaining a good feed conversion ratio (GrowUp Urban Farms, 2018).

4.11. Example 4: Isle of Gigha

The Halibut fish farm on the Isle of Gigha produce ‘sustainable Scottish Atlantic Halibut’ in tanks whereby the water is pumped directly from the Atlantic. Steps taken to ensure the sustainability of this site include using 100% fish trimmings from onsite as their feed (Gigha Halibut, 2018), resulting in no pressure on the feed production industry and reduced carbon footprint. Further to this in their ‘smoking’ process, they utilise wood chips from casks from the Islay ‘Kilchoman Distillery’, showing efficient integration across industries. The farm produces 75 tonnes of Halibut per year and supports the preservation of a species under threat.

4.12. Example 5: IMTA in Loch Fyne

A trial of IMTA has been initiated in Scotland in Loch Fyne by use of a grant from Zero Waste Scotland, supporting the development of a circular economy. It is being carried out by the Scottish Salmon Company

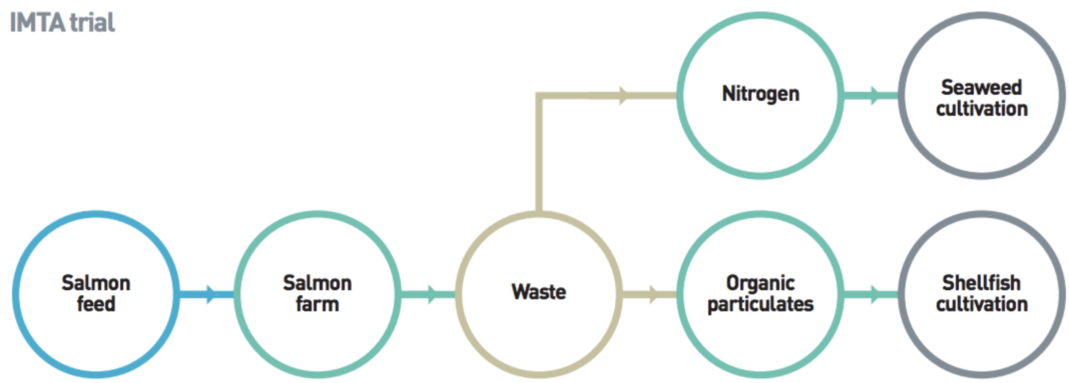


Figure 29: Flow diagram of IMTA Trial (Zero Waste Scotland, 2018)

Shellfish species that have been utilised in this Scottish trial are well established mussels, oyster and queen scallops along with less established sea urchins. The key seaweed cultivated is kelp (Zero Waste Scotland, 2018). Reportedly, the trial is going well and higher growth rates have been observed in both the seaweed and shellfish (Zero Waste Scotland, 2018). By investing in IMTA, the farm has potential for greater profitability by utilising a resource that would have otherwise been a harmful waste.

5. Life Cycle Assessment Review

The following section reviews the suitability of LCA in determining the environmental impact of Atlantic Salmon. It summarises literature available for LCA that have been carried out in this sector and how this has influenced the direction of this thesis.

5.1. Overview of LCA

The life cycle assessment (LCA) is a tool that allows for environmental assessment as and it is part of the ISO 14000 environmental management standards. It follows a products life cycle from ‘cradle to grave’ in assessment of all energy and material inputs at every stage of the products life; raw material extraction, processing, manufacturing, distribution, use, repair and maintenance and disposal or recycling at end of life (Liu et al., 2016). LCA allows for a holistic approach in understanding the potential environmental impact that products produced in the aquaculture industry imply. It is not as well developed in the food industry due to its complex nature as it is in other sectors such as the petro-chemical industry (Badiola et al, 2017). However, it is generally utilised and accepted as a suitable tool in analysing the environmental sustainability of a product or process. LCA can aid in eco-design by identifying opportunity or hotspots whereby there is greatest environmental impact and scope for improvement.

In literature, LCA has been utilised for various fish species. However, across the aquaculture industry, methods of production are highly varied depending on various factors such as different species with different farming requirements and different location. This has resulted in vast research and development having been put into the methods of production across various regions (Badiola, 2017).

5.2. LCA Methodology

The Life-Cycle Assessment can be carried out by following four key steps; definition of system limits, data inventory, data translation into environmental impact indicators and results analysis & interpretation.

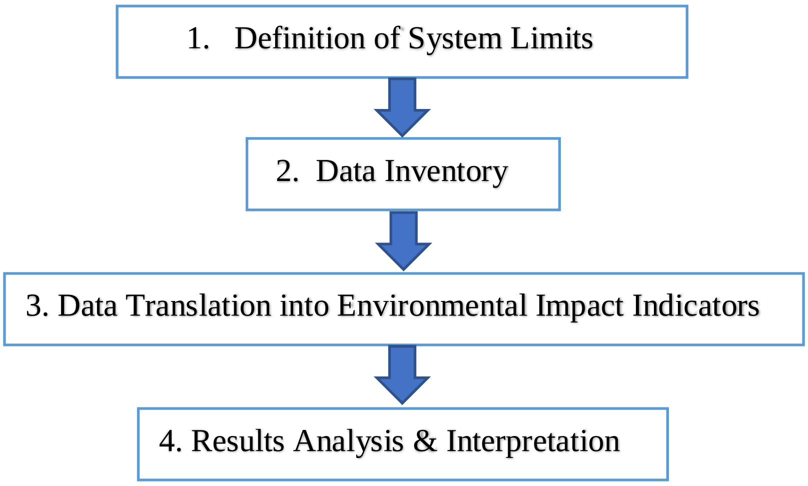


Figure 30: Life Cycle Assessment Method

LCA in aquaculture generally quantifies the raw materials and energy inputs at all stages of the process from raw material extraction to the final product quantified as either live-weight salmon or head on gutted salmon (HOG) which is the salmon weight after processing.

The following impacts categories were the most prominent in LCAs carried out for Salmon production.

Abiotic Depletion (ABD) is utilisation of natural resources such as iron ore and crude oil leads to abiotic depletion. By treating waste streams, they can be utilised as a valuable source of reducing the carbon footprint and potentially resulting in 'negative emissions' and result in a reduction in depletion.

Global Warming Potential (GWP) occurs when greenhouse gases released are absorbed by the atmosphere, impacting the rate by which energy escapes into space which is presumed to cause global warming.

Acidification (ACD) of seawater is the continuous decrease in the pH as the ocean absorbs CO_2 from the atmosphere. Respiration of fish, releasing CO_2 in intensive open net pens can impact the pH of the local environment, impacting the habitat of other species.

Eutrophication (EUT) occurs whereby there is an excessive level of nutrients in a lake or body of water. This results in excessive growth of plants and algae which then may deplete the oxygen in the water and cause an undesirable disturbance to the natural balance of organisms and water quality.

Cumulative Energy Demand (CED) is the total energy required for producing a certain quantity of product.

5.3. Literature Review of LCA for Salmon Industry

The following section summarises some of key papers that have been utilised in understanding the environmental impacts of Atlantic salmon which have influenced the direction of this thesis.

'Mapping the impacts of farmed Scottish salmon from a life cycle perspective' (Newton and Little, 2017)

An LCA was carried out for the Scottish Salmon Industry; 'Mapping the impacts of farmed Scottish salmon from a life cycle perspective' (Newton and Little, 2017). The study procured data by surveying an international feed mill, six farms and a key processor; considering the cycle up to the stage of head-on gutted Atlantic Salmon (HOG) (Newton and Little, 2017). It found that Scottish Salmon is not such a "local" product as consumers both in the UK and globally may be led to believe. It in fact supports an extensive global supply chain as approximately 50% of feed ingredients are sourced from South America with only 25% of feed ingredients being from the UK (Newton and Little, 2017); only up to 10% of grains going to feed are sourced in Scotland (HIE, 2017). The ingredients procured for Salmon grow-out feed in Scotland were found to be as seen in figure 31. The data was collected directly from the Scottish feed mill; some data more origin specific than others.

Ingredient category/%	Ingredient	Country of origin	Transport type
Marine meals	Fishmeal[1]	Peru	Oceanic freight/road lorry
25.9%	Fishmeal[1]	Denmark	Oceanic freight/road lorry
Marine oils	Fish oil[1]	Peru	Oceanic freight/road lorry
22.0%	Fish oil[1]	Denmark	Oceanic Freight/road lorry
Vegetable proteins/fillers	Soybean meal[1,2,3]	Brazil	Oceanic freight/road lorry
44.8%	Maize gluten[1]	Europe	Road lorry
	Wheat gluten[1]	Europe	Road lorry
	Fava beans[4]	UK	Road lorry
	Sunflower seed cake[5,6,7]	Ukraine	Oceanic freight/road lorry
	Whole wheat[1,8,9,10]	UK	Road lorry
	DDGS[1,4]	UK	Road lorry
Vegetable oils	Rapeseed oil[5,11,12,13,]	UK	Road lorry
4.1%			
Vitamin and minerals[4]		UK	Road lorry
1.5%			

Ingredients were modelled according to the following references: (1) Henriksson et al. 2014b, (2) Dalgaard et al. 2008, (3) Fitwi et al. 2013, (4) Frischknecht et al. 2005, (5) Iriarte et al. 2010, (6) Spinelli et al. 2013, (7) Spugnoli et al. 2012, (8) Hererra Huerta et al. 2012, (9) Wang et al. 2014, (10) Williams et al. 2010, (11) Iriarte et al. 2011, (12) Schmidt 2010, (13) Felten et al. 2013

Figure 31: Ingredient list and origin of ingredients included in grow-out salmon feed taken from literature (Newton and Little, 2017)

The study identified trade-offs in the choices of raw materials. The eutrophication impact on the farm was largely due to the fishmeal and fish oil content of the feed as it is high in nutrients. However, the vegetable-based ingredients whilst having lower eutrophication potential, have a greater energy demand for production. The Global Feed Institute has plans to create a LCA database for feed ingredients, this will aid accountability and transparency in the procurement of raw materials and understanding the global spread of impacts (Newton and Little, 2017).

Over 90% of the total impact was found to be down to the feed with the majority of impacts not actually occurring in Scotland. However, as the industry is predominantly open net pens, the greatest eutrophication potential was found to be on the farm due to direct emissions (nitrogen) to the local marine environment, which accounted for approximately 77.4% of all eutrophying emissions (Newton and Little, 2017).

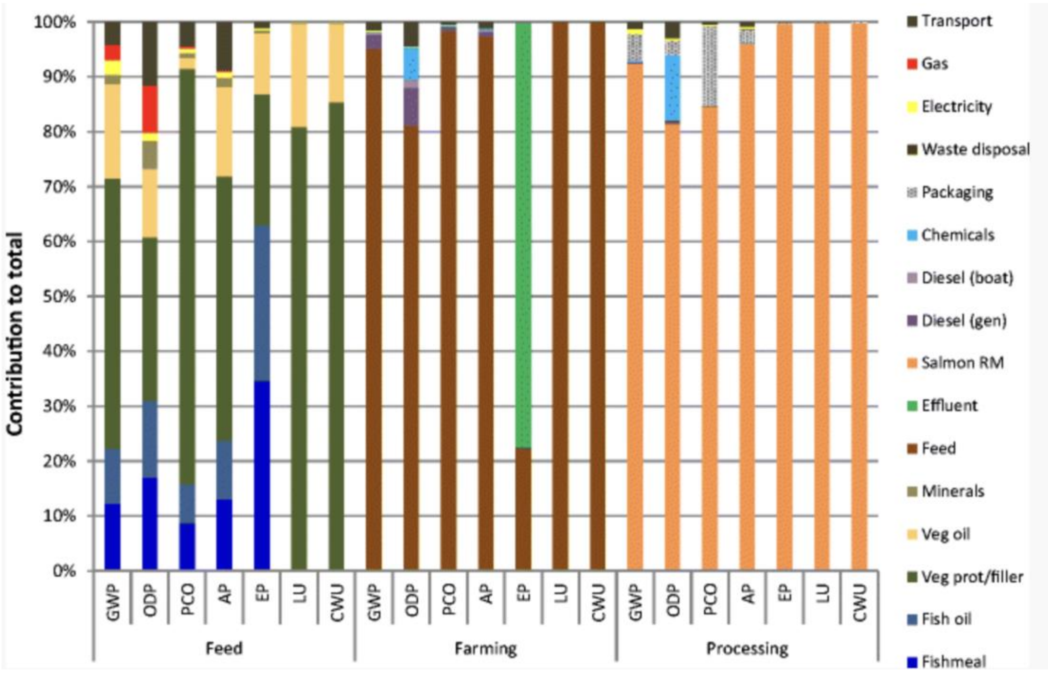


Figure 32: Split contribution analysis for producing HOG salmon at the primary processor (Newton and Little, 2017)

'Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada' (Ayer and Tyedmers, 2009)

A study carried out in Canada in 2009 used LCA to compare 4 aquaculture systems for salmonid: (1) an open net-pen, (2) a marine floating bag, (3) a land-based flow-through system and (4) a land-based recirculating aquaculture system (Ayer and Tyedmers, 2009). Their study addressed abiotic depletion (ABD), global warming potential (GWP), human toxicity potential (HTP), marine toxicity potential (MTP), acidification (ACD), eutrophication (EUT) and cumulative energy demand (CED). Their conclusion resulted in the recirculating system having the worst overall performance, however this was largely due to the primary source of energy being 77% coal. This highlights the importance of identifying how renewable energy can be integrated into recirculating aquaculture systems. In 2015, Scotland procured 57.7% of their electricity from renewables and the value continues to increase.

Option 2 in a marine floating bag was found to be the most environmentally friendly however this was largely due to its utilisation of hydroelectricity and a lower overall energy demand. In further analysis of the results, the marine floating bag had a lower feed input per tonne of salmonid produced however the recirculating aquaculture system had a high unexplained mortality rate, impacting the feed input per live-weight output. Figure 33 shows the relative contribution of each system; of the four systems, the RAS system causes the least eutrophication emissions, however performs the worst for all other impact categories.

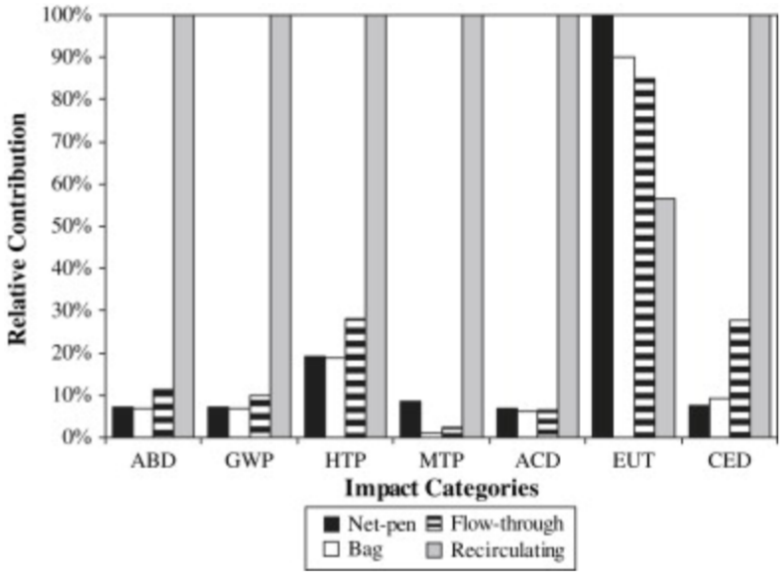


Figure 33: Relative comparison of the life cycle contributions to environmental impact categories for the four studied culture system (Ayer and Tyedmers, 2009)

The study concluded that the shift to recirculating aquaculture systems would reduce local ecological impacts; as found in Newton and Little (2017). The waste generated on farm was collected in the RAS, resulting in no emissions due to the grow-out stage and avoided burdens as the waste collected was used as fertilizer (Ayer and Tyedmers, 2009). Figures 34 and 35 show the environmental impacts for the open net pen (ONP) and recirculating aquaculture systems (RAS).

ONP	**ABD (kg Sb eq)**	**GWP (kg Co2 eq)**	**ACD (kg SO2 eq)**	**EUT (kg PO4 eq)**	**CED (MJ)**
Smolt Production	0.01	2.1	0.02	0.01	46.1
Grow-Out Infrastructure	1.2	185	1.4	0.3	2560
On-Site Fuel Use	0.4	55.8	0.3	0.03	798
Grow-Out Emissions	0	0	0	28.1	0
Feed Production	10.5	1830	16.3	6.9	23500
Total	12.11	2072.9	18.02	35.34	26904.1

Figure 34: Life Cycle Impacts Associated with the production of 1tonne of live-weight fish from ONP

RAS	**ABD (kg Sb eq)**	**GWP (kg Co2 eq)**	**ACD (kg SO2 eq)**	**EUT (kg PO4 eq)**	**CED (MJ)**
Juvenile Production	0.4	69.2	0.6	0.1	884
Grow-Out Infrastructure	1.3	161	3.2	0.1	2470
Electricity Production	143	23700	220	10.4	291000
On-Site Fuel Use	6.2	974	2.1	0.2	14400
Chemicals Production	5	749	6.9	0.9	9970
Avoided Burdens	-0.2	-70.6	-0.3	-0.04	-469
Grow-Out Emissions	0	0	0	0	0
Feed Production	15.7	2660	22.6	8.4	34700
Total	171.4	28242.6	255.1	20.06	352955

Figure 35: Life Cycle Impacts Associated with the production of 1tonne of live-weight fish from RAS

As can be seen from the above, the grow-out infrastructure emissions are relatively similar compared to other emissions, suggesting it shouldn't be a dominating factor in choice of system. The feed production emissions are likely to be considerably higher for the RAS as it suffered a higher rate of mortalities hence higher feed input per tonne output of salmon. Overall, the greatest disparity in emissions can be seen in electricity production with respect to GWP due variations in energy sources and grow-out emissions for eutrophication potential.

'Integration of energy audits in the Life Cycle Assessment methodology to improve the environmental performance assessment of Recirculating Aquaculture Systems' (Badiola et al., 2016)

A study carried out in Spain in 2016, proved RAS to be a viable solution to solving the water pollution that European aquaculture is facing by integrating the LCA with energy audits (Badiola et al., 2016). Their study was conducted for Atlantic cod in the Basque coastal area and concerned 4 of the impact categories present in the previous study: abiotic depletion, acidification potential, eutrophication potential and global warming potential.

The study highlighted the importance in including energy assessment in the development of RAS regarding the environmental and economic sustainability of the system. It proposed a methodology for energy audit LCA that allows for greater understanding of energy consumption patterns that can support decision making to increase efficiency in energy and resource use whilst understanding economic feasibility (Badiola et al., 2016).

A heat pump was incorporated into the design of the system for periods whereby the temperature in the rearing tank surpassed the desirable rearing temperature. It highlighted the importance of ensuring appropriate devices were used in the design of recirculating aquaculture systems such as identifying potential for geothermal energy or waste heat from industry to reduce reliance on fossil fuels in a cost effective manner (Badiola et al., 2016).

'Not All Salmon Are Created Equal: Life Cycle Assessment (LCA) of Global Salmon Farming Systems' (Pelletier et al., 2009)

As discussed briefly in chapter 2 of this report, this study carried out a large-scale LCA of Atlantic Salmon in the four major farming regions, Norway, the UK, Canada and Chile. The following life cycle inventory data was obtained for the respective countries, showing the inputs per live tonne weight of salmon; some of which was incorporated in the tool as detailed later in the report. The study highlights the variability in input requirements for Atlantic salmon across the countries despite it being a well-established commodity.

Inputs per tonne of Salmon	Unit	Norway	UK	Canada	Chile
Feed	(t)	1.103	1.331	1.313	1.493
Feed Transport	(t-km)	290.3	321.7	316	298.7
Smolts	(kg)	17.4	22.2	16	15
Smolt Transport	(t-km)	1.2	3.9	3.2	3
Total On-Farm Energy Use	(MJ)	646.8	904	933.7	1199
Farm-Level Emissions (kg N)	(kg)	41.1	58.7	51.4	71.3
Farm-Level Emissions (kg P)	(kg)	5.2	8.5	13.6	12.6
Energy for feed milling (MJ)	(MJ)	902.6	1090.1	1393.2	1118.7
Crop-Derived meals	(%)	35.3	32.3	43.4	36.9
Crop-Derived oils	(%)	6.1	1.1	5.1	5.8
Animal-derived meals	(%)			16.8	15.1
Animal-derived oils	(%)			3.1	0
Fish-derived meals	(%)	33.1	40.5	20.9	25.1
Fish-derived oils	(%)	25.5	26.1	10.7	17.1

Figure 36: Aggregate Life Cycle Inventory Data for Salmon Farming and Salmon Feed Milling in Norway, the UK, Canada and Chile in 2007 (Pelletier et al., 2009)

5.4. Value Chain Definition

The following diagram shows the life cycle flow chart from Ayer and Tyedmers (2009) for assessing salmonid farming; these stages were considered in the following chapters.

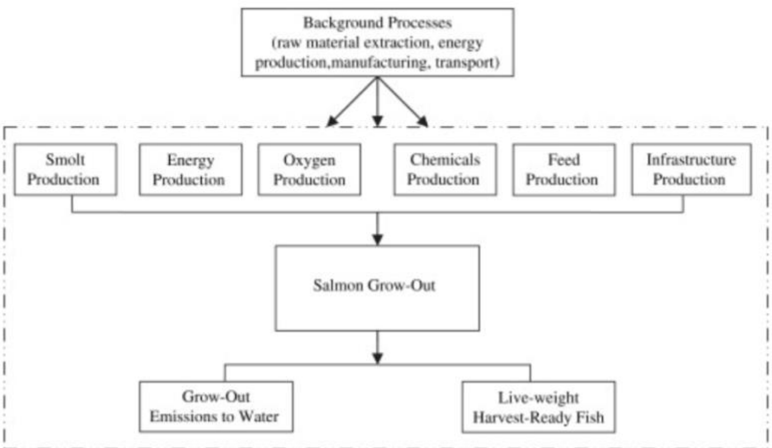


Figure 37: A simplified life cycle flow chart for salmonid farming (Ayer and Tyedmers, 2009)

6. Pre - Farm

The following section details the literature review carried out for the pre-farm part of the study and considerations that have been made in creating the tool to make it applicable in a Scottish context. This includes the raw material procurement, feed production, ova procurement, smolt production and transport between stages.

6.1. Raw Material Inputs

Raw Materials

Global salmon feed currently relies on three key sources of protein: fish meal, soy meal and land animal protein however, in the UK a higher proportion of the ingredients are from marine resources and imported vegetable protein sources (e.g. soy protein concentrates) (Scottishaquaculture.com, 2018). Feed production has resulted in overfishing hence the desirability to use other products such as fish processing by-products and non-marine products such as vegetable proteins and oils in place of fishmeal and fish oil. However, as seen in the figure below and discussed previously, Marine ingredients (fish meal) have the lowest environmental impact for these categories.

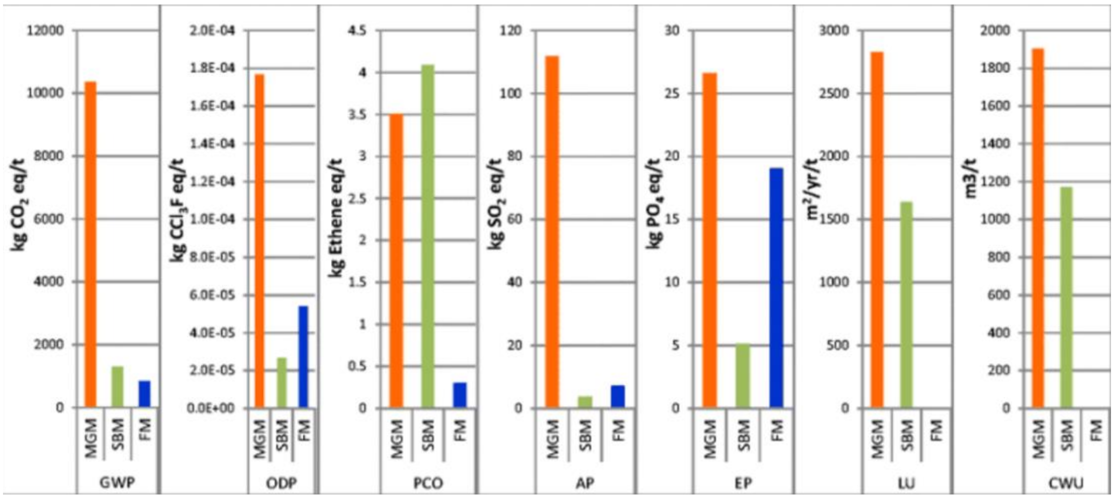


Figure 38: LCA of three major feed ingredients per tonne: Maize gluten meal (MGM), Soy bean meal (SBM) and Fish meal (FM)

Pharmaceuticals

As discussed, poor fish health is becoming a major issue for the Scottish Salmon Industry; levels of disease and hence antibiotic requirements are continuously fluctuating on a site by site basis and so were determined as out-with the scope of this study to quantity.

Feed Developments

Feed development motivated by greater sustainability is an area of research attracting a lot of attention globally (Martins et al.,), it is out-with the scope of this thesis to completely understand the direction by which this industry may take however an attempt has been taken to understand utilisation and production in Scotland despite lack of transparency by feed production sites and choices in procurement by Scottish fish farms. Projects being carried out by the Scottish Aquaculture Innovation Centre (SAIC) include conducting research to identify alternative protein sources that are available locally and have low environmental impact. It is anticipated that this source could mainly be from avian-derived protein which could reduce feed costs and hence overall production costs (Scottishaquaculture.com, 2018).

6.2. Feed Production

Feed Mill Locations

Currently, there are three feed suppliers; Ewos in Bathgate, Biomar in Grangemouth and Skretting in Invergordon. *A new feed plant by Marine Harvest is set to open in Autumn 2018, creating 55 full time jobs which is of great benefit economically and socially for to Scotland. During construction, the build reportedly provided 250 jobs. Due to its location, it is anticipated that the feed will be transported via sea routes to both locations in Scotland and further afield, cutting out approximately 10,000 annual road journeys (HIE, 2017).*

Figure 39: Marine Harvest £93 million feed plant at Kyleakin (Moore, 2018)

Feed Mill Energy and Feed Transportation

Transport is measured in t-km representing the transport of one tonne of item by given transport. Feed transport is assumed to be a mix of ocean and road km based on the raw materials and smolt assumed to be road as found in literature for production of 1 tonne live weight of Salmon (Pelletier et al., 2009). This study does not include the transport of ova.

6.3. Ova

Scotland has increased its dependency on Ova imports in the past 10 years, predominantly from Norway. In preparation for an incident which may "close the border" and restrict the import of ova to Scotland, companies are beginning to increase their egg production in Scotland such as Norwegian supplier AquaGen (Moore, 2018). This movement would be highly beneficial to Scotland in delivering increased security of production for the industry, increasing job opportunities and minimising the footprint associated with importing the ova.

The total exports for ova have dropped considerably; most of the exports were accounted for by Chile and so it is likely that as production boomed and their industry became well established, they increased their Ova production to reduce costs. In 2016, Scotland imported 78.2% of Ova from Norway (Marine Scotland Science, 2017).

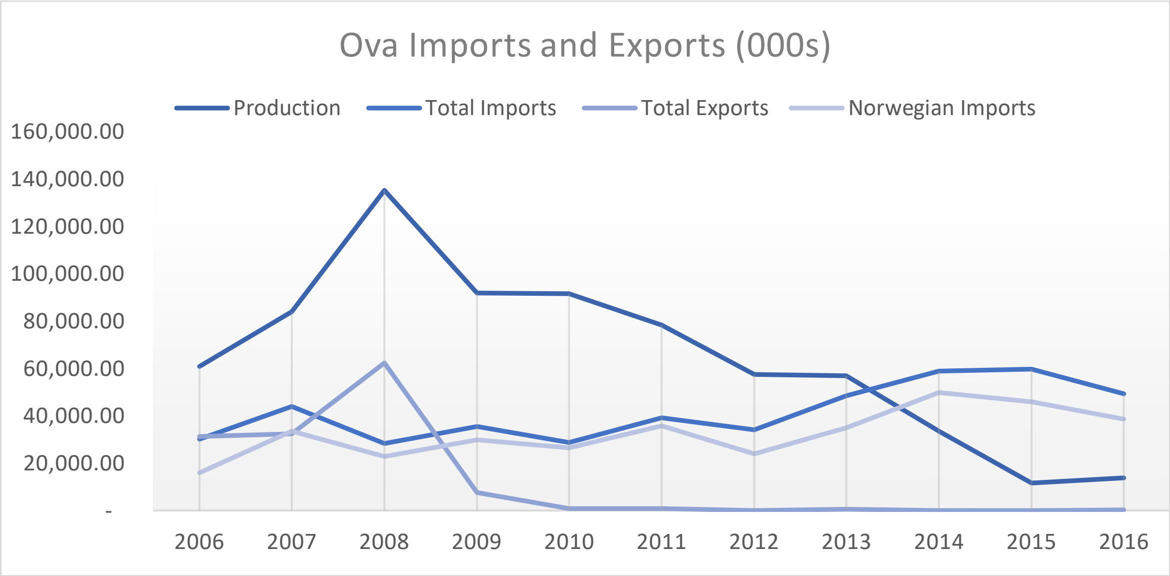


Figure 40: Scottish Ova Imports and Exports (Marine Scotland Science, 2017)

6.4. Smolt Production in Scotland

Scotland Overview

Smolt are produced by categorisation of four different age groups. S1 and S2 are smolt that traditionally enter the sea after 1 or 2 years in freshwater during Spring (April to June). S1/2 and S2 however are the "out-of-season" smolt that have become possible due to photoperiod manipulation (Ellis et al., 2016).

	S1/2 (S0)	**S1**	**S1 1/2**	**S2**	**Total**
Period	<12 months	12-18 months	19-24 months	>24 months	-
2014	22,367	22,473	164	0	45,004
2015	23,850	20,711	10	0	44,571
2016	25,072	17,822	0	0	42,894

Figure 41: Smolt Production Time-Scale and Scotland Data (Ellis et al., 2016)

According to the fish farm survey, there weren't any smolt produced to the S1 ½ and S2 timescale in 2016 but instead there was an increase in S ½ by 5.1% and a reduction of S1 smolts by 13.9%.

The Scottish Fish Farm Survey reported that from 2015 to 2016, the average stocking densities in cages reduced (smolts/m3) whereas it continued to increase for tanks and raceways as can be seen in figure 42.

	Tanks and Raceways					**Cages**				
	2012	**2013**	**2014**	**2015**	**2016**	**2012**	**2013**	**2014**	**2015**	**2016**
Total Capacity (000 m3)	51	64	65	47	46	349	372	351	355	400
Production (000 Smolts)	17,442	19,547	22,188	26,436	27,010	51	64	22,816	18,135	15,884
Stocking Density (Smolts/m3)	342.0	305.4	341.4	562.5	587.2	0.1	0.2	65.0	51.1	39.7

Figure 42: Smolt Production Scotland (Marine Scotland Science, 2017)

For 2016, tanks and raceways offered a stocking density almost 15x that of cages; this promotes the former as a better choice for smoltification in respect to intensifying the industry. The reason for the considerable increase in average stocking density for tanks and raceways from 2014 to 2015 is unknown however it is likely that it is due to increased monitoring and control of the key factors in smoltification allowing for more efficient production. Based on the 2016 density recorded for tanks and raceways, assuming an average smolt size of 70g per smolt, the stocking density is only approximately 8.4kg/m^3 which is particularly low compared to values found in literature.

Flow through and raceways do not collect and treat waste streams as they are not reusing the water and may result in various ramifications to the environment, particularly in eutrophication potential.

Companies have been striving to achieve larger smolt weight in a shorter production time to reduce the time spent in open net pens at sea. This reduced 'grow-out' time can result in less environmental damage and most importantly reduce the chances of the salmon contracting sea lice. This is generally carried out in closed containment smolt production with the Norwegian salmon farming industry is reportedly aiming to increase the size of their smolt production from approximately 100g to 300g.

Closed Containment Smolt Production

The trend for smolt farmers in NW Europe is transitioning from flow-through farms into RAS based on two main reasons: seasonal changes limit the water supply and hence the production volume and lower water temperature restricts the production during autumn to spring (Bergheim et al., 2009). In 2009, they were not yet reported as common however since then, Norway has seen many farmers convert their single-pass flow through systems to RAS.

Marine Harvest in Scotland built a large RAS smolt production facility in Inchmore, Glenmoriston that is anticipated to satisfy approximately half of their requirement (Moore, 2018). Scottish Sea Farms' were also reported to have invested a total of £37million on an onshore RAS hatchery (Scottish Construction Now!, 2018). The site has the capacity to support the growth of 12million smolts to 120grams (Billund-aqua.dk, 2018).

A study investigation the energy and resource consumption of Atlantic salmon smolt hatcheries in the Pacific Northwest (USA) concluded the following seen in figure X for various types of land-based hatcheries. The study was carried out in 2008 whereby the smolt were reared till approximately 80g. A similar study could be beneficial, with the smolt grown to a greater weight, satisfying current trends.

Parameter	Ranking		
	Best	Second best	Worst
Water use	RU	PR-T	FT-P
Feed use	Little difference among systems		
Direct energy use	PR	RU	FT-P
Indirect energy use	FT-G	PR	FT-P
Total energy use	FT-G	PR	FT-P
Electrical/fuel energy use	FT-G	PR	PR-T
Land area	RU	PR PR-T	FT-P
Solids discharged	RU	PR-T	FT-G
Total nitrogen discharged	RU	PR-T	FT-P PO
Total phosphorus discharged	RU	PR-T	FT-P PO
Total greenhouse gases	FT-G	PR	PR-T
Energy efficiency	FT-G	RU	FT-P

[a] Key to systems

- FT-G Flow-through with a gravity water supply
- FT-P Flow-through with a pumped water supply
- PO Flow-through with pure oxygen
- PR Partial reuse system
- PR-T Partial reuse with heating
- RU Reuse system

Figure 43: Rearing System Rankings for various performance parameters (Colt et al., 2008)

Based on this research and the general direction of the industry, RU, the reuse system which is equivalent to RAS was incorporated into the tool as it allows for greater control over the rearing conditions and performs relatively well compared to other systems.

The study by Colt et al. (2008) also concluded that for the total reuse system (RAS), they were capable of being 3 times larger than the other systems due to an increase in water depth (from 1m to 3m) hence allowing for a reduction in land usage – it also allowed for decreased capital costs and heat transfer losses.

7. On-Farm

The following section details the literature review carried out for the on-farm part of the study and considerations that have been made in creating the tool to make it applicable in a Scottish context. This includes the grow-out Salmon stage after smolt production.

7.1. Open Net Systems

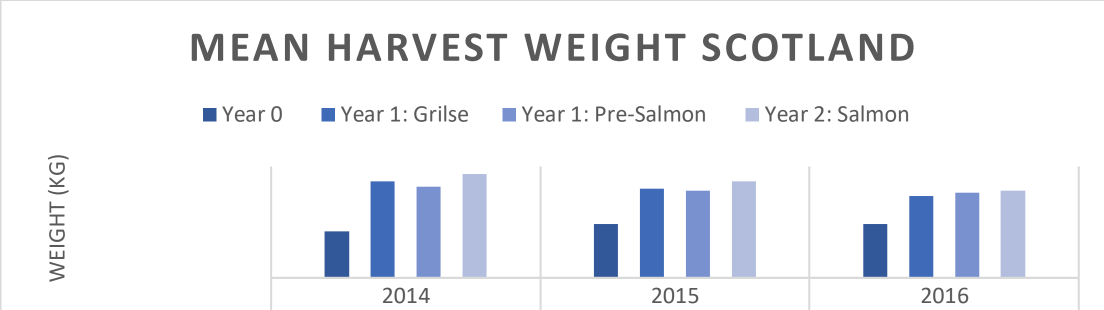
Scotland Overview

Salmon production in Scotland occurs predominantly in seawater cages (open net pens) however in recent years, there has been deployment of seawater tanks. As can be seen in figure 44, in 2015, 179 tonnes of salmon production occurred in a tank however the Scottish Fish Farm Survey states that for reasons such as high installation and running costs, the majority of production remained in cages. Many of the seawater tanks were reportedly re-purposed for other marine finfish species and salmon broodstock. It is unknown if the tanks and cages were used to full available capacity (m3) however 2015 shows a tank stocking density greater than 3 times that of seawater cages.

	Tanks			Cages		
	2014	**2015**	**2016**	**2014**	**2015**	**2016**
Total Capacity (000m3)	6.1	6.2	7.4	19,481	20,338	20,067
Production (tonnes)	0	179	21	179,022	171,543	162,796
Stocking Density (kg/m3)	0	28.9	2.8	9.2	8.4	8.1

Figure 44: Salmon Production Methods and Stocking Densities in Scotland (Marine Scotland Science, 2017)

In Scotland, salmon are typically harvested according to 4 age groups running up to 2 years and resulting in a variation in weight. The average harvest weights in Scotland from 2014 to 2016 can be seen in figure 45.



	2014	2015	2016
Year 0	2.5	2.9	2.9
Year 1: Grilse	5.2	4.8	4.4
Year 1: Pre-Salmon	4.9	4.7	4.6
Year 2: Salmon	5.6	5.2	4.7

Figure 45: Salmon Mean Harvest Weight Scotland (Marine Scotland Science, 2017)

Sea production has the potential to operate at 25kg/m^3 despite only operating at approximately 8.1kg/m^3 in 2016; this may be due to high levels of mortalities.

Increased Smoltification Period

Many companies and stakeholders still believe open net systems to be the way forward for the industry so they are seeking ways by which they can reduce their environmental impact and risk of mortality. To reduce the time that salmon spend at sea in the open net systems, a new method involves keeping the salmon in RAS systems for a longer period than the typical smolt production as detailed in the previous section. This means the farming time spent in the sea is reduced to approximately 10 months rather than the typically 14-24 months (Syse, 2016). Whilst this reduces damage to the sea environment it results in more time spent in the more energy intensive on-land stage.

Offshore

By locating fish farms further offshore it is mitigating the environmental impact on a local scale as greater sea currents allow for greater dissipation of fish faeces and excess feed. However, the waste input remains and the offshore farms continue to pollute the environment. This is also being negligent of the value chain, ignoring the opportunity in harnessing the waste to create valued products such as energy or fertiliser as described.

Offshore sites require more robust cages, nets and moorings and fuel to enable transport offshore for both staff and raw materials required in the operation of the farm. Further to this, offshore farms tend to utilise diesel generators as investment in grid connection is difficult and technically challenging. However, perhaps there is opportunity to be sought in the increase of offshore wind farms in Scotland (Mee, 2006).

A key pillar in industry growth is social development however offshore farms are more likely to implement automatic feeding to reduce the requirement for staff travelling offshore, hence these types of farms would not offer proportional employment to inshore or onshore farms.

7.2. Recirculating Aquaculture System

In general, recirculating aquaculture systems allow for greater control of inputs and costs to create a more economically beneficial system. The economic potential for closed cage fish farming and the total economic value of the wild salmon stock Thesis completed in Norway finds a greater potential in NOK (£) per produced kilo. This is mainly due to reduction in pathogens and resultant economical loss through mortalities. This technology reutilises the waste water which means less energy for heating is required however the system requires a highly efficient water-filtration system comprised of both mechanical and biological filters. There are various concepts or technologies that can be used in RAS which have been detailed in literature (source) however, the key components are as seen in figure 46.

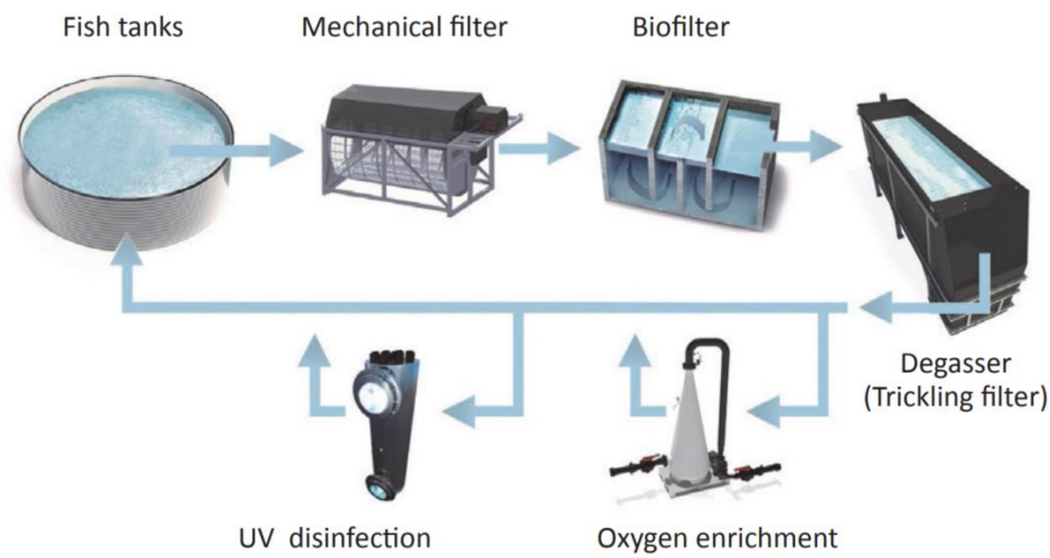


Figure 46: RAS recirculation key components (FAO, 2015)

Mechanical Filtration: removal of solids. The solids upon production should leave the tank as fast as possible to allow for effective separation before the water flow continues to the bio-filter. Figure 47 shows efficiencies of filtration dependant on micro-screen size fitted to filters; they typically range from 40 to 100 microns (FAO, 2015).

Parameter	Raceway	Raceway	Raceway	Self cleaning tank	Self cleaning tank	Self cleaning tank
	40 µ	60 µ	90 µ	40 µ	60 µ	90 µ
	Efficiency, %	Efficiency, %	Efficiency, %	Efficiency, %	Efficiency, %	Efficiency, %
Tot-P	50-75	40-70	35-65	65-84	50-80	45-75
Tot-N	20-25	15-25	10-20	25-32	20-27	15-22
TSS	50-80	45-75	35-70	60-91	55-85	50-80

Figure 47: Removal of Nitrogen, Phosphorous and Suspended Solids by mechanical filters (FAO, 2015)

Bio filtration: biological treatment. The key purpose of the bio-filter is to process the ammonia produced by the fish as if it is left untreated it can reach levels that are toxic to the fish. The finest particles also pass through, as seen in figure X, not all particles are removed in mechanical filtration hence they must be treated with the N and P. Ammonia (NH_3) is transformed into nitrate and the breakdown of organic matter occur by bacteria in the biofilter. Nitrifying bacteria converts the NH_3 and heterotrophic bacteria oxidises the organic matter to produce CO_2, NH_3 and sludge (FAO, 2015). For this to be effective the temperature should be between 10 to 35°C and pH levels between 7 and 8. This is in line with the rearing conditions of Atlantic Salmon.

Degasser: CO_2 removal. CO_2 is produced by the fish and biological activity in the bio filtration stage hence aeration (often referred to as stripping) must occur in the degasser.

Oxygen enrichment: injecting required oxygen. When the water leaves the fish tank, the saturation of oxygen in the water is approximately 70% however the equilibrium is around 100%. Aeration typically reaches around 90% and often it is desirable to enrich the water with >100% to enable more effective fish growth; this is often done by mixing oxygen and the water under pressure.

UV disinfection: pathogen control. Light is applied at various wavelengths to destroy DNA in the biological organisms, it causes no harm to the fish as it is carried out-with the rearing tank. UV lights should be submerged in the water for greater efficiency than to be expected if placed outside the water.

Alkalinity control: pH adjustment. Nitrification in the bio filtration stage results in a drop in the pH hence a base must be added to the water to maintain the pH at a desirable level. It is typical to install a lime mixing.

Temperature control: As discussed, temperature control is one of the most vital design components of the system as it is intrinsic to fish growth. A common way to control the temperature is by the extra water taken in each day, with a well-designed control system that monitors the temperature as heat is generated most notably by both fish metabolism, the bio-filter and friction due to pumping.
Heat pumps or heat exchanges could be installed to minimise energy that would be lost by removing heat. The heat pump can utilise energy from discharge water and similarly the heat exchanger may remove heat from the discharge water and use it to heat the incoming stream of cool water if required. These are well established technologies that could be integrated efficiently into an RAS design. It may be of particular use in a cold climate such as Scotland whereby the water temperatures are typically lower than the optimal rearing temperature.

Pumping: placement of the pumps is important in efficient design, they mustn't be placed before mechanical filter to avoid producing smaller particles, hindering separation. Design should be carried out to allow for gravity assisted flow where possible, implementing only one lift after the sump pump allowing the water to flow through the system without pumping after this point.

Energy Usage

In closed-cage systems, energy consumption can vary considerably depending on some of the following key factors: species being farmed, rearing water temperature, local climate and design and management of the site (Badiola et al., 2017). However, the greatest energy use is generally in pumping the water supply to the tanks and heating if temperature control is implemented on the respective site (Badiola et al., 2017).
A study integrating the use of energy audits and LCA for Cod in the south of Spain in a trial found the following breakdown in energy requirement for the RAS plant. The

kWh are for the time frame of 15 months which was the experiment length. In summary, the demand varied seasonally with an average of 28.40kWh/kg fish, maximum of 40.57kWh/kg of fish and minimum of 18.43kWh/kg fish. Energy required to heat the tank accounted for more than half of the required energy.

Pilot-scale devices	kW	kWh[a]	kWh/kg	Consumption (%)
Main pump (25 Hz)	0.5	3905.3	2.3	7.0
Secondary pump (25 Hz)	0.5	3905.3	2.3	7.0
Skimmer	0.8	6652.8	3.9	11.9
Ultraviolet1	0.1	695.5	0.4	1.2
Ultraviolet2	0.1	635.0	0.4	1.1
Heat Pump	4.0	40,320.0	23.7	71.8
Total		56,114.0	33.0	

Figure 48: Energy consumed per each energy-consuming device for a recirculating aquaculture system (Badiola et al., 2016)

Location of an RAS farm can have a great influence on the energy required for pumping. This has been proven by the Kuterra model in BC Canada whereby they have enabled a gravity-assisted flow in their design. They make further energy savings by use of geothermal heating and cooling (Kuterra.com, 2018). RAS operationi is generally on-land hence a grid connection may be easily facilitated. They may save on transportation fuel.

7.3. Efficient Design Considerations

In the design of the tank, many factors should be considered depending on company priorities such as restricted land space or cost of construction. A key benefit of RAS is the capability for modular design.

Modular Design

Modular design as seen in figure 50 allows for easy scale-up and scale-down, so there is flexibility in meeting demand and optimising operating costs. Considering the Scottish aquaculture industries plans for steady growth, this design could particularly attractive.

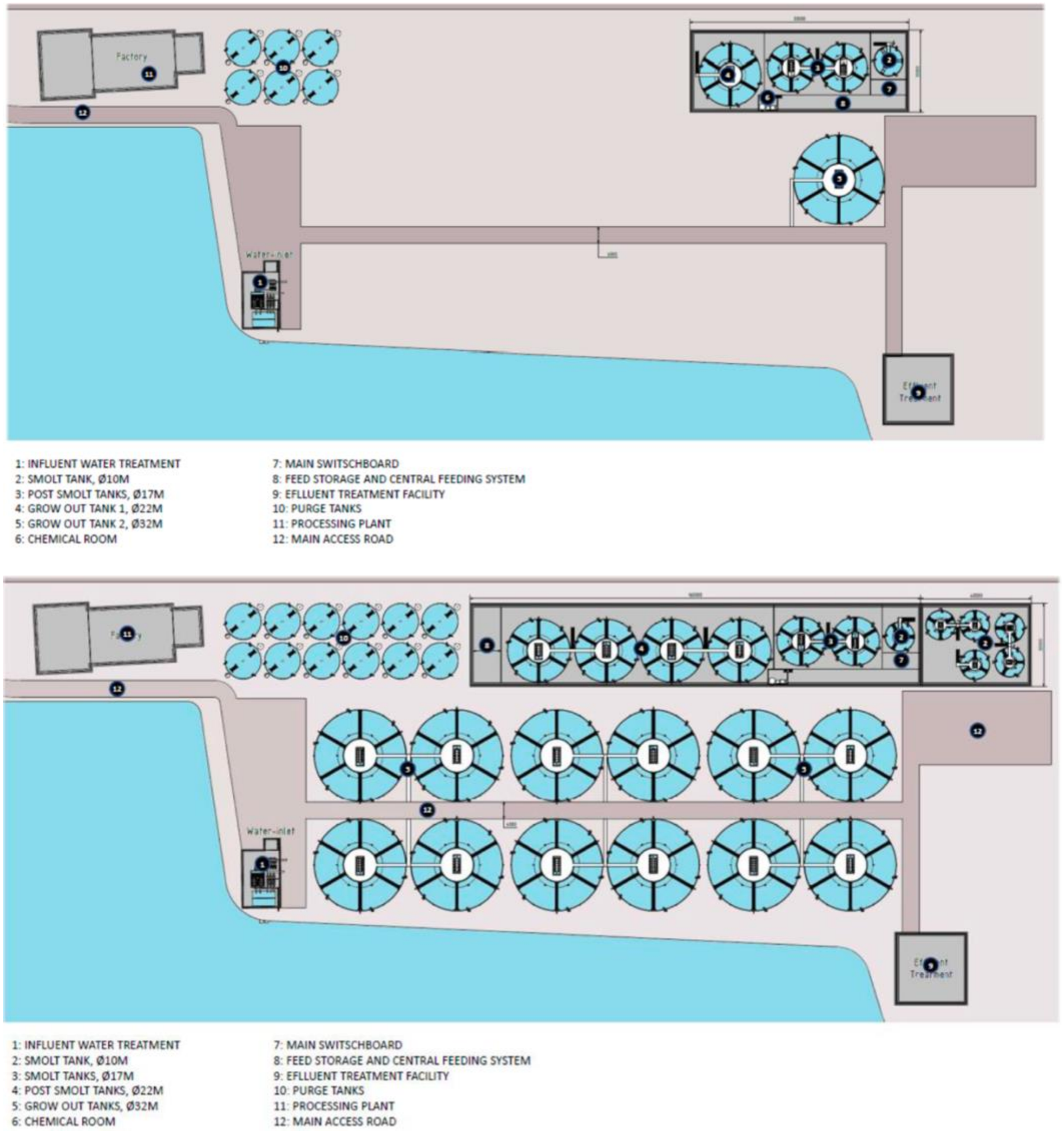


Figure 49: Example of modular design for a recirculating aquaculture system plant (Niri.com, 2018)

8. Tool Creation Method

The following section details the method of creating the decision-making tool, RAq, based on findings from this thesis. This section details the modelling of salmon growth and other parameters impacting the growth in both open net pens and recirculating aquaculture systems.

8.1. Overview

Firstly, in creating this tool, it was important to have a clear understanding of the salmon production cycle; the two key stages being smolt production and salmon production to marketable weight. This section lays out the method of quantifying the behaviour, growth and overall optimum rearing conditions of Atlantic salmon. The equations in this section are the basis of the model in calculating the resources required and outputs generated for the desired production.

8.2. Tool Function (RAq)

The following flowchart shows the key inputs, parameters and outputs for the RAq tool. The tool was created using excel.

USER INPUTS		
Production required (kg)	Smolt Weight (g)	Harvest Weight (kg)
Location Temperature (for ONP only)		
INPUT PARAMETERS (can be adapted per case study)		
Temperature Growth Coefficient (TGC)	Feed Conversion Ratio (FCR)	Rearing Temperature (for RAS only)
Mortality Rate (%)	Stocking Density (kg/ m^3)	Water consumption rate (for RAS only)
OUTPUTS		
Cycle Time (days)	Number of Ova Required	Oxygen (kg)
Rearing Volume	Excess Water (for RAS only)	Feed Required (kg)
Energy Required (kWh)	Operating Cost (£)	Capital Cost (£)
Profit Estimation (£)	Waste generated (kg)	Aquaponics Potential

Figure 50: Key inputs, parameters and outputs for the RAq tool

8.3. Rearing Conditions

Key Parameters

There are various parameters to be considered when creating the optimum rearing conditions for efficient growth as can be seen by figure 51. Recirculating aquaculture systems allow for greater control and monitoring of temperature, dissolved oxygen, carbon dioxide, pH, ammonia, nitrite and solids – this allows for higher density of fish in the cages hence greater production level per unit area (FAO, 2015).

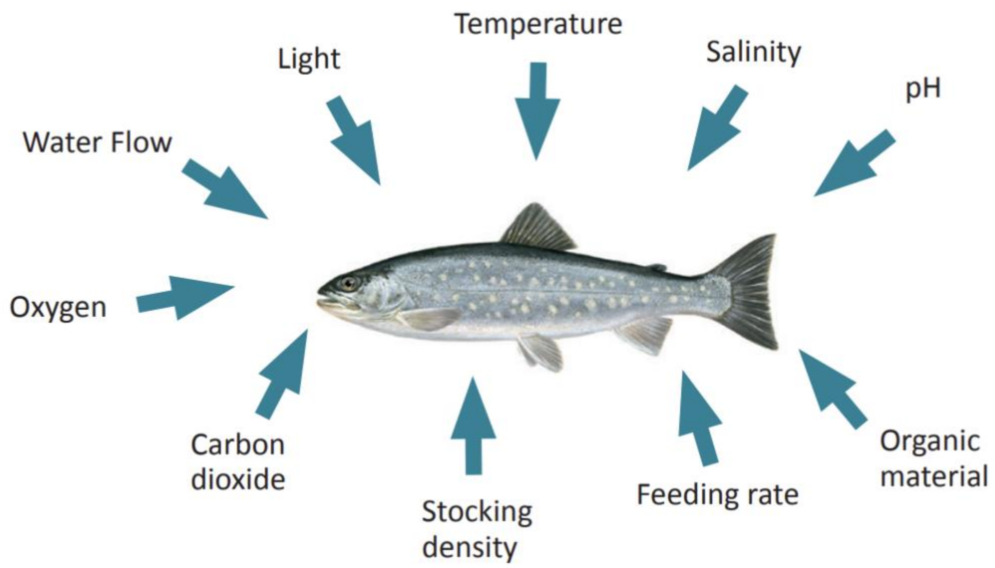


Figure 51: Fish Rearing Parameters (FAO, 2015)

Summary of Accepted Desirable Limits for Key Parameters

Below is a summary of the limiting criteria required for water quality (Colt et al., 2008); the limits are important in determining rearing volume, flowrate and process treatment performance requirements.

Parameter	**Limits**
Dissolved Oxygen	>7.0 mg/L
Carbon Dioxide	<10mg/L
pH	>6.0
Ammonia	15 μg /L (NH_3-N)
Nitrite	<0.1mg/L (NO_2^-N)

Figure 52: Desirable Limits for Key Parameters (Colt et al., 2008)

8.4. Growth Model

Linear Temperature Dependant Model

The utilisation of a mathematical model of fish growth is important in conducting good fisheries management. The following is a simple model that has been used to predict growth of salmonids in hatcheries hence it has been tested and cited as reliable in literature (Iwana and Tautz, 1981) (Colt et al., 2008).

The change in weight can be modelled based on the following equation:

$$W_f^{\frac{1}{3}} = W_i^{\frac{1}{3}} + G_C \left[\frac{T}{1000}\right] x\ t$$

eq. 2

Whereby W_f is the final weight of the fish (g), W_i is the initial weight of the fish (g), G_c is the correction factor ($g^{1/3}/(Ct)$), T is the temperature (ºC) and t is the time of the production cycle in days.

This was used to calculate the time in days required for rearing of smolt or salmon production. As discussed below, for RAS, the temperature was taken as a constant optimal temperature however for ONP a varying monthly temperature was assumed.

Temperature Growth Coefficient (TGC)

The temperature growth coefficient was found in literature as seen in figure X with temperature; the graph is for Baltic salmon Salmo salar L.

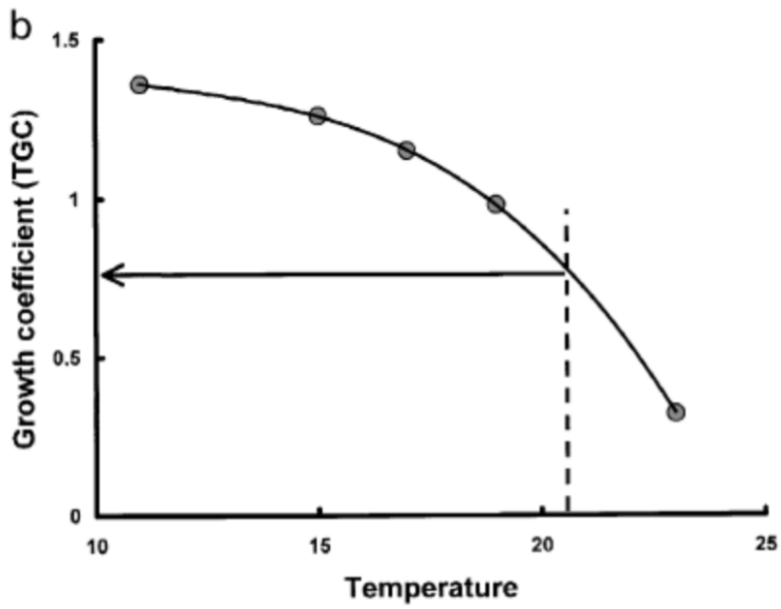


Figure 53: Temperature Growth Coefficient (Jobling, 2003)

Values from the above graph however, didn't produce results as anticipated and required a particularly long rearing time.

Salmon reared in Scotland in open net pens were found to grow from approximately 70g smolt to an average of 4.5kg harvest weight in approximately 22 months (Newton and Little, 2017). Based on this, a TGC was calculated. For the TGC to be calculated an average seawater temperature for Scotland had to be calculated; this was done by considering 3 locations in attempt to gain a representative value of the west coast of Scotland whereby ONP Salmon fishing is most prominent. The 3 locations chosen were Isle of Lewis, Oban and Ayr; the temperature was calculated based on averages monthly temperatures for a year (World Sea Temperatures, 2018). The TGC calculated using the following equation (Summerfelt et al., 2013):

$$TGC = \frac{1000 * (W_f^{\frac{1}{3}} - W_i^{\frac{1}{3}})}{t * T_{avg}}$$

eq. 3

Whereby t was calculated to be approximately 670 days and T_{avg}, the average temperature was taken to be 10.7 ºC as can be seen in figure 54 and the TGC calculated accordingly. Based on this, the TGC used in the tool for ONP salmon growth was 1.73.

Location	Average Seawater Temperature (ºC)	Temperature Growth Coefficient
Isle of Lewis	10.45	1.77
Oban	10.62	1.74
Ayr	11.04	1.67
Average	10.71	1.73

Figure 54: Average Sea Temperature and Temperature Growth Coefficient for Salmon Growth in ONP in Scotland

Trial Data

A study by Colt et al. (2009) based on the growout trial by The Conservation Fund's Freshwater Institute found the temperature growth coefficients to be as following for each stage of the salmon life cycle using RAS technology; Fry: 1.25, Smolt: 1.40, Pre-

Growout: 2.00 and Growout: 2.30. A further study, found the temperature growth coefficient for smolt to be 0.91±0.21, using a value close to the mean at 1.05 (Colt et al., 2008). This mean value was used for both RAS and ONP smolt production.

Namgis, an RAS trial in Canada, have achieved the growing of Salmon smolt from 100grams to 4.5/5kg in 12 months (Warrer-Hansen, 2015). The Langsand site in Denmark predicted growth as seen in figure 55 below from 200grams to 4.5/5kg in 10 months however they did not achieve it; growth was 25% less than predicted. Based on this, the following growth were predicted and utilised in growth calculation. The actual growth would be faster than the calculated growth which lags by 25% and it can be demonstrated that the period growth increases as the salmon matures. Modelling the salmon growth to this extent was not possible due to time constraints for this thesis.

Month	**Wi**	**Wf**	**Period Growth**	**-25%**	**Wf -25%**
1	200	350	150	112.5	312.5
2	350	525	175	131.25	443.75
3	525	750	225	168.75	612.5
4	750	1050	300	225	837.5
5	1050	1455	405	303.75	1141.25
6	1455	2025	570	427.5	1568.75
7	2025	2700	675	506.25	2075
8	2700	3570	870	652.5	2727.5
9	3570	4350	780	585	3312.5
10	4350	5250	900	675	3987.5
11	-	-	-	675	4662.5
12	-	-	-	675	5337.5

Figure 55: Data from Langsand Denmark Site and Calculation (Warrer-Hansen, 2015)

The following graph shows a comparison of 3 periods of growth in RAS from 200g Smolt. The first, shows the growth using the TGC as calculated for the ONP as 1.73, the second is the TGC of 2.3 as taken from literature and then the Langsand growth as seen in the column ‘Wf-25%’ in the above figure 55.

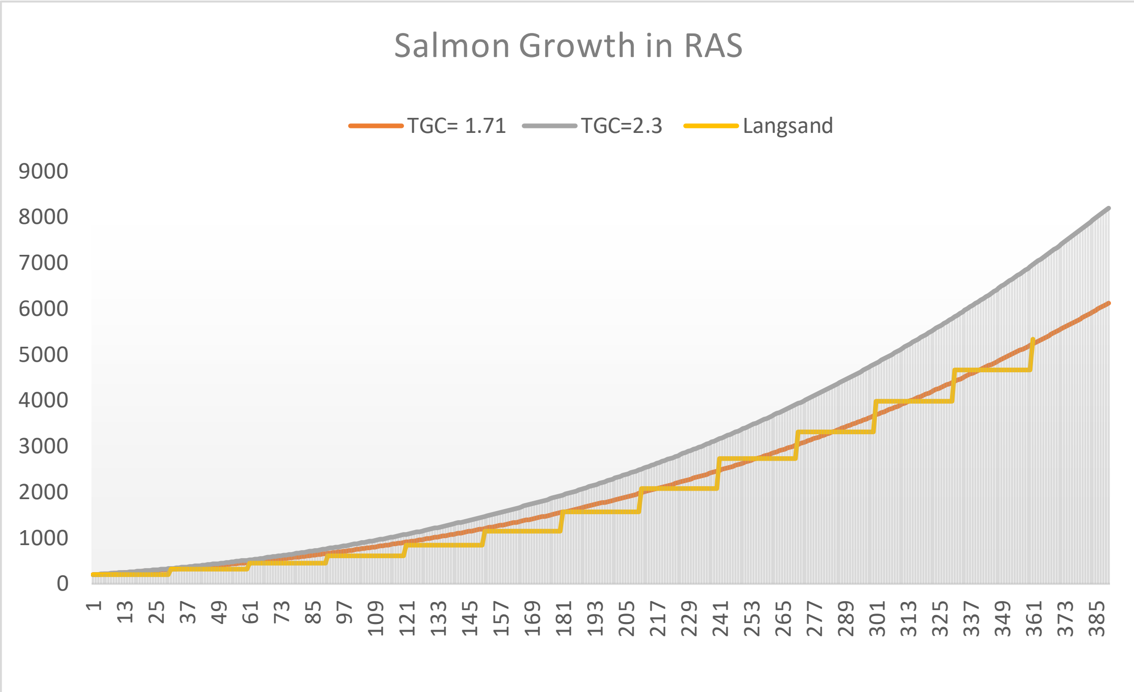


Figure 56: Salmon Growth in RAS for various temperature growth coefficients

8.5. Temperature

Recirculating Aquaculture System Temperature

Salmon species generally have a wider optimal temperature range which reduces pressure in control and costs however the optimal values from literature were found to be from 14 degrees Celsius (FAO, 2015) to 16 degrees Celsius (Colt et al., 2008) in the case of both smolt and salmon production despite the growth coefficient in figure 53. By increasing the temperature from 10 to 16 degrees Celsius it was found that the smolt production time could be reduced from 371 to 231 days to achieve growth to 80g (Colt et al., 2018).

In controlling the temperature, both local seawater or freshwater temperatures must be considered as well as the air temperature to understand the heat transfer that may occur from the tank to the surrounding area. RAS plants often require heating inside the buildings in winter time depending on the location or have sufficient insulated buildings (FAO, 2015).

Despite the likely heat transfer that would occur between the inside of the rearing tank and the surroundings, for the basis of this model it is assumed to be constant. It could remain relatively constant with excess costs on heating in the building and effective insulation around the tank. However, heat exchange may be beneficial as other considerations that may impact temperature control for RAS are heat generated by the fish metabolising and heat generated in the system through pumping. With the implementation of an accurate sensor and control system, the desired temperature of the water could be maintained in the rearing tank.

Open Net Pen Temperature

For open net, it is assumed that the air temperature does not have considerable impact as the fish are submerged in an open body of water of either seawater or freshwater. The sea temperature was taken for the Isle of Lewis.

8.6. Feed Consumption

The feeding rate depends on the feed consumption rate (FCR) of the farmed species. In practice, it can be calculated by the following:

$$FCR = \frac{Total\ feed\ (kg)}{Total\ fish\ growth\ (kg)}$$

eq. 4

In literature, generally the FCR for Atlantic Salmon is 1.2kg/kg however this varies and can be different for different types of aquaculture systems. For open net cages, feed falls to the benthic floor, resulting in a less effective feeding system, loss of profits and damage to the environment. In an RAS system, the feeding rate can be efficiently managed to ensure minimum food waste, resulting in a lower FCR than the open net system.

The following ratios for FCR were taken from a study specifically comparing the two systems, basing the data on pre-conducted trials.

FCR	RAS	ONP
Fry	0.75	-
Smolt	0.9	-
Pre-Growout	1	-
Growout	1.1	1.27

Figure 57: Food Consumption Ratios Comparison (Liu et al., 2016)

A study found the feed conversion ratio in the UK for ONP to be 1.331kg feed per kg live-weight tonne of salmon (Pelletier et al., 2009). For smolt FCR in ONP, values also varied in literature from 1kg feed/ kg live-weight fish (Ellis et al., 2016) to 1.1 (Colt et al., 2008) for non-temperature controlled production.

The economic feed conversion ratio (eFCR) should also be taken into consideration when portraying the true cost of feed per output of fish as it incorporates uneaten feed, mortalities and escapees. It shows the feed required (kg) per 1kg of salmon produced. It was found to average at 1.19± 0.10kg in a study conducted over 6 fish farms in Scotland (Newton and Little, 2017).

8.7. Oxygen Consumption

Oxygen consumption is generally dependent on the feeding rate and according to literature can be taken as 0.2 to 0.25kg of oxygen per kg of feed however it is also temperature dependent so may also be quantified by the following:

$$Oxygen\ Consumption = K_2 T^a W^b$$

eq. 5

Whereby oxygen consumption is the lb of oxygen/ 100lb of fish per day, T is the temperature (°F) and K_2, A and b are constants given in the table below and W is the fish size (lb/fish). This equation was input to the model.

	Temperature (°F)	K_2	a	b
1. Salmon	≤ 50 (10°C)	7.2×10^{-7}	3.200	-0.194
2. Salmon	> 50 (10°C)	4.9×10^{-5}	2.120	-0.194

Figure 58: Oxygen Consumption Constants (Wheaton, 2002)

In an RAS system, the oxygen demand can be 1.5 times the demand required by the fish for the bacteria that is required to break down the organic waste. Extra oxygen may also be required during harvest as the fish get excited and in the case of disease or stress (FAO, 2015).

The oxygen consumption or input requirement on recirculation can be calculated using the following equation for cumulative oxygen consumption (COC) in mgO_2/L (Colt et al., 2008).

$$COC = DO_{out} - DO_{in}$$

eq. 6

whereby DOout and DO_{in} are measures of dissolved oxygen in the effluent out of and influent into the rearing tank in mgO_2/L.

8.8. Water Flow and Efficiency

Water Flowrate

For RAS smolt farms, a specific water flowrate was found in literature to be approximately 0.42 L/ (kg min) (Bergheim et al., 2009). This value was used to calculate the flowrate of water for each day required in both smolt and salmon grow-out production by the following equation:

$$Qf = 0.42 \frac{L}{(kg\text{min})} * Total\ weight\ in\ tank\ (kg)$$

eq. 7

Water Recirculation

In respect to recirculating aquaculture systems, the water flowrate is heavily dependent on the system design. The level of recirculation has been quantified as (FAO, 2015):

$$Degree\ of\ recirculation = \frac{(Internal\ recirculation\ flow)}{(Internal\ recirulation\ flow + new\ water\ intake)} x\ 100$$

eq. 8

Values for various types of systems can be seen below in figure 59. RAS Intensive was utilised in the model to calculate water consumption.

Type of System	**Consumption of new water per kg fish produced per year (m^3)**	**Consumption of new water per day of total system water volume (%)**	**Degree of Recirculation at system vol. recycled one time per hour (%)**
Flow-through	30	1028	0
RAS Low Level	3	103	95.9
RAS Intensive	1	34	98.6
RAS Super Intensive	0.3	6	99.6

Figure 59: Degree of recirculation comparison for flow through and RAS (FAO, 2015)

8.9. Mortality Rate

The mortality rate found for smolt production in RAS was predicted 14% from ova to smolt; the mortality rate was 22% for systems without temperature control (Colt et al., 2009). As there was no site-specific data or method for modelling the rate of mortalities throughout the production cycle or determining at which stage the mortalities generally occurred, the mortality rate was assumed to be 0% for both systems however it could be anticipated that open net systems would generally result in a higher mortality rate.

8.10. Stocking Density (kg/m^3)

A study was carried out investigating stocking density limits for post-smolt Atlantic Salmon in commercial scale semi-closed sea systems, looking at the welfare of the fish and the growth performance in production (Calabrese et al., 2017). It was determined that salmon post-smolts in RAS could be reared at up to $75kg/m^3$ without suffering from poor welfare conditions and limiting performance. A stocking density of $40kg/m^3$ was taken for RAS smolt based on literature (Colt et al., 2008).

8.11. Waste Generation

On-Farm

There is a very limited amount of valid and reliable literature and research data quantifying the amount of waste production for each species in aquaculture. This would be valuable in assessing the potential for harnessing waste for energy generation or other purposes for proposed adaptations or new sites. As can be seen in figure 60, the salmon consumes feed and takes in oxygen through its gills; ammonia and carbon dioxide are released along with faeces from the fish after the inputs have been metabolised.

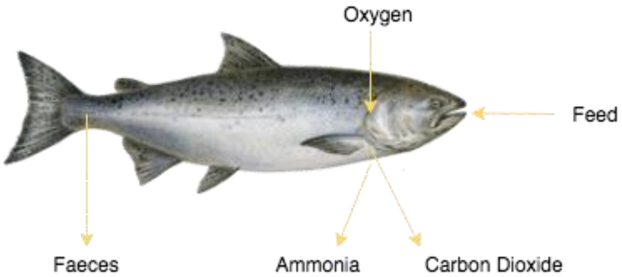


Figure 60: Fish metabolising (FAO, 2015)

Nitrogen and phosphorus are the nutrients that pose eutrophication potential and organic carbon leads to impacts to the benthic ecosystems. Ecosystems typically breakdown organic carbon into inorganic carbon by respiration of organisms.

The waste generation can be quantified as a function of the feed fed as can be seen in figure 61 (Wheaton, 2002). The concentration of the waste in the waste water is dependent on the water flowrate as for example if the flowrate of RAS is 10-100times lower, then the concentration of waste will also be 10-100 times higher (Martins et al., 2010).

Waste Product	**% (kg waste product/ kg feed fed)**
Ammonia-N	0.289
Nitrite-N	0.024
Phosphate-P	0.0162
Suspended Solids	0.52
BOD	0.6
COD	1.89

Figure 61: Waste Production based on feed input (Wheaton, 2002)

COD is the chemical oxygen demand that is a measurement of all chemicals in the waste effluent including organics and inorganics. BOD is the biochemical oxygen demand that measures the amount of oxygen that would be required to degrade the bacteria (organic components) in the waste effluent.

Post-Farm

In the primary processing stage, the fish are typically gutted and packed in ice in polystyrene boxes before being transported to a secondary processing stage (Newton and Little, 2017). Assuming that 1.16kg of live-weight fish resulted in 1kg of head-on gutted fish (HOG) (Newton and Little, 2017), waste generated at the processing stage could be calculated.

8.12. Farm Energy Usage

Open Net Pen

Energy for ONP systems is predominantly required for delivery of feed hence the energy required is largely dependent on the level of production; it was found to be approximately 56 GJ/ tonne of whole fish required in intensive Salmon ONP (Muir, 2018), including feed input. For on-farm energy usage only, a value of 904MJ per tonne of salmon output was taken from literature (Pelletier et al., 2009); equivalent to 0.25kWh/ kg salmon.

Recirculating Aquaculture System

Energy in RAS is mainly required for recirculation of water in pumping, aeration and heating or cooling. The following table summarises non-feed related energy requirements for 3 categories of aquaculture system; open net pen, intensive flow-through tank/pond and recirculating aquaculture system. This highlights the higher energy requirement of intensive flow-through tanks; they do not generally collect and process waste and so may culminate in larger environmental impacts via effluent release and energy requirement.

System (kW/ tonne output)	Pumping	Aeration	Heating/ Cooling	Vehicle/ Vessel Fuel	Miscellaneous Power
Open Net Pen	n/a	n/a	n/a	0.033	Negligible
Intensive Flow-through tank/ pond	0.66	0.75	n/a	Negligible	0.03
Recirculating Aquaculture System	0.33	0.21	0.4	Negligible	0.06

Figure 62: Energy Capacity Required for respective systems (Muir, 2018)

The energy demand for pumping water were calculated using the following equation (Muir, 2018):

$$P_p = \frac{9.81 * h * Q_f}{\eta}$$

eq. 9

Whereby P_P is the pump capacity required (kW), h is the head required by the pump (m), Q_f is the water flowrate (m^3/s) and η is the efficiency of the pump. From literature, the lifting height (head) required by most intensive recirculating aquaculture systems was found to be between 2-3m (FAO, 2015); hence, an average of 2.5m was taken in the model. The efficiency of the pump was taken to be 75% (Pumps and systems, 2018). A centrifugal pump is required in pumping the oxygen into the water under high pressure

The model assumes values for aeration, heating/cooling and miscellaneous power that the energy consumption is relative to the calculated pumping power, calculating ratios from figure 62. There are further energy demands to be analysed for the RAS such as if the system has light control or de-nitrification. Other farm activities that require energy such as overheads for offices were not included in quantifying the energy usage as it was assumed they would be relatively low compared to the key activities.

8.13. Costing Analysis

Operating Costs

Values for costs of electricity and gas were taken from online which represent the current market in the UK as 12.499pence/ kWh for electricity and 2.78pence/ kWh for gas (Ukpower.co.uk, 2018). Whilst open net pens often use diesel generators or fuel in boat transportation, it was assumed that the energy used on the ONP farm was electricity.

The following operating costs were found in literature as NOK/unit however a conversion unit was applied; 10NOK per £1. Cost for ova were taken from a major producer, Aquagen to be approximately 7.5pence per egg (Aquagen, 2018). The feed and oxygen liquid were taken to be £1.0235/kg and £0.1602/kg respectively (HIE, 2016). Further operating costs applied to the tool are for sea lice treatment, fish health & medication and pH control, calculated using values from literature as £/kg of production.

	ONP (£/kg)	RAS (£/kg)
Lice Treatment	0.066	-
Fish Health & Medication	0.05	0.025
pH control	-	0.007

Figure 63: Operating Costs (£/kg) (HIE, 2016)

Capital Costs

The comparative study of producing 3300MT of salmon in open net pen and recirculating aquaculture system estimated the following capital costs (Liu et al., 2016):

ONP system cost components	Cost (US$)	LBCC-RAS system cost components	Cost (US$)
Licences	23,571,429	RAS Systems	26,640,557
Floating rings	1,834,286	Effluent treatment	3,487,500
Nets	857,143	Water supply	675,000
Moorings	342,857	Processing	2,112,030
Boats	1,285,714	Building	9,426,413
Feed barges	1,371,429	Engineering	5,080,980
Camera systems	214,286	Construction management	1,058,538
Feed distributors	34,114	Bond	254,049
Power systems	188,571	Contingency (10%)	4,848,102
Total	29,699,829	Total	53,583,169

Figure 64: Capital Expenses for a 3,300 MT HOG LBCC-RAS and ONP Atlantic Salmon Farm (Liu et al., 2016)

The costs are in US dollars, assuming a conversion rate of approximately £0.77 (Xe, 2018) to the dollar, the expenses are approximately £22.9 million for the ONP and £41.25 million for the RAS. The following does not make clear whether RAS would benefit from economy of scale; 2-4 show that RAS would benefit from economy of scale however 1 does not. The data has been obtained from separate sources hence it may be that that scope for capital costs varied, an average (£/kg) capital cost was calculated for use in the tool however further research would be required to gain more accurate capital cost predictions.

	Production Capacity (T)	**ONP (£million)**	**£/ kg capacity ONP**	**RAS (£million)**	**£/ kg capacity RAS**	**Cost RAS vs. ONP**
1	3300	22.9	6.94	41.25	12.5	1.80
2	2500	3.90	1.54	17.4	7.0	4.52
3	1000	2.31	2.31	9.24	9.24	4
4	470	-	-	5.375	11.44	-
Average (£/kg capacity)			3.60		13.38	

Figure 65: Capital Cost Comparison for ONP and RAS systems (1) (Liu et al., 2016) (2-4) (HIE, 2017)

The average £/kg capacity for the capital expenses was calculated from the data in figure 65; 1 (Liu et al., 2016); 2 and 3 are based on feasibility studies (HIE, 2017) and 4 is data for the Namgis farm in Canada (HIE, 2017).

Price of Salmon

The following diagram show the average price of salmon fillets per kg. Approximately 1kg live weight salmon is 0.86 kg of salmon that can be sold (Newton and Little, 2018). This value was utilised to calculate the approximate weight of salmon that could be sold. The price of salmon was taken to be £16.00/ kg from the graph below.

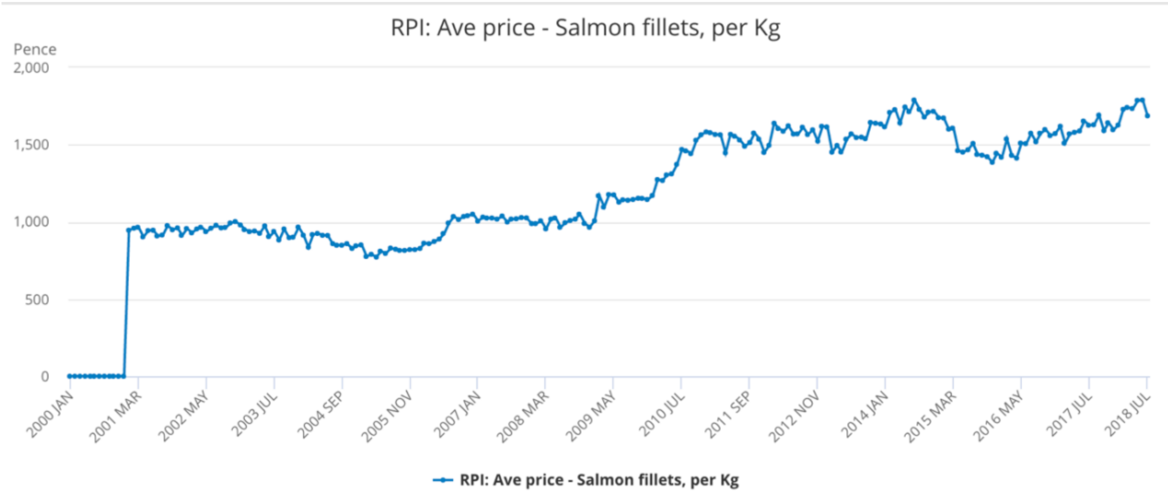


Figure 66: RPI: Average price of Salmon fillets per kg (Ons.gov.uk, 2018)

Annual Profit

To estimate the annual profit generated for each scenario the following equation for annual repayment was used

$$Annual\ Repayment = \frac{Cr(1+r)^n}{(1+r)^n - 1}$$

eq. 10

Whereby C is the capital cost of the system; r is the rate of interest taken as 6% and n is the payback period taken as 15 years.

8.14. Waste Utilisation

Anaerobic Digestion

Anaerobic digestions may achieve energy by converting organic waste such as waste water sludge, agricultural and food waste and animal and human manure into biogas. The digestate is a valuable by-product itself that can be used for various applications such as fertiliser.

There is limited research available regarding anaerobic digestion of aquaculture sludge due to the more traditional methods of open net pens, ponds and flow-through systems remaining the predominant methods of farming (Mirzoyan, Tal and Gross, 2010). The ammonia present in the sludge was found to be inhibitory to anaerobic digestion however since studies have been carried out to determine methods for sludge-stabilization (Mirzoyan, Tal and Gross, 2010). The biogas produced by the anaerobic digester depends on the carbon and nitrogen content of the waste which depends on the content of the feed. Exact calculations for this were outside the scope of this thesis however research has been carried out to support this calculation (Mirzoyan, Tal and Gross, 2010) (Brod et al., 2017) (Ward and Slater, 2002).

Aquaponics

The potential calculated for aquaponics assumes the pH of the waste stream is within the recommended limits for efficient plant growth of 5.0-7.0 (Harmon, 2005). The potential is dependent on the feed input to the system and was found to be 2.4g/plant/day for an unspecified plant or 1.3g/plant/day for lettuce (Harmon, 2005). The total feed input was averaged for the number of days that the smolt or salmon grow-out production occurred to gain a steady state value. It was found that lettuce types varieties can take from 45 to 100 days to mature (Burpee.com, 2018); 100 days was taken as the input for the tool. This is a basic calculation incorporated into the tool however it gives a rough guide of aquaponics potential.

8.15. Summary of RAq Tool Parameters

The following table shows the input section for production required in the tool, in this case a production requirement of 117000kg was input. The average smolt weight was chosen to be 200g and the harvestable weight chosen to be 4.5kg. These inputs can be altered depending on desired levels of production.

PRODUCTION REQUIREMENT				
Total Production (kg)	**Smolt Weight (g)**	**Harvest Weight (kg)**	**Number Salmon**	**Location**
117000	200	4.5	26000	Isle of Lewis

Figure 67: Production requirement input for tool

The following table shows the parameters used in the tool calculations based on literature, adapted to a Scottish context where possible.

ONP SMOLT GROWTH	
Desired Number Smolt Output	26000
Biomass Gain (kg)	5194.8
Required Egg Input	26000
Initial Weight (g)	0.2
End Weight (g)	200
Location	Isle of Lewis
Growth Constant (Gc)	1.05
Max Density (kg/m3)	25
Total Volume Water (m3)	208
FCR	1
Mortality Rate (%)	0

ONP SALMON GROW-OUT	
Number of Smolts	26000
Biomass Gain (kg)	111800
Smolt Required	26000
Initial Weight (g)	200
Final Weight (g)	4500
Location	Isle of Lewis
Growth Constant (Gc)	1.73
Max Density (kg/m3)	8.1
Total Volume Water (m3)	14444
FCR	1.27
Mortality Rate (%)	0

RAS SMOLT GROWTH	
Desired Smolt Output	26000
Biomass Gain (kg)	5195
Required Egg Input	26000
Initial Weight (g)	0.2
End Weight (g)	200
T (deg C)	16
T (deg F)	60.8
Growth Constant (Gc)	1.05
Max Density (kg/m3)	40
Total Volume Water (m3)	130
Water Consumption (L/kgmin)	0.42
FCR	0.9
Mortality Rate (%)	0

RAS SALMON GROW-OUT	
Number of Smolt Input	26000
Biomass Gain (kg)	111800
Required Smolt Input	26000
Initial Weight (g)	200
Final Weight (g)	4500
T (deg C)	16
T (deg F)	60.8
Growth Constant (Gc)	2
Max Density (kg/m3)	75
Total Volume Water (m3)	1560
Water Consumption (L/kgmin)	0.42
FCR	1.1
Mortality Rate	0

Figure 68: Screenshot of System Parameters from RAq Tool for RAS and ONP Smolt and Salmon Grow-Out

9. Results

The following section details the key results obtained by utilising the tool created in this thesis. Four scenarios were chosen for analysis as detailed in the first subsection.

9.1. Scenarios for Analysis

Based on the literature review carried out in this thesis, three key routes were identified for assessment of their potential for enabling sustainable growth within the industry. Scenarios 2 and 3 investigate the transition to RAS for smolt production; scenario 3 specifically reducing time spent in seawater for salmon grow-out stage. Scenario 4 investigates the transition to recirculating aquaculture systems for both smolt and salmon production. The tool was used to analyse these three key scenarios of production along with the current practice carried out in Scotland to determine advantages and disadvantages of each scenario.

Table 2: Scenarios Analysed Using Tool

Scenario	Smolt Production	Salmon Production
1. Current Practice (70g smolt)	Open Net Pen (ONP)	Open Net Pen (ONP)
2. Smolt in RAS to 70g	Recirculating Aquaculture System (RAS)	Open Net Pen (ONP)
3. Smolt in RAS to 200g	Recirculating Aquaculture System (RAS)	Open Net Pen (ONP)
4. Smolt & Salmon in RAS (200g Smolt)	Recirculating Aquaculture System (RAS)	Recirculating Aquaculture System (RAS)

For all scenarios, the production required was taken to be that of the capacity of the Niri RAS farm based in Machrihanish, Scotland. The recirculating aquaculture tank has the capacity for 26,000 smolts, growing them to harvestable size between 4-5kg (Hjul, 2018). The tank used was 1600m^3, located in a former Nato air base. For the tool, the desired harvestable weight was input as 4.5kg reaching a total production weight of 117000kg.

9.2. 70g Smolt Production

The following is table of the resources required for smolt production to 70g from ova at 0.2g and salmon grow-out from 70g to 4.5kg. It assumes a mortality rate of 0%. Highlighted in green are the areas where RAS performed better than ONP and highlighted red for areas where ONP performed better than RAS.

Table 3: Resource Consumption for 70g Smolt Production from tool

70g Smolt	ONP Smolt	ONP Salmon Grow-Out	RAS Smolt	RAS Salmon Grow-Out	Resource Difference for Smolt (RAS/ ONP)	Resource Difference for Salmon Grow-Out (RAS/ ONP)
Time taken (days)	321	683	211	389	0.66	0.57
Farm Biomass Gain (including mortalities) (T)	2	115	2	115	1.00	1.00
Total Feed Required (T)	1.8	146.8	1.6	127.0	0.91	0.87
No. of Ova Required	2600	0	2600	0	1.00	-
Total Oxygen Required (T)	-	-	11	469	-	-
Total Volume Required (m3)	73	14,444	46	1,560	0.63	0.11
Total Additional Water Intake (m3)			306	26,494	-	-
Total Electricity Required (kWh)	456	28,923	1,114	85,344	2.45	3.86
Total Natural Gas Required (kWh)	-	-	743	56,896	-	-

9.3. 200g Smolt Production

The following is table of the resources required for smolt production to 200g from ova at 0.2g and salmon grow-out from 200g to 4.5kg. It assumes a mortality rate of 0%. Highlighted in green are the areas where RAS performed better than ONP and highlighted red for areas where ONP performed better than RAS.

Table 4: Resource Consumption for 200g Smolt Production from tool

200g Smolt	ONP Smolt	ONP Salmon Grow-Out	RAS Smolt	RAS Salmon Grow-Out	Resource Difference for Smolt (RAS/ ONP)	Resource Difference for Salmon Grow-Out (RAS/ ONP)
Time taken (days)	507	604	314	334	0.62	0.55
Farm Biomass Gain (including mortalities) (T)	5	112	5	112	1.00	1.00
Total Feed Required (T)	860	31,670	408	17,873	0.90	0.87
No. of Ova Required	26000	-	26000	-	1.00	-
Total Oxygen Required (T)	-	-	0.2	5.4	-	-
Total Volume Required (m3)	208	14,444	130	1,560	0.63	0.11
Total Additional Water Intake (m3)	-	-	1,243	40,805	-	-
Total Electricity Required (kWh)	1,304	28,084	4,531	133,028	3.47	4.74
Total Natural Gas Required (kWh)	-	-	3,020	88,686	-	-

9.4. Scenario Growth

The following graph shows the growth patterns for all four scenarios from Ova to Salmon.

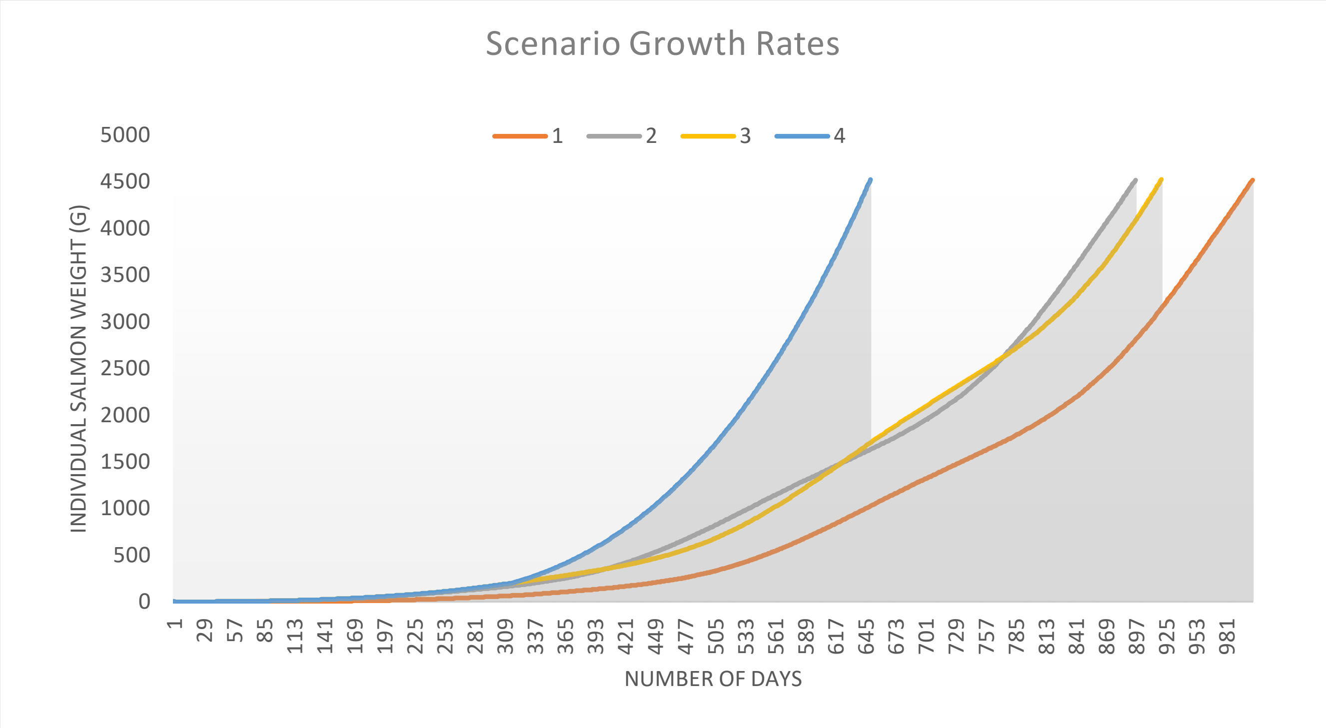


Figure 69: Scenario Growth Rates from tool

The time taken for the salmon to reach harvestable size for each scenario was as follows: (1) 1005 days (2) 896 days (3) 920 days (4) 649 days.

9.5. Feed Consumption

The table below summarises the kg of feed per kg weight of live salmon for each scenario. Scenario 4 consumes 60.5% of the feed required by Scenario 1, 60.3% of Scenario 2 and 56.7% of Scenario 3.

Table 5: Feed Consumption for each scenario from tool

Scenario	1	2	3	4
Smolt Feed (T)	1.8	1.6	4.7	4.7
Salmon Grow-Out Feed (T)	146.8	146.8	142.1	123.6
Total Feed Req. (T)	148.6	148.4	146.8	128.3
kg Feed/ kg live-weight Salmon at Harvest	1.27	1.27	1.25	1.10

9.6. Energy Consumption

The table below summarises the kWh of energy (electricity + natural gas) per kg weight of live salmon for each scenario. Scenario 1 consumes approximately 12.8% of the energy required by Scenario 4.

Table 6: Energy Consumption for each scenario from tool

Scenario	1	2	3	4
Total Smolt Energy Req. (kWh)	456	1,857	7,551	7,551
Total Salmon Grow-Out Energy Req. (kWh)	28,923	28,923	28,074	221,714
Total Energy Req. (kWh)	29,379	30,780	35,625	229,265
kWh Energy/ kg live-weight Salmon	0.25	0.26	0.30	1.96

9.7. Water and Land Consumption

The table below summarises the volume required for the ONP or RAS and the additional water intake required. The total rearing volume required for Scenario 4 is approximately 11.6% of that required for Scenario 1.

Table 7: Water Consumption for each scenario from tool

Scenario	1	2	3	4
Smolt Stocking Density (kg/m3)	25	40	40	40
Smolt Volume (m3)	73	46	130	130
Salmon Grow-Out Stocking Density (kg/m3)	8.1	8.1	8.1	75
Salmon Grow-Out Volume (m3)	14,444	14,444	14,444	1,560
Total Volume (m3)	14,517	14,490	14,574	1,690
Additional Water Intake (m3)	-	306	1,243	42,048

9.8. Waste Generation

The following graph shows the nitrogen (N), phosphorus (P) and suspended solids (SS) waste generated for each scenario. Scenario 4 produces approximately 58.8% of the waste generated by Scenario 1. The cells highlighted in green show waste that can be collected to be utilised as the farm is RAS.

Table 8: Waste generated for each scenario from tool

Scenario	1	2	3	4
Smolt N (T)	0.53	0.47	1.4	1.4
Smolt P (T)	0.03	0.03	0.1	0.1
Smolt SS (T)	0.95	0.85	2.4	2.4
Salmon Grow-Out N (T)	42.73	42.73	41.1	38.7
Salmon Grow-Out P (T)	2.40	2.40	2.3	2.0
Salmon Grow-Out SS (T)	76.89	76.89	73.9	64.3

9.9. Waste Utilisation

Anaerobic Digestion

As Scenario 4 Salmon Grow-Out stage produced the largest volume of waste it was chosen for evaluation using the AD Calculator. The minimum (44.63 kg/ day) and maximum (354.22 kg/ day) suspended solids volume of waste per day was input to the AD calculator, assuming this to be the weight of wet mass. The key results are as follows for approximate energy (kWh) produced per day. The tool assumes 11.04kWh energy per m^3 biogas produced in anaerobic digestion.

Biogas/methane power outputs	Estimates			
	Lowest	Middle	Highest	Units
Total biogas per day	2.7	6.7	26.8	m^3
Methane content range of biogas	50.0%	60.0%	65.0%	%
Total methane per day	1.3	4.0	17.4	m^3
kWh per day @ 11.04 kWh/m^3	14.8	44.3	192.2	kWh
kW average power (methane)	0.6	1.8	8.0	kW

Figure 70: AD Calculator output for minimum waste/ day output Scenario 4

Biogas/methane power outputs				
		Estimates		
	Lowest	Middle	Highest	Units
Total biogas per day	21.2	53.1	212.4	m^3
Methane content range of biogas	50.0%	60.0%	65.0%	%
Total methane per day	10.6	31.9	138.1	m^3
kWh per day @ 11.04 kWh/m^3	117.2	351.7	1524.2	kWh
kW average power (methane)	4.9	14.7	63.5	kW

Figure 71: AD Calculator output for maximum waste/ day output Scenario 4

Aquaponics

The aquaponics potential, calculated as a % of the average feed input per day throughout the production was calculated for Scenario 4 for both smolt and salmon grow-out. The weight of a lettuce was assumed to be 1lb (approx. 0.45kg).

Table 9: Aquaponics Potential from tool

	RAS Smolt			**RAS Salmon Grow-Out**		
	Min Feed	Avg. Feed	Max Feed	Min Feed	Avg. Feed	Max Feed
Feed(kg/day)	0.42	20.40	40.38	85.83	383.51	681.19
Lettuce Capacity (number)	319	15,691	31,064	66,023	295,007	523,990
Total Lettuce Weight (kg)	144	7,061	13,979	32,681	146,028	259,375
kg lettuce / kg fish	0.00	0.06	0.12	0.28	1.25	2.22

9.10. Operating Costs

The following table shows the operating costs calculated by the tool for all 4 scenarios.

Table 10: Operating Costs for Scenarios 1-4

Scenario	1	Cost (£)	2	Cost (£)	3	Cost (£)	4	Cost (£)
Ova (number)	26000	£1,950	26000	£1,950	26000	£1,950	26000	£1,950
Feed (Tonnes)	148.6	£152,092	148	£151,887	142	£145,439	124	£126,505
Electricity (kWh)	29379	£3,672	30037	£3,754	32605	£4,075	137559	£17,193
Gas (kWh)	--	--	743	£21	3020	£84	88686	£2,465
Oxygen (Tonnes)	--	--	11	£1,762	38	£6,088	710	£113,742
Lice Treatment		£7,722		£7,722		£7,722		-
Fish Health & Medication		£5,850		£5,850		£5,850		£2,925
pH control								£819
Total		£171,286		£172,947		£171,208		£264,781
Price per kg		£1.46		£1.48		£1.46		£2.26

9.11. Capital Costs

The following table shows the capital costs estimated for all 4 scenarios.

Table 11: Capital Costs for Scenarios 1-4

Scenario	1	Cost (£)	2	Cost (£)	3	Cost (£)	4	Cost (£)
Smolt	ONP	6,474	RAS	24,082	RAS	66,895	RAS	66,895
Salmon Grow-Out	ONP	414,313	ONP	414,313	ONP	402,804	RAS	1,498,447
Total Capital Cost		420,786		438,395		469,699		1,565,342

9.12. Profit

To estimate the profit, the time required for each production cycle for each scenario was considered to calculate a value for profits per year.

Table 12: Estimated Profits per year for scenarios 1-4

Scenario	**1**	**2**	**3**	**4**
Production Cycle Time	1005	896	920	649
Production per year (kg)	42493	47662	46418	65801
Operating Costs (£/kg)	1.46	1.48	1.46	2.26
Annual Repayment (£/ yr)	43325	45138	48362	161172
Maintenance (£/ yr)	1300	1354	1451	4835
Total Annual Costs (£/ yr)	106834	116945	117737	314921
Salmon (kg)	36544	40989	39920	56589
Salmon (£)	584697	655827	638718	905425
Profits per year	£477,864	£538,882	£520,981	£590,504

9.13. Pre-Farm

The following table shows energy required at the feed mill for the feed required by each scenario, taken based on estimated values for UK production (Pelletier et al., 2009). It also shows the feed transport in (t-km) and smolt transport (t-km); the calculation for smolt transport assumes that the smolt production RAS units (Scenarios 2-4) are situated in locations close to the salmon grow-out facility hence the transport assumed to be negligible.

Table 13: Pre-Farm Calculations from tool

Scenario	1	2	3	4
Feed (Tonnes)	148.6	148	142	124
Feed Mill Energy (kWh)	33807	33761	32328	28119
Feed Transport (t-km)	35916	35868	34345	29874
Smolt Transport (t-km)	316.2	negligible	negligible	negligible

Scenario 1 required a total of 36,232t-km for transport of feed and smolt; scenario 4 required approximately 82.5% of scenario 1.

10. Discussion

The following section discusses the key outcomes from the literature review conducted in this thesis and the results from the tool created. It addresses limitations and assumptions made.

10.1. Growth Model

Limitations and Assumptions

The foundations of this tool are built on the reliability of the growth model; the model shows linear growth dependant on temperature which is not truly accurate as other key factors such as oxygen concentration in the rearing area may impact growth. Growth modelling is imperative to understanding resources required and the waste outputs from the system. In literature, there was disparity between values utilised as temperature growth coefficients in calculating the rate of growth of Atlantic salmon, however the temperature growth model for open net pens was calculated based on literature available for average growth of Scottish Salmon. The tool assumes that all smolt and salmon at grow-out reach the average size stated for each case however it is unlikely that all salmon will reach harvestable weight and some will exceed harvestable weight. The Isle of Lewis sea temperature was used in both smolt and salmon growth model for ONP. This is not an accurate reflection of temperature that may be in freshwater smolt production; data for freshwater in Scotland was difficult to obtain. However, the ONP smolt production to 70g required 321 days the model; suggesting it is accurate for S1 smolt that require a year for growth (Ellis et al., 2016).

Results Analysis

The results from the tool give the estimated time for growth to a harvestable weight of 4.5kg. The results determined that scenario 4 by utilising RAS for both smolt and salmon production allowed for the fastest growth (approx. 645 days) and the current situation with both stages in ONP resulted in the slowest growth (approx. 1005 days). Scenario 2 for growing smolt to 70g resulted in the salmon reaching 4.5kg earlier (896) than that of the 200g smolt (920). This is due to the temperature growth coefficient (TGC) for the smolt stage in ONP and RAS input being the same at 1.05 (Colt et al., 2008) however in literature TGC for salmon throughout all stages have been estimated as follows based on a Growout trial: Fry, 1.25; smolt 1.40; Pre-growout 2.0 and growout

2.30 (as taken for RAS salmon growout TGC). The model wasn't developed to this detail however by inputting a smolt TGC of 1.40 for scenarios 2 and 3 it resulted in a growth time of 842 days and 840 days respectively.

10.2. Feed Consumption

Limitations and Assumptions

For all scenarios, the level of mortalities was assumed to be 0% however if a mortality rate were to be applied to the model, it would show an increase in farm biomass gain, an increase in ova required to meet required production and an increase in feed. The biomass gain represents all weight gained by salmon on the farm including mortalities. To due time limits and apparent lack of data relating to rates of mortalities, and at which stage the mortalities occur in the production cycle, this was not incorporated into the model. However, considering that in 2017 approximately 13% of Scottish salmon (tonnes) was lost due to mortalities, as discussed earlier in the report, this implies a 13% increase in required feed and hence the costs and emissions associated with it in order to maintain the same level of production.

Results Analysis

As anticipated, the results for feed consumption showed a lower requirement of feed (kg feed per kg live-weight Salmon at harvest) for scenario 4 using recirculating aquaculture systems than that required by scenario 1 for open net pens. Scenario 2 required only 2 tonnes less of feed than that of Scenario 1 due to smolt production being carried out in RAS; showing it is not a particularly effective transition for dealing with reducing feed consumption. Scenario 3 resulted in a reduction of 0.2kg feed/ kg live weight salmon required as the smolt were kept in RAS till 200g.

Scenario 4 resulted in the lowest requirement of feed however it does have the higher requirement of oxygen consumption. Oxygen may be produced onsite or offsite and transported to the farm. Other inputs detailed in the operating costs include sea lice treatment, fish health & medication and pH control. Further analysis is required to understand how these inputs impact the total transport of resources to the farm site.

10.3. Energy Usage

Limitations and Assumptions

The value for ONP on-farm energy usage was taken from an LCA that surveyed 6 Atlantic salmon farms in the UK. The value for RAS on-farm energy usage was determined by calculating the pump power required and scaling the other energy requirements based on data from literature (Muir, 2018).

The energy requirement for smolt was assumed to be the same as for salmon grow-out however, energy requirements for smolt production in freshwater may be lower than that required by salmon grow-out; further research or data collection from farms could clarify this.

Results Analysis

The tool found that the energy required by scenario 4 for RAS was approximately 1.96kWh per kg of live-weight fish; this corresponds with values from Langsand Laks RAS trial in Denmark for an energy efficiency of 1.3-2.11kWh/kg fish (HIE, 2017).

The following graph shows data taken for the increase in energy required for the RAS Salmon Grow-Out Stage. As the energy required is dependent on the water recirculation required which is then dependent on the weight of fish in the tank, the energy usage increases as the weight of the fish increase.

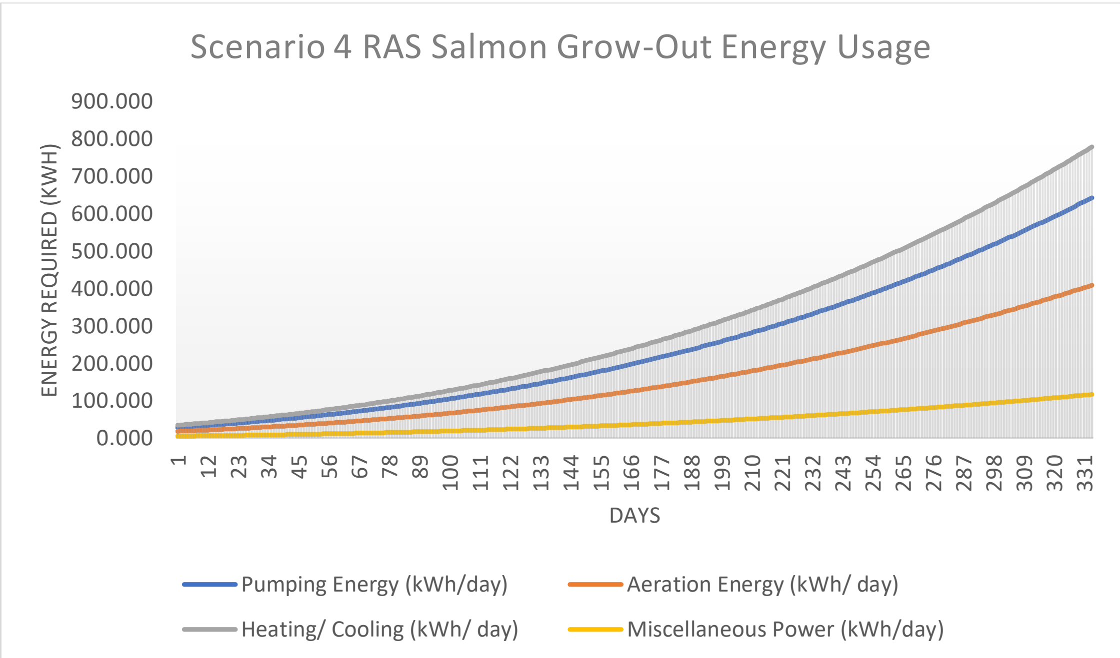
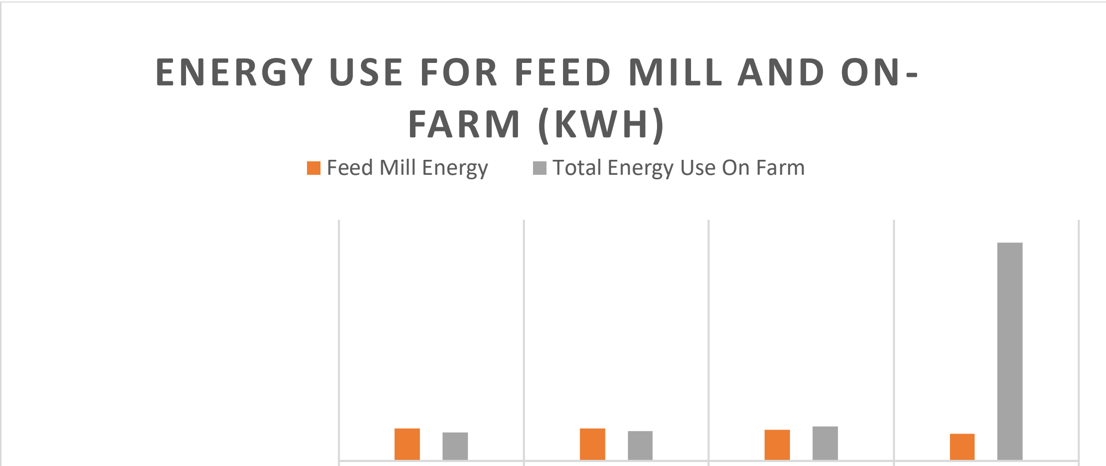


Figure 72: Scenario 4 RAS Salmon Grow-Out Energy Usage from tool

The tool found that the maximum pump power required was 26.75kW and the minimum 1.19kW. This resulted in a pump power requirement of 0.23kW/ tonne output; this was lower than that found in literature of 0.33kW/ tonne (Muir, 2018). Further investigation and research could allow for greater accuracy in equipment requirement.

The following graph shows the comparison of energy use at the feed mill stage compared to energy use on farm for each scenario. Based on values from literature for feed mill energy usage (Pelletier et al., 2009), scenarios 1 and 2 required more energy at this stage than on farm.



	1	2	3	4
Feed Mill Energy	33,807	33,761	32,328	28,119
Total Energy Use On Farm	29,379	30,780	35,625	226,245

Figure 73: Energy Use for Feed Mill and On-Farm (kWh)

Energy required on-farm for scenario 4 remained the highest; for smolt and salmon production in RAS compared to both in ONP it was found to require approximately 7.7 times more energy.

Energy Audits

Energy audits could benefit the farm on a local management level to determine where they may seek improvements or where there may be problems in the system. By conducting energy audits across all farms in Scotland, efficient systems could be identified and knowledge shared to achieve efficient energy use on all farms

Energy audits throughout all stages and for all methods of farming in aquaculture would allow for improved modelling energy demands for different systems. By conducting trials of an recirculating aquaculture systems, it would allow for greater understanding of the hourly, daily and monthly variations in demand on a salmon farm to understand where renewable energy may be suitably integrated.

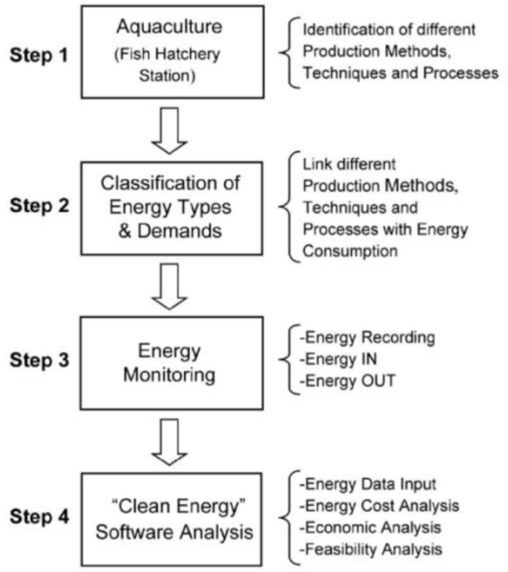


Figure 1. Proposed framework for energy audit in aquaculture; A step by step analysis

Figure 74: Proposed framework for energy audit in aquaculture: A step by step analysis (Ioakeimidis, Polatidis and Haralambopoulos, 2013)

Energy audits could be integrated into the Scottish annual Fish Farm Survey for comparisons to be drawn and farms with higher energy usage per production may be identified.

10.4. Waste Generated

Limitations and Assumptions

The waste generated was calculated as a percentage of the feed input to the system however the waste generated is also dependent on the composition of the feed and the species reared. Due to time limits for this thesis, this level of investigation could not be carried out to determine exact release of waste and composition of waste however, this could be calculated on an individual farm basis with knowledge of feed composition from the feed supplier.

Results Analysis

The waste generated for each scenario correlated with the feed conversion ratio as can be seen in figure 71. With a lower feed conversion ratio, there was a lower production of waste resulting in the scenarios featuring open net pen systems resulting in a higher production of waste. The open net pen systems do not collect waste generated on the farm, instead it is released into the local environment which as discussed in the life cycle assessment review, is a major source of environmental impact in aquaculture.

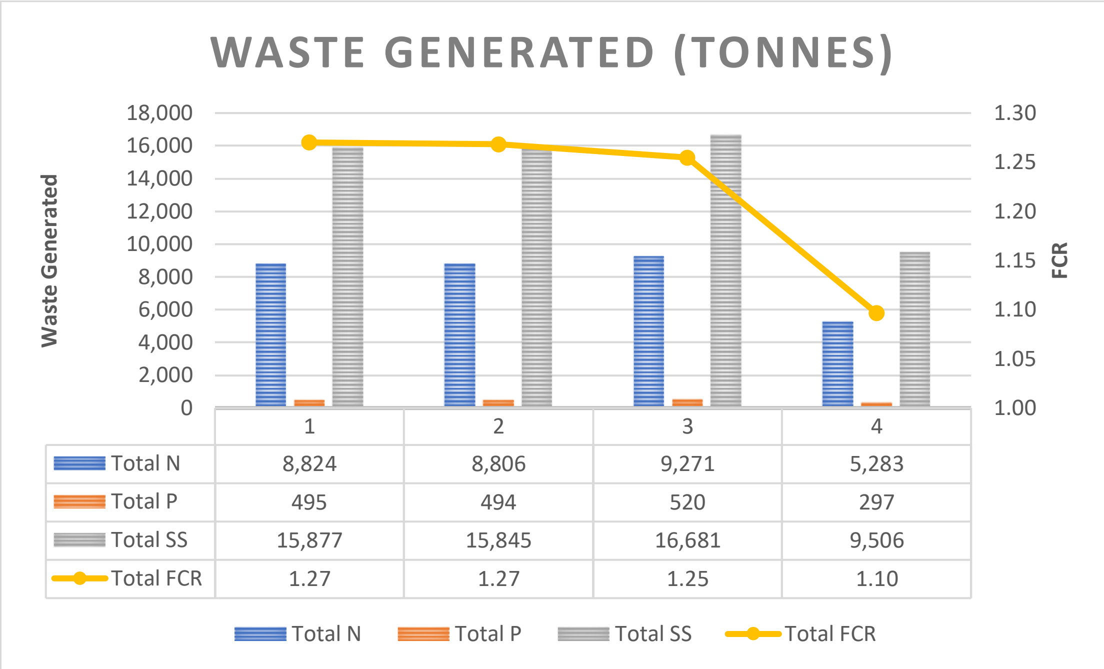


Figure 75: Waste generated for each scenario with respective feed conversion ratio (FCR)

10.5. Anaerobic Digestion

Limitations and Assumptions

The AD Calculator used to calculate potential for anaerobic digestion from the waste from RAS salmon grow-out assumes a carbon to nitrogen ratio of 5:1. The input assumed no other waste was added to the anaerobic digester however, the optimum carbon to nitrogen ratio from the tool is 25:1, with a minimum and maximum of 20 and 30 respectively. Hence, in implementation of anaerobic digestion it would be important to manage the feed to the anaerobic digester to ensure other industry or domestic wastes are added to increase the carbon to nitrogen ratio. The OHLEH circular economy example combines waste from the fish processing plant and household waste making it an appropriate case study for future work.

Results Analysis

The variation in the quantity of waste generated throughout the year requires efficient system design. The amount of waste generated at the start of the production cycle differs largely from that at the end of the fish production cycle. By implementing various RAS tanks and starting the production cycles in series throughout the year, this could allow for a steadier flow of waste through the waste treatment system. However, a key problem with the integration of various tanks by utilisation of the same waste treatment system is if a problem occurs in one tank such as disease contraction, this could result in the spread to further tanks. This factor highlights the importance of control and water monitoring for RAS.

GIS Mapping

Map of various industries and anaerobic digesters. Currently there are private consultancies offering similar services however it could be an initiative run by the government to support sustainable development as suggested by Zero Waste Scotland. A map of suggested anaerobic digester 'hotspots' was created based on locations of grain and malt distilleries, breweries and fish processors (Zero Waste Scotland, 2015); the map can be found in the appendix.

10.6. Aquaponics

Limitations and Assumptions

The value taken from literature for the aquaponics system was for an unspecified lettuce however assumptions were made to quantify what may be an average weight of a lettuce head (0.45g) and the approximate time required for growth (100 days). As discussed in this thesis, interest and research is increasing globally for this integrated food production system hence literature may increase in research for commercial scale aquaponics systems.

Results Analysis

The results provided by the tool for the aquaponics potential from waste suggest there may be greater efficiency for larger scale aquaponics systems in terms of kg lettuce production per kg fish production. This was in line with data procured for the Grow Up Farm in England; as can be seen in figure 76, the larger system producing 4,000kg of fish allows for a higher level of lettuce production.

Grow Up Farm

Fish Production (kg)	Lettuce Production (kg)	kg Lettuce/ kg fish
4,000	20,000	5
150	435	2.9

Figure 76: Grow Up Farm Production Capacity

The values provided by the tool assume only one cycle of lettuce production is carried out however as the lettuce takes approximately 100 days and the fish production almost 3 times that value, there may be a larger capacity for lettuce production. However, further research would be required to understand the time taken to plant new lettuce after maturation of the first batch. By operating various RAS tanks in series, beginning grow-out at different periods throughout the year, it may be possible to achieve a more constant flow of waste to allow for a constant level of plant production.

10.7. Cost Analysis

Limitations

Operating and capital costs for both open net pens and recirculating aquaculture systems varied as detailed in the tool creation section of the report. Variations in operating costs ranged from ONP costing 78% of RAS (HIE, 2016) to ONP costing 90% of RAS (Liu et al., 2016). Capital cost RAS to ONP ratios ranged from 1.80 to 4.52. The tool calculates the operating costs for key input resources however there are other operating costs to be considered such as insurance, salaries, depreciation in equipment, interest, administration, onsite offices etc. Due to time constraints these could not be accurately predicted however the tool provides a basis for further development in cost analysis of the systems.

Results Analysis

Both capital investment and operating costs were found to be highest for scenario 4; mainly due to energy consuming equipment however due to a considerably shorter production time, scenario 4 was found to be the most profitable. Scenario 4 was calculated to be approximately 24% more profitable per year by taking an average level of production per year.

10.8. Environmental Impact Factors

The feed requirement for the recirculating aquaculture system for scenario 4 is approximately 17% less than that of the open net pen Scenario 1. As discussed previously in the report, the key emissions are related to the feed and farm emissions as can be seen in the following diagram.

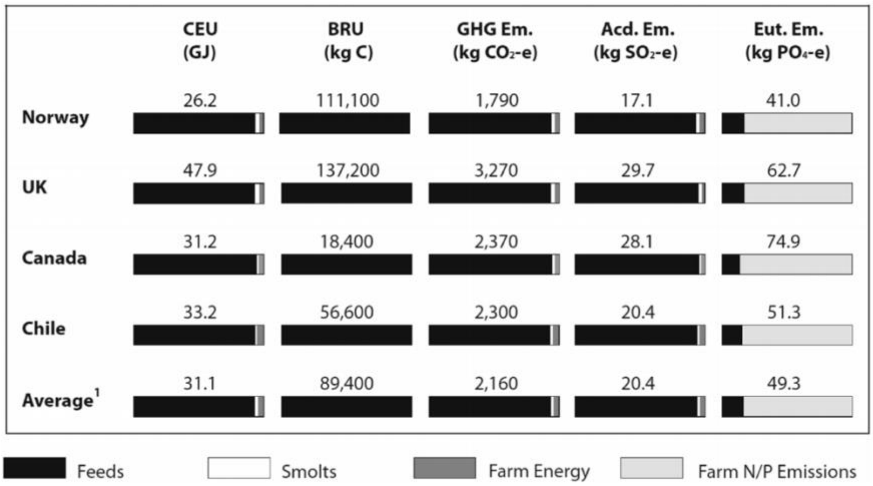


Figure 77: LCA for the Production of 1 Live-weight Tonne of Salmon in Norway, UK, Chile and Canada in 2007 (Pelletier et al., 2009)

By reducing the feed required by 17%, the majority of the impact factors can be reduced considerably also. The eutrophication emissions produced on farm can be assumed to be negligible (Ayer and Tyedmers, 2009) as the recirculating aquaculture systems collect the waste for utilisation, eliminating eutrophication potential.

Whilst energy usage is reduced for feed milling in the case of recirculating aquaculture systems in scenario 4, the energy usage increases for farm operations. However, by procurement of energy from clean energy sources, these impacts can be kept relatively low as emissions from energy production are highly dependent on the source (Ayer and Tyedmers, 2009). Negative emissions can also be considered for recirculating aquaculture systems by using the waste generated, closing the nutrient cycle.

10.9. Comparison of Scenario 1 and Scenario 4

Scenario 1 represents the current practice in Scottish aquaculture whereas scenario 4 represents perhaps the most ambitious transition. However, as a summary of the outputs from the tool; scenario 4 has the potential for a reduction in environmental impact factors by reducing feed requirement and capturing waste generated on the farm, with the potential to create other valued products by means of anaerobic digestion or aquaponics. Scenario 1 gave a lower capital investment and operating costs however, the tool calculated that due the production cycle time for scenario 4 being almost half that of scenario 1, scenario 4 could be more profitable.

10.10. Analysis of Further Species

As detailed earlier, the rainbow trout is the second most farmed species in Scotland. There is value in analysing this species and its suitability for RAS. A high-level review of current literature on this species was carried out to initially scope opportunity for success in this case. The following table was taken from the study ‘Waste treatment in recirculating aquaculture systems’ comparing solids, nitrogen and phosphorous in waster generated by the following species (Van Rign, 2013).

Fish Species	Total Solids (kg/ton fish)	Total N (kg/ton fish)	Total P (kg/ton fish)
Rainbow Trout	148-338	41-71	7.5-15.2
Brown Trout	438 (589)	49.2 (45.8)	6.2 (10.5)
Atlantic Salmon	224	32	1.1

Figure 78: Comparison of waste generated on farm for different species (Van Rign, 2013)

For brown trout, the numbers in parenthesis represent values that were obtained by direct quantification of the waste in the culture water. Rainbow Trout in RAS can have an FCR as low as 0.8-1.1, lower than that required by Atlantic Salmon (Van Rign, 2013); while the range of solids produced could be greater than that of Atlantic Salmon, resulting in higher costs, it is also more nutrient rich, which could perhaps increase how valuable it is for use after the waste treatment process. However, further research is required to quantify feasibility.

10.11. Increased Reporting

The Scottish government publishes annual reports on the Scottish finfish farming industry and has done so for more than 35 years (Ellis et al., 2016), detailing figures for imports, exports, fish escapes and more. However, a key factor missing in this to allow for sustainable development of the industry is reporting on feed production and raw material procurement for the feed.

Increasing accountability is likely to require incentive. Progressing, the government should be creating more eco-centric policies and incentives surrounding the industry to support and motivate farmers and companies to adapt or change the way in which they farm. A tool such as that created for this thesis, could allow for determining fishery impact and sustainability in a way that could be easily implemented across the sector. As different methods of farming tend to have variations in length of rearing time, the data could be quantified by production cycle. This method would also allow for drawing comparisons between the sustainability of different farming methods and species.

Consumers may be concerned by the idea of purchasing fish reared in tanks on-land compared to their more natural environment in the sea. This is the importance of consumer awareness and education; by means of eco-labelling or carrying out campaigns, the customer can select products with greater knowledge of the ethical nature of such product concerning impacts to the environment and animal welfare.

11. Conclusions

This thesis investigated the sustainability of pursuing a route to increasing the presence of recirculating aquaculture systems in Scotland. This is an opportunity for Scotland to be a leader in sustainable aquaculture. They have a major global presence in the Atlantic Salmon market and therefore the capability to invest in and research methods of production that are more sustainable.

The literature review of life cycle assessments carried out within aquaculture, specifically applicable to Atlantic salmon, allowed for the identification of the key impact caused by the open net pen salmon production that is carried out in Scotland. The two key impacts from aquaculture in Scotland were found to be incorporated in the feed and the eutrophication potential on the farm. Open net systems cause harm to the environment by uncontrolled waste release, and require a higher feed conversion ratio than other aquaculture systems, due to lack of control and non-optimal conditions in the rearing environment. The RAq tool was created to help investigate the feasibility of recirculating aquaculture systems replacing open net pens and how this transition could enable sustainable growth of the Scottish aquaculture industry.

The higher energy demand for operating recirculating aquaculture systems, compared to open net pen systems, can be generated by clean renewable sources that are well established in Scotland. However, the raw materials for feed are unlikely to be substituted to a sufficient extent to reduce the severe environmental impact. It seems evident that Scottish aquaculture will be dependent on the damaging supply chain that comes with feed production for the near future, making the recirculating aquaculture systems capability to reduce feed requirement very attractive.

Recirculating aquaculture systems are typically associated with higher investment costs, and so lower profitability, however results obtained from the RAq tool showed that a greater profit was feasible for the recirculating aquaculture system compared to the open net system. This was largely due to the shorter production cycle time required for production in recirculating aquaculture systems compared to open net pens. Recirculating aquaculture technology is a technology that is continuously developing due to increase in both quantity and quality of research and industry participation in this field.

12. Future Work

The following section details suggestions for future work to be carried out to address assumptions and limitations of this thesis.

Recirculating aquaculture systems are a relatively new technology compared to open net systems, hence they are still in development and trial stages. Based on the findings of this thesis, various suggestions have been made for future work; they have been divided into relevant categories.

12.1. Renewable Energy

Hydropower: As detailed in this thesis, gravity assisted flow can considerably reduce the energy requirement of RAS. Considering that Scotland has a relatively large percentage (approximately 13%) of hydropower in its energy generation mix, this implies scope for investigation of hydropower to assist RAS in Scotland. This could result in a reduction of costs whilst ensuring a clean energy source. Research may include investigation into suitable sites and modelling energy flows for a RAS hydropower system.

Heat Pump: Temperature control in RAS requires a large energy consumption. Heat pumps could be investigated as a technology for integration with RAS to enable a cleaner energy source than natural gas from the grid.

Renewable Energy and Storage: There are many renewable energy sources that are well established such as wind and solar energy. The suitability of these sources could be investigated for existing and potential new farms. This could be investigated alongside storage options; hydrogen energy storage could be an attractive choice for aquaculture, as the electrolyser required to produce hydrogen energy produces the by-product of oxygen, which is required in controlling rearing conditions in RAS. The OHLEH circular economy could be used as a suitable case study once it is fully operating and data has been collected for efficiency of the system.

12.2. Circular Economy

Anaerobic Digestion: Research is required to quantify and model the chemical composition of RAS waste streams based on the composition and metabolism of the fish. This will allow a more accurate prediction of potential for generating energy from fish farm waste and quantifying the economic benefits.

Aquaponics: Further investigation is required into quantifying the potential of aquaponics. Research could be carried out for different fish species and plant species to understand how they may be chosen as complimentary to each other; this may depend largely on the composition of feed for certain fish species.

IMTA: IMTA is not only beneficial by reducing the ecological impacts to the local environment, other value products can be produced to increase profits. Capability for IMTA integrated into RAS systems could be researched to determine feasibility and design.

12.3. Tool Development/ Modelling

Modelling of heat generation: Scotland is a relatively cold climate, particularly in winter, hence modelling should be carried out to quantify the variation in the demand for heating the water entering the recirculating aquaculture system. Modelling could be effective also in understanding heat generated by the fish metabolism and heat generated within the system for example by pumping.

Finfish and Shellfish: Other species that are in high demand from the UK but are imported could be considered for RAS. The UK currently imports a large volume of sea bass from Greece and Turkey; by deploying approximately 2-3 RAS farms in the UK, approximately 60-70% of imports from Greece and Turkey could be substituted (HIE, 2017). Rainbow Trout is anticipated to see growth in demand in coming years along with Salmon and as Scotland's second most produced finfish it would be beneficial incorporating it into the tool.

GIS Mapping: By utilising Geographic Information System mapping technology, Scotland could take steps in fulfilling the route to a more circular economy by understanding areas whereby industries can overlap in creating value out of waste or by-products. It may also help to identify hotspots for optimum RAS location such as being close to a suitable water source, anaerobic digestion facilities, fish processing facilities etc. in order to reduce costs and emissions for transport.

Aquaculture Systems: The tool could be developed by integration of other aquaculture systems, such as offshore systems, marine closed net pen and flow-through to allow for further comparisons with ONP and RAS to enable efficient decision-making for future systems. In particular, investigation into flow-through and RAS system comparison for smolt production could be of most relevance to the Scottish aquaculture industry.

Fish Growth Modelling: Development of the fish growth model in the tool could allow for more accurate predictions of time and resource requirements in producing a certain output from the farm. This would allow for more accurate planning by companies and farmers, and enable well-informed decisions in farm development or investment. Mortality rates may also be modelled and input.

Rearing Tank Control System: Increased research into efficient control of recirculating aquaculture for other parameters, such as dissolved oxygen, carbon dioxide, pH, ammonia etc. is required. Modelling could be carried out for a batch reactor to understand and quantify how these parameters change depending on resource input and fish species.

Life Cycle Assessment: Further research is required for developing the quantification of impacts using LCA in a Scottish context for all areas of the product life cycle, including processing. If greater transparency from the industry were to ensue, an LCA could be carried out more accurately to compare aquaculture systems.

Location: The tool could be developed to make it adaptable to whatever location chosen by input of an automatic database however this would require more accurate data for water temperatures, particularly freshwater temperature. Investigation into impact of air temperature may also be relevant in understanding energy consumption for maintaining temperature control.

12.4. Industry Accountability

Energy Audits: The Scottish Government annual fish farm survey could be adapted to include monitoring of energy consumption on farms for levels of production to allow for companies and farmers to identify hotspots in reducing energy consumption by comparison with other farms.

Eco-Labelling and Consumer Awareness: To understand the acceptance that may come with recirculating aquaculture systems, research is required into consumer awareness in Scotland of the current state of the aquaculture industry, particularly the Atlantic Salmon industry. An understanding of current consumer perception is essential and increasing education of the current impacts that are ingrained in the industry to enable a transition away from open net pen systems. This could be an important step not only in the UK, but internationally in countries whereby Scottish aquaculture products are exported.

12.5. Other

Modular Design: By modular design of an RAS farm, design could be optimised to reduce energy consumption, operating and capital costs. This may be investigated alongside an investigation into benefits of economy of scale for various RAS plant sizes.

Demand and Supply: Farms typically have certain times throughout the day where there are spikes in energy consumption due to temperature control, delivering feed, processing the waste water etc. Modelling for managing demand and supply would be beneficial to identify where costs could be reduced and renewable energy integrated into systems.

RAS Trials: Investigation into routes for grants and funding for aquaculture projects, such as deployment of recirculating aquaculture systems or other systems detailed in the circular economy section, should be carried out in Scotland to help progress the technology.

Sea Lice Treatment: As some of the industry's major producers claim to have made a breakthrough in tackling sea lice by method of 'cleaner-fish'; the resultant impacts by using this method of sea lice treatment should be addressed and quantified.

Feed Raw Materials: Algae production has been cited as the most sustainable feed for the future of aquaculture. Further research could be carried out into how this route may be fulfilled, particularly by utilisation of digestate from anaerobic digestion.

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14. Appendix

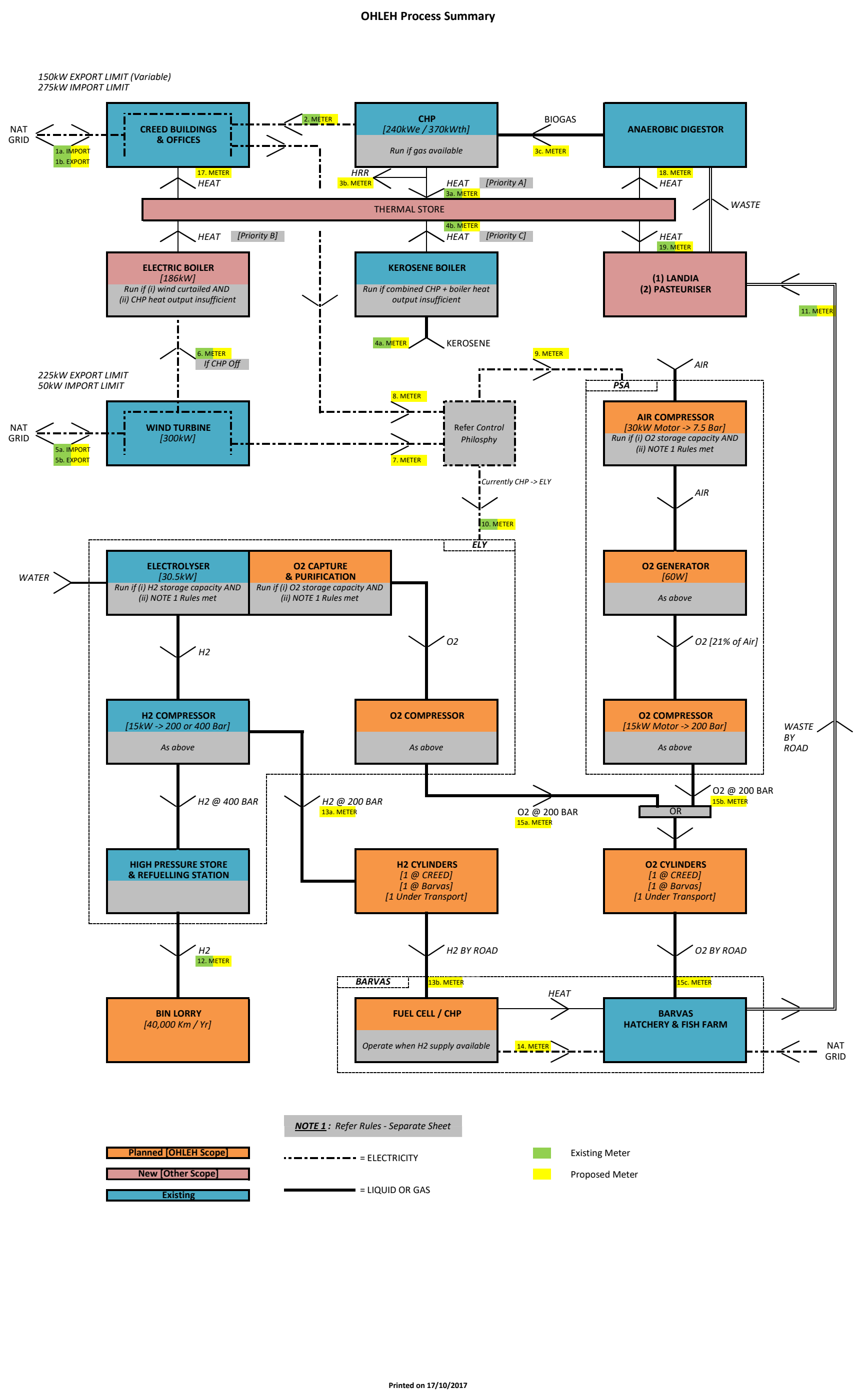

Figure 79: OHLEH Process Summary obtained from contact at Community Energy Scotland

		ONP	RAS
System Parameters	**Total Culture Volume (m3)**	180000	960
	Average Stocking Density (kg/m3)	20	73
Infrastructure Inputs (kg/t)	**Concrete**	6.5	919
	Steel	2.9	13.8
	Zinc	0.2	0
	Polyethylene	0.4	0
	Polystyrene	0.2	0
	Nylon	5.7	0
	Foam	0.2	0
	PVC pipe	0	4.2
	Polyester Scrim	0	0
Infrastructure Inputs (/t fish)	**Smolts (kg)**	20.6	238
	Feed (kg)	1300	1448
	Propane (l)	9.5	0
	Diesel (l)	28.8	0
	Gasoline (l)	36.3	0
	Heating Oil (l)	0	279
	Electricity (kWh)	0	22600
	Primary Source	90% Hydro	77% Coal
	Liquid Oxygen (m3)	0	0
	Calcium Chloride (kg)	0	481
	Soda ash (kg)	0	804
Operational Outputs (kg/t)	**Harvest Weight (kg)**	2-5.5	1.5
	Mortalities	90	301
	Cu Emissions to Water	0.5	0
	N Emissions to Water	31.3	0
	P Emission to Water	4.9	0
	Sequestered N	0	6.8
	Sequestered P	0	3.2
	Live-Weight Fish produced (tonnes)	3600	46.2

Figure 80: Inputs and outputs to produce 1 tonne of live-weight fish from an open net system and recirculating aquaculture system (Ayer and Tyedmers, 2008)

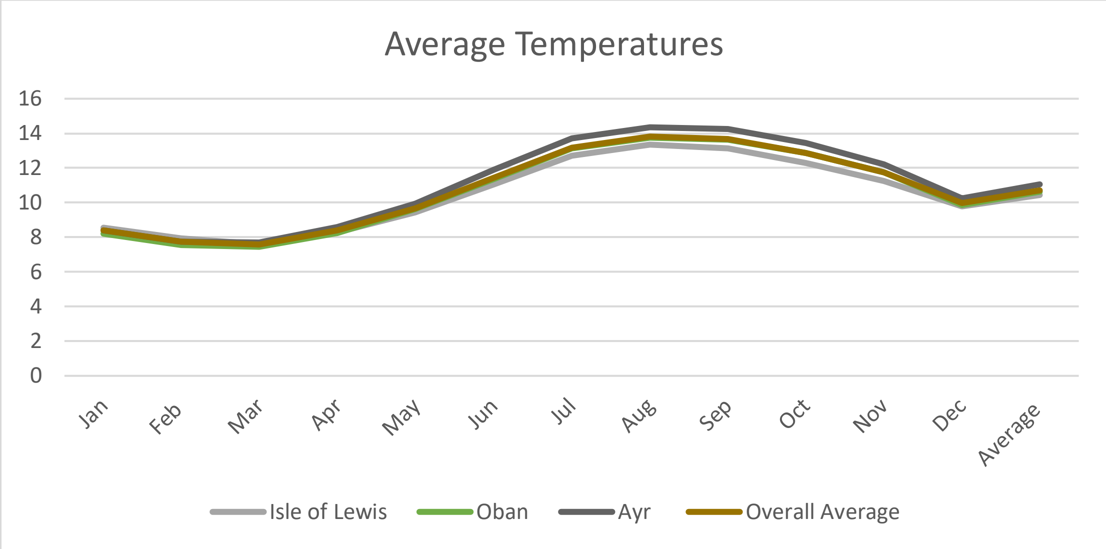

Figure 81: Graph of average temperatures for Isle of Lewis, Oban and Ayr (World Sea Temperatures, 2018)

Company	**Langsand Laks**[20]	**Fishion**	**Fishion**	**Traditional RAS'**[1]	**Open Aquaculture**
Species	Atlantic salmon	Hybrid African catfish	Tilapia	Tilapia	Various
Culture medium	Salt water	Fresh water	Fresh water	Fresh water	SW & FW
Grow-out weight range (kg)	0.125 to 4.5	0.12 to 1.4	0.12 to 0.8	0.12 to 0.8	Various
Grow-out time (months)		7 to 8	6 to 7	6 to 7	
Annual farm production capacity (live-weight t)	1,000[3]	1600	600		
Capital Investment (€ mill)	4.07[4]	2.5	2.5		
Max Biomass Density (kg/m^3)	85-100	>300	80		
Energy efficiency (kwh/kg)[2]	1.3 to 2.11	0.8	2 to 2.5		
Main pumps	0.97				
Other system pumps etc	0.25				
Cooling, denitrification, light, ventilation and other	0.89				
Water efficiency (l/kg)	250	20	25	300 to 500	3,000 to 30,000
Economic feed conversion efficiency	1.05 to 1.4	<1	<1		
Production cost (€/kg LWE)	3.1		1.4		

[1] Tilapia RAS without de-nitrification
[2] The energy efficiency of most industrial capture fisheries is typically >2.5 kwh/kg
[3] 700t production forecast in 2014
[4] $3.5 million private investment and $2million Government grant

Figure 82: Data for resource requirements for various recirculating aquaculture systems (HIE, 2016)

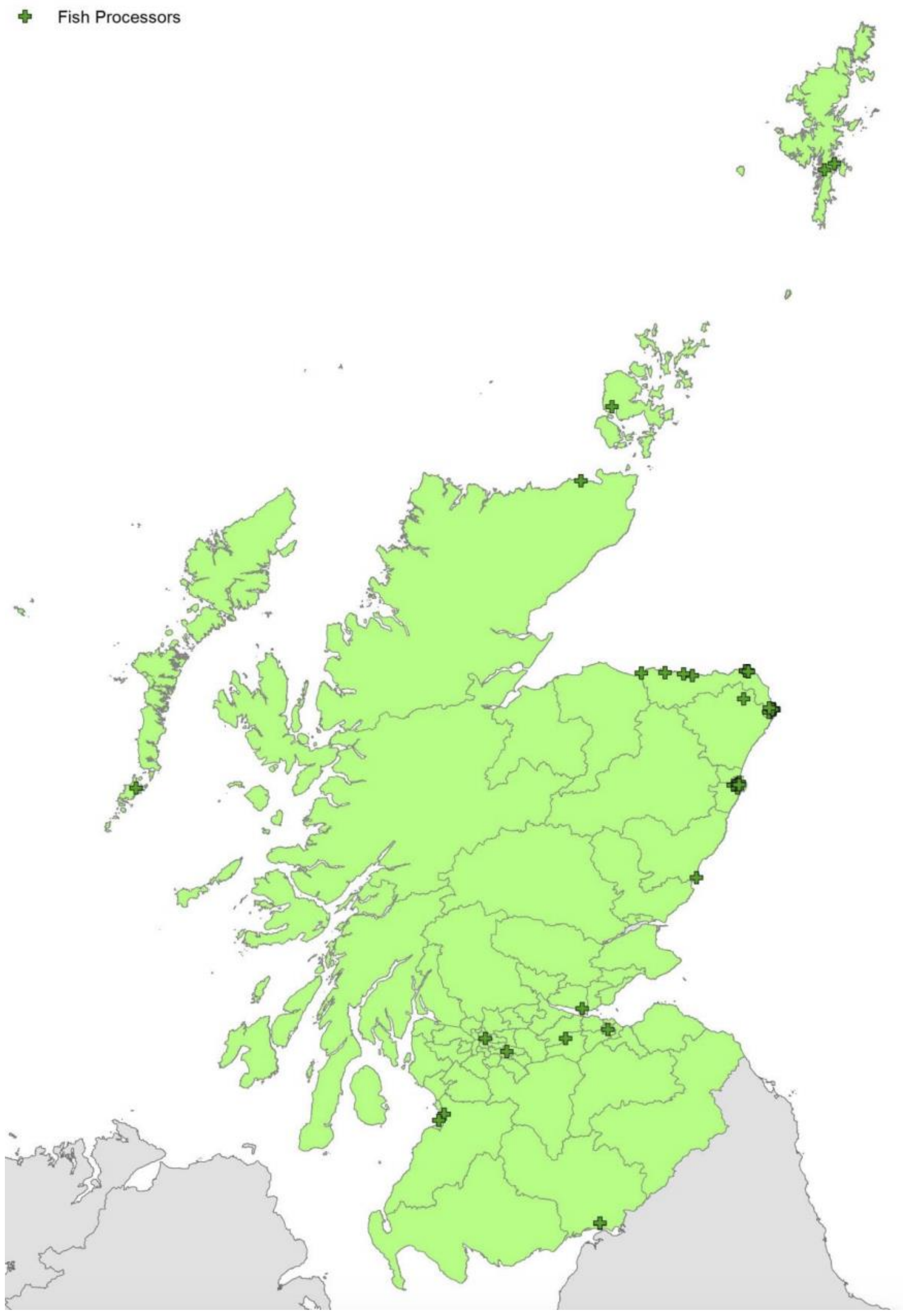

Figure 83: Map of Fish Processors in Scotland (Zero Waste Scotland, 2015)

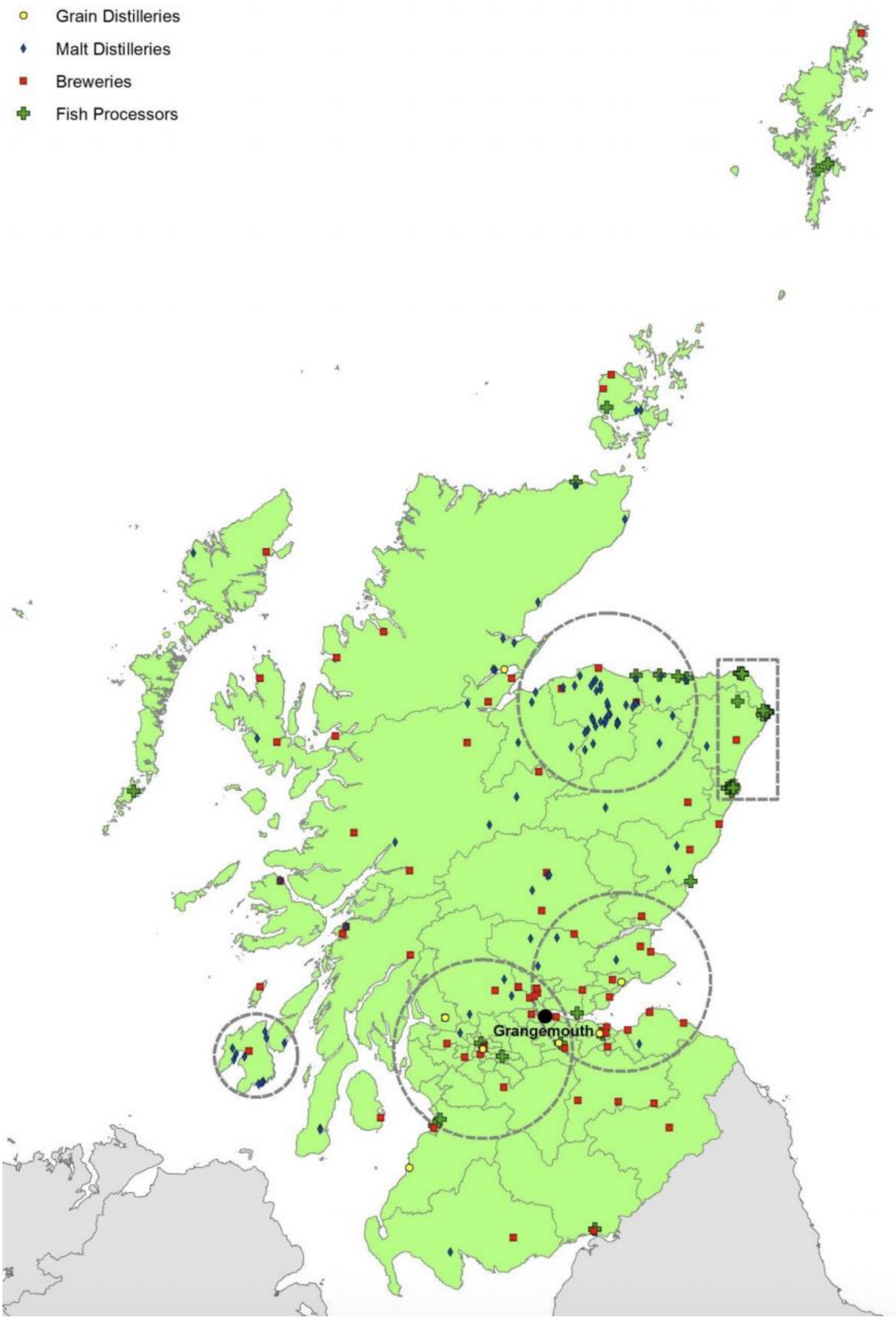

Figure 84: Map of Anaerobic Digester 'Hotspots' (Zero Waste Scotland, 2018)

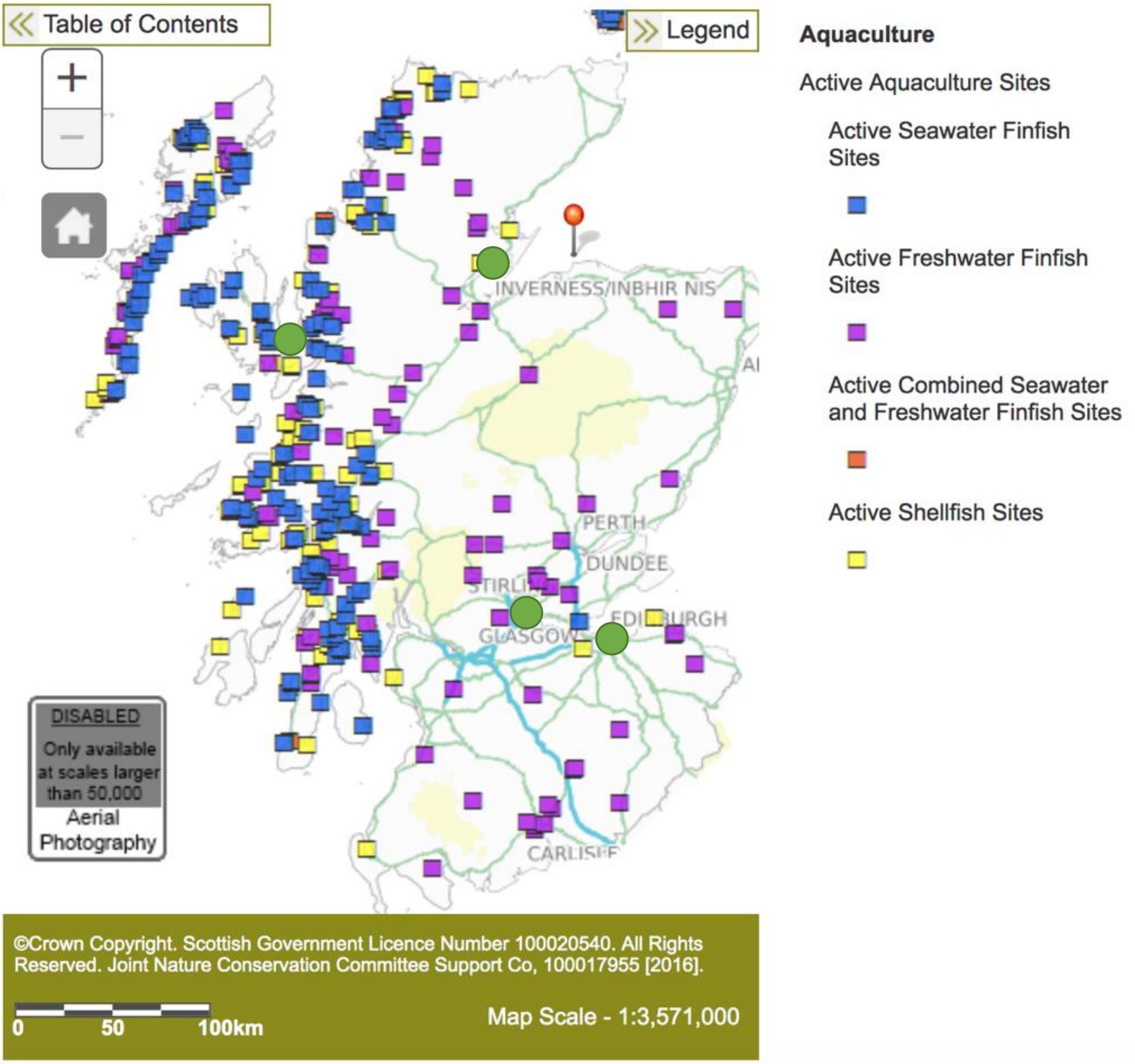

Figure 85: Map of fish feed production mills in Scotland