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Current status of recirculation aquaculture systems (RAS) and their profitability and competitiveness in the Baltic Sea area

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Abstract

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This report on recirculation aquaculture systems and their profitability and competitiveness in the Baltic Sea area is based on the process of HELCOM to renew recommendation for sustainable aquaculture in the region. Firstly, current status of RAS (recirculation aquaculture systems) sector especially in the Baltic Sea region but also in the global perspective is reviewed. Of the Baltic Sea countries, Denmark has been the pioneer of RAS farming and is also a strong player as a RAS technology developer and supplier. Denmark has invested in RAS farming R&D and the regulation includes incentives to adopt discharge abatement technologies.

In the second part, nutrient abatement technologies and typical nutrient discharges are presented and an overview of various RAS technologies is given. Depending on technological details, phosphorus and nitrogen discharges can be reduced by appr. 80-90 % in comparison to cage aquaculture. However, carbon footprint of RAS farming is much larger than in cage farming especially due to high electricity consumption of the RAS processes.

In the third part, RAS cost items are presented, whereafter both literature feasibility studies and RAS company accounting data are used in the economic analysis for discussion what can be considered as BAT in the Baltic Sea aquaculture. Based on the available data, the economic performance of RAS companies is much poorer than estimated in feasibility studies, where preconditions for RAS projects have been evaluated. Despite public subsidies for the investments, RAS farms are mostly heavily on red and several companies have terminated their activities or are bankrupt. Although large RAS projects are still being launched especially for Atlantic salmon smolt production but also to grow larger fish, it is questionable to argue that RAS farming is the best available technology for market size rainbow trout farming in the Baltic Sea countries.

Keywords: aquaculture, recirculation aquaculture systems, BAT, Best Available Technology, nutrient discharges, profitability, production costs

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1. Background

Recirculation Aquaculture Systems (RAS) sector is rapidly growing although still forming only a fraction of the global fish farming. It offers a more controlled and closed system in comparison to open aquaculture such as cage farming. RAS farming has pros and cons from the sustainability point of view, which will be discussed in more detail later in this report. From the Baltic Sea eutrofication point of view, RAS farming would offer better nutrient discharge control.

As a regional platform for environmental policy making HELCOM, The Baltic Marine Environment Protection Commission, prepares recommendations on environmental measures to various sectors and these recommendations are to be implemented by the HELCOM Contracting Parties through their national legislation. HELCOM CG Aquaculture is discussing what are Best Available Techniques (BAT) and Best Available Practices (BEP) for the Baltic Sea aquaculture. As a part of this process, The German Environment Agency commissioned a work by AquaBioTech Group to produce a background report including an overviewing report of aquaculture in the Baltic Sea region (Prescott et al. 2020). The report made proposals for BAT/BEP to avoid or minimize nutrient pollution from aquaculture, specifically discharge limits, waste management practices and fish feed composition. Due to extensive list of topics of the report, RAS technology as well as the status of commercial RAS farming was not discussed in detail. Therefore, Natural Resources Institute Finland (Luke) offered to prepare a working document on technology, environmental performance and economics of RAS for further discussions at HELCOM CG Aquaculture on what could be considered BAT in the Baltic Sea aquaculture.

In the current report, status of RAS sector especially in the Baltic Sea region but also in the global perspective is reviewed. Overview on RAS principles and discharge control technologies are presented. The third part of the report focuses on RAS economics. Typical cost items, feasibility studies on RAS profitability and available RAS company accounting data are presented. This publication present writers' opinions and is not a position of Finland HELCOM delegates.

The term RAS is commonly used for aquatic animal farming technologies, where a considerable part of water is re-used by utilizing processes to remove harmful substances from the water before re-use. At highest water recirculation intensities only evaporated water is added, while most commercial systems add more new water to maintain adequate water quality. Differences between RAS, partial RAS or water re-use systems stem from the water recirculation intensity, and these RAS technologies and definitions on water use intensity are described in more detail in Chapter 4.

The report focuses strictly on RAS and does not include information on the so-called closed containment systems (CCS). CCS concept consists of various forms of floating marine farms, where water is pumped from the depths into the farming closures. Closures can be made from PVC or similar liners, fiberglass, steel, metal mesh etc. CCS-farms are being developed to combat the sea lice problems especially in Norway, whereas they do not decrease discharges unless the concept is further developed into that direction. Sea lice does not survive in the Baltic Sea and is not therefore relevant for HELCOM contracting parties. Closed containment systems do not recirculate water, particle capture systems are seldomly included and discharges of dissolved nutrients cannot be well controlled. There are also massive land-based farms being built or planned in Norway. Some of them appear to use partial water recirculation, whereas some of them use flow-through. Efficacy of these land-based farms to mitigate nutrient discharges remains to be seen, and these technologies are not presented here, either.

2. Status of the global RAS sector

RAS sector is rapidly growing although still forming only a fraction of the global fish farming. Conventional salmon farming companies are investing hundreds of millions of euros to build RAS farms for salmon smolt production in especially in Norway, Scotland and Chile. By using RAS smolts, which can be grown larger than in conventional smolt farms, cage farming phase can be shortened which is beneficial for many reasons, not least to decrease the problems caused by sea lice. In addition to growing smolts to 150–200 grams, some companies produce so-called post smolts, which can be over 500 grams before transferring fish to the net cages. In addition to shorter production cycle, RAS is an essential tool to increase production volumes due to the shortage of fresh water supply in the smolt sector. In the context of this report, it should be noticed, that the ability to control nutrient discharges is not a strong driver in salmon smolt RAS development.

With some changes, similar RAS technologies employed in the smolt production can be used to grow salmon and large rainbow trout to the market size of appr. 3–5 kg. During the last couple of years, new RAS projects for market size fish have been published almost on a monthly basis (IntraFish 2018, Undercurrent News 2020). Planned land-based salmon projects would increase global salmon production by some 60% (app. 1.5 million tons), if full capacity will be achieved, and it would require over almost 20 billion € investments. However, several of these projects are still at very early planning phases and may not be realized. Uncertainties in global financial sector in 2022 may also slow down the growth of RAS sector. Figure 1, global RAS projects as of 2020 are summarized. EU perspective on RAS production has been recently reported by EUMOFA (2020).

Figure 1. Number of land-based salmon or large rainbow trout projects per country in 2020 (Undercurrent News, 2020).

3. Status of the RAS sector around the Baltic Sea countries

3.1. Denmark

Various forms of recirculation aquaculture have been developed in Denmark during several decades, and currently Danish production forms appr. half of the EU RAS production (EUMOFA 2020). Denmark was the European pioneer of rainbow trout farming and the sector dates more than a century back. Basic land-based farming technologies were employed until the first sea cage farms were established in 1956, and the cage farming increased more rapidly in 70’s and 80’s. Eel farming started to grow in the 80`s and many current Danish aquaculture technology companies have strong links to the eel sector, where experience in aeration, oxygenation, particle removal and biofiltration have been employed to save the water heating costs. Lately, the eel sector has decreased and currently produces mostly juveniles for restocking purposes.

During the 80’s and 90’s limited water availability stimulated the adoption of aeration and oxygenation systems in the land-based rainbow trout farming. Furthermore, the Danish licensing included early forms of incentives as farms were regulated by feed quotas instead of regulating the annual production. The next step towards more intense production was taken during 2010’s, when the concept “model fish farms” was developed as a collaboration between aquaculture companies, research and administration (Svendsen et al. 2008). From the regulation perspective, land-based farm regulation evolved to be discharge limited for those farms investing in the model fish farm technologies. By decreasing the nutrient discharges, farms were allowed to increase the production (Nielsen 2012). Currently, the use of “model farm” is being replaced by using the production size as a way to differentiate the different types of production (0–25 tons, 25–230 tons and above 230 tons).

The current trend in Danish RAS sector is that water use is getting more intense and to control discharges new technologies such as denitrifying woodchip reactor are being used (FEAP; Pless-Jesner, pers. comm.). This is due to the Danish discharge-based regulation, which encourages companies to increase the production by implementation more technology, so that increased revenues would cover the investments. In 2019 there were 118 traditional, 17 Model 1-type and 16 Model 3-type fish farms, and 19 cage farms in Denmark (Danmarks Statistik online data). Model 1- and 3-type farms differ in water use intensity, with type 1 farms using more water and thus not necessarily having need for biofiltration.

Until 2021, two indoor RAS farms producing market size Atlantic salmon existed in Denmark (e.g., Undercurrent News, 2020). Danish Salmon and Atlantic Sapphire, former Langsand Laks, both started operations in early 2010’s. Exact production volumes are not available in public, but the production volume is in the range of 1,000–2,000 tons based on revenues reported in financial statement analysis. Both of these companies have had periods of no production due to various technical reasons. In August 2021, fire caused massive damages at Atlantic Sapphire and the site will not be rebuild by the company. In addition to these two salmon RAS farms, one large salmon RAS farm is under construction in Skagen. One RAS farm produces market size pikeperch (AquaPri, company also having rainbow trout farming) and one RAS farm produces *Seriola* species for the European sushi markets (Sashimi Royal). Model fish farm type farms producing rainbow trout juveniles have also been constructed indoors, such as by FREA A/S. Some marine RAS-farms and a part of freshwater farms discharge to the North Sea or

Skagerrak, while a large portion of Danish aquaculture discharges to Limfjorden or Kattegat and one large marine RAS farm in Skagen will discharge to Kattegat.

3.2. Finland

First RAS farm in Finland started in the 90's as a hatchery for Arctic charr farming. Various RAS technologies such different biofilter configurations have been tested and developed at the site, and it currently serves as juvenile production site for Nordic Trout until 2023, when it will be closed down due to municipality use of the well water. During 2010's, several RAS farms were constructed with a total of 11 RAS farms in operation at the peak. However, five of them are either in bankruptcy or have ended the operation (Table 1). In addition to these farms, two companies have received environmental licenses: one to produce rainbow trout juveniles for cage farming (RAS Fish Oy; 100–150 tn production target, under construction) and the other to produce market size salmonids in larger quantity (HTM-Yhtiöt; 3,000 tn production target).

3.3. Sweden

So far, Sweden has no commercial scale RAS farms, but there are several plans for very large scale commercial operations. The most concrete project is located at Åre, where company Cold Lake AB has received environmental permit in 2019 for some 4,000 tn capacity of Arctic charr farming. However, only preliminary earth constructions for the facilities has started to date. Smögenlax has been given a permit for 6 000 tn salmon production in Sotenäs. There is also another, gigantic 40,000 tons Atlantic salmon project launched in Sotenäs by a company Quality Salmon. The environmental permit for the farm is being processed. Premium Svensk Lax AB has started earth constructions of 10,000 tn RAS farm in Säffle. In addition, Hushållningssällskapet is preparing an environmental permit application for 10,000-ton RAS for arctic char production in Luleå. Finally, company Big Akwa is planning 3,000 tn rainbow trout farm in collaboration with SCA paper in Härnösand. (Data from the web and per comm. by Erik Olofsson).

Several smaller projects include e.g., Ljusterö Lax o Gös AB, which is a pilot farm collaborating with universities and producing some 5–8 tons of pikeperch per annum. Johannas Stadsodlingar AB was founded in 2018 and mainly aiming at aquaponics production. It has received R&D funding but may not be at production, yet. Cibum Sverige AB started environmental permitting process at Ljusdal but the process has been terminated. OmegaFish i Malmö AB was founded in 2018 with no activities so far. Hamra Fisk AB has started small scale farming and bigger facilities were supposed to be finished by 2020. (Data from the web and pers. comm. by Alf-Håkan Romar).

Table 1. Finnish RAS companies. Size of the operations is an estimation and based on public financial statements, environmental licenses and news.

Company	Production	Status
Nordic Trout (Myrskylä)	Established in 1998 and new RAS built in 2005 by former company Myrskylän hautomo, currently producing rainbow trout juveniles < 50 tons	In operation
Imatran Kala ja Kaviaari	Farming at pulp mill area started in 2002. Pilot system with 10–50 tn production of mostly sturgeon and pikeperch.	Production ended in 2015
Savo Lax (Rautalampi)	Farming started in 2010. European whitefish and rainbow trout juveniles appr. 100 tons.	In operation
Finnforel (Huutokoski)	Established in 2010 by company Huutokosken Arvokala. Currently rainbow trout juveniles for Finnforel Varkaus site appr. 100 tons.	In operation
Polar Fish	Traditional farm converted to RAS in 2010. Arctic charr 50–100 tons.	In operation
Carelian Caviar (Varkaus)	Farming at the pulp and paper mill area started in 2010. Caviar (and sturgeon) production.	Production ended in 2021
Kuhina (Imatra)	Farming at landfill site (using landfill methane for energy) started in 2011. Pikeperch 50–100 tons.	Bankruptcy 2016
Caviar Empirik (Ilomantsi)	First sturgeon in 2011, no production estimate.	Production ended in 2013
Sybimar	Farming started in 2011. European whitefish and rainbow trout 100–200 tons. Connected to biogas plant and small greenhouse.	Production ended in 2021
Fifax (Eckerö Åland Islands)	Farming started in 2016. Nominal capacity appr. 3 milj kg of 2–3 kg rainbow trout, production few hundreds of tons.	In operation
Finnforel (Varkaus)	Farming started in 2017. Production appr. 800–1,000 tons.	In operation, permit to increase the capacity to appr. 2,500 tons

3.4. Germany

In 2020, there were at least 53 RAS farms (> 90% reuse of water) in commercial operation in Germany, producing at least 2,625 tn of fish and seafood including over 10 species. Both the number of systems as well as production are likely to be underestimated, as for data protection reasons, in case of small numbers of farms per state (as statistical unit), data are not reported. In addition, there is a number of farms producing salmonids, mostly rainbow trout, with partial recirculation. As of writing this report, information on those farms in the drainage area of the Baltic Sea is lacking.

3.5. Other countries in the Baltic Sea drainage area

In Poland, RAS production was app. 2,000 tn in 2018 (EUMOFA 2020). In the Baltic coastline, Jurassic Salmon started RAS production of market size salmon in 2013. Based on the public revenue information, the production is appr. 500 tn. Aqua Maof, an Israeli RAS tech company purchased a tilapia RAS farm near Warsaw and converted it into salmon RAS, farming few hundred tons of Atlantic salmon to develop the technologies for Aqua Maof's bigger projects globally. There are also few model fish farm-type RAS operations in Poland.

In Estonia, three RAS-farms operate at Saaremaa (Ösel Harvest OÜ, rainbow trout; Aquamyk OÜ, rainbow trout but currently empty; Conversio Design OÜ, rainbow trout) and four RAS-farms at the continental Estonia (Jaesto OÜ, sturgeon; Lapavira OÜ, sturgeon; BM Trade OÜ, eel; For Angula OÜ, eel). In 2018, Estonian RAS production was 160 tn according to EUMOFA (2020), whereas in 2020 it was around 209 tn based on annual Estonian permit reporting. The emission from five RAS farms in 2020 were around 11 tn on nitrogen and 1 tn of phosphorus per year. Two previously mentioned RAS operations have previously gone through bankruptcy but have started operation in 2021 by new owners. (Katrina Lang, pers.comm.).

According to EUMOFA (2020), in 2018 Latvian RAS production was 80 tn, whereafter at least one Arctic charr RAS-farm, constructed by Finnish Clewer Aquaculture, started operations in Latvia in 2020. Lithuania produces appr. 350–400 tn in RAS (EUMOFA 2020). In the North-West Russia, Republic of Karelia, company ZAO Virta has produced rainbow trout juveniles appr. 100 200 tn per year in RAS. Belarus has few RAS operations producing rainbow trout and sturgeon. The size of these operations is at maximum few tens of tons per farm.

4. RAS technologies and the environmental performance of RAS farms

4.1. Basics of RAS water treatment

In this chapter, typical RAS water treatment steps are introduced. The technologies vary and especially intensity of water use defines what treatment steps and technologies are employed. The information is based on numerous scientific articles and on the most comprehensive handbook on RAS technology by Timmons & Ebeling (2018).

Good RAS water quality and efficient discharge control starts with properly designed fish tank. Tanks can be round, hexa-/octagonal or raceway-type. Round or octagonal tanks can have so called dual drains, where main water outflow is from the tanks side wall, located at the water surface level, whereas smaller part of the outflow is from the bottom of the tank. The latter flow has high solids and phosphorus contents, and this sludge flow is directed to further treatment. In raceways, solids are removed by sludge cones usually located at the end of the raceway.

The main water flow from the fish tanks goes through a mechanical filter, typically a drum filter, which removes particles larger than appr. 30–50 µm. In drum filters, particles are trapped inside of the rotating drum and directed to a backwash area and transported out of the filter to sludge thickening units.

Typically, particle removal is followed by biofilter. Biofilter uses a nitrification process, where bacteria transform toxic ammonia first into nitrite, still very toxic to fish and finally to nitrate. Nitrate is tolerated at much higher concentrations than ammonia and nitrite. Numerous different biofilter designs exists, but they all have a carrier media where the nitrifying bacteria form a biofilm. So-called fixed bed filters have carrier media which is not moving. Fixed bed filter can further remove fine particle, whereas moving bed filters do not trap fine particles. On the other hand, moving beds aid in carbon dioxide removal and add some oxygen. Nitrification process consumes alkalinity, the capacity to buffer against pH changes and therefore, alkaline chemicals such as lime or caustic soda are added to maintain pH at appr. 6.5–7.2. Biofilters are essential for fish welfare, whereas they have less impact on nutrient discharge reduction.

Both fish and the biofilter microbiota produce carbon dioxide, which would accumulate in RAS at harmful and toxic levels without removal. CO_2 removal is called degassing, aeration or stripping and can be done both in the fish tanks and/or as a separate step before the water flows back to the tanks. Aeration can be done by pumping air into the water, or by pumping water in the air, and several technical principles can be applied in the design. Aeration process has practically no direct effect on nutrient discharge control.

When leaving the fish tank, O_2 saturation level in the water is typically appr. 70% and the level is further reduced in the biofilter. Aeration can bring the saturation level up to appr. 90%, but due to the intensity of RAS production, supersaturated O_2 levels are used in the tank inflow water. Oxygen can be added at high pressure in oxygen cones or under lower pressure using systems such as low-head oxygenators. The oxygen cones use more energy (electricity) than low-head oxygenators.

Ozone treatment removes organics and improves microbial water quality and is often but not always included in the water treatment. Typically, ozone treatment is followed by UV, which brakes down possibly remaining ozone harmful for fish. The RAS water treatment processes described above are illustrated in Figure 2.

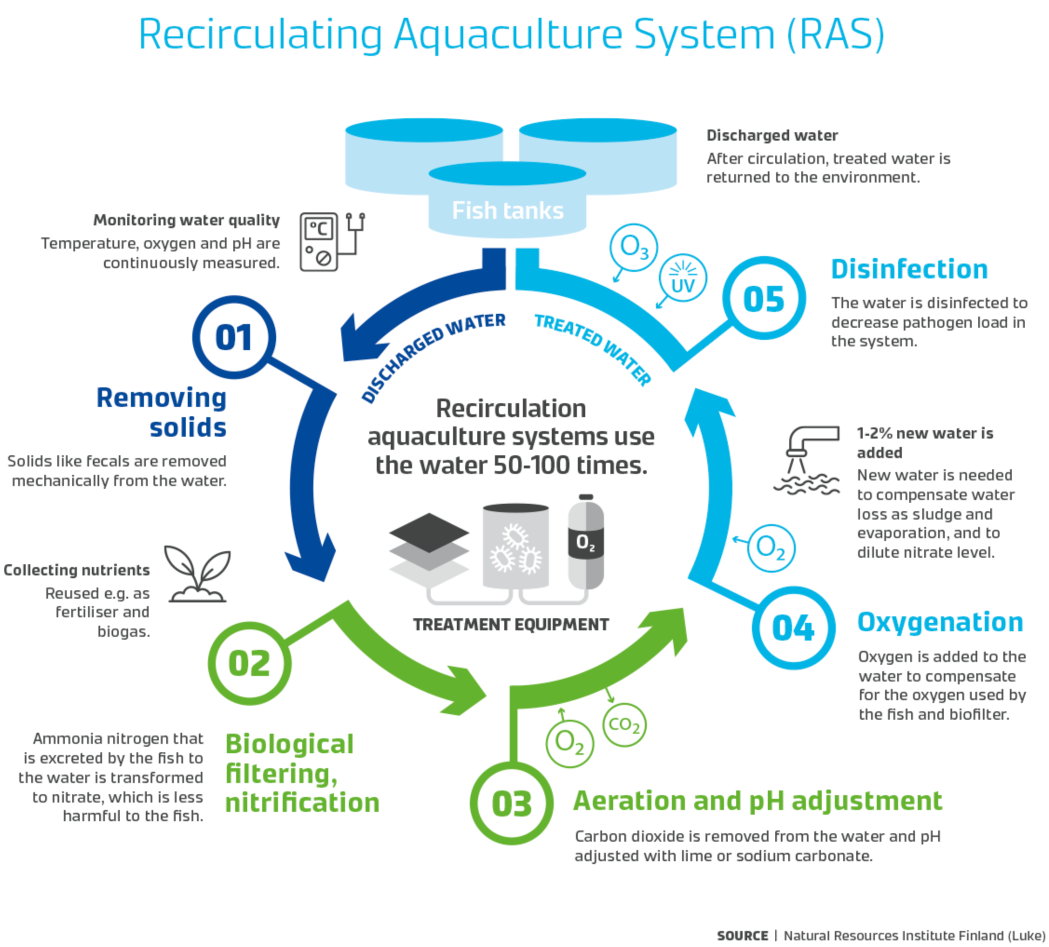

Figure 2. Typical water treatment steps of a RAS farm.

As noted above, typically RAS has two primary water flows. A smaller volume consists of sludge originating from sedimentation systems, particle filtration and biofilter backflush and has high percentage of phosphorus and organic matter. A larger volume of water has lower solids level but contains most of the nitrogen discharge. These two streams, “sludge” and “overflow” are typically processed separately to reduce RAS nutrient discharges.

Sludge is further concentrated by sedimentation or filtration processes, typically with the aid of chemicals. RAS farm can have a sedimentation basin or pond, where sludge and pH stabilizing chemicals are combined. Sludge basin is frequently emptied and used as a fertilizer in field or taken to a biogas plant. In most intense RAS farms, sludge thickening process is carried out at an indoor system. Typical municipal coagulants and flocculants are mixed with the sludge, whereafter concentrated sludge is separated by belt filters, flotation or screws. Depending on the regulation, overflow of sedimentation pond or sludge coagulation can be discharged without further treatment or led to a nitrate discharge treatment. In the Danish model fish farm concept, the larger water flow and sludge overflows are led to constructed wetlands and/or woodchip reactors, which are efficient at nitrogen removal. Nitrogen discharges can also be reduced in compact denitrification reactors with external carbon source to drive the process.

Water recirculation percentage has been used to describe water use intensity, but more exact way would be to calculate volume of new water per amount of feed fed to fish. In typical RAS farms, appr. 500–1,000 liters of new water is used per kg feed used. Danish model farms are less intense, using some 3,000–5,000 l/kg. The very intense zero-exchange RAS replaces only the water lost through sludge and evaporation, and water use can be down to 50–100 l/kg (Figure 3). 100 liters per kg feed would be appr. 99.9%, 1,000 liters/kg would be appr. 99.0%, and 10,000 liters/kg would be appr. 90% water recirculation rate.

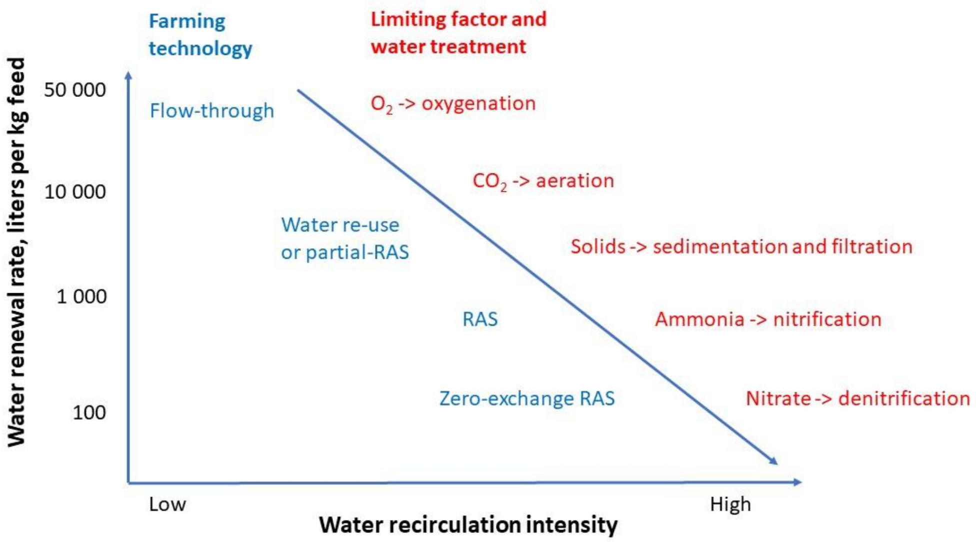

Figure 3. Water use intensity, limiting water quality parameters and applied water treatment technologies in RAS farming.

4.2. Environmental performance

Nutrient discharges of RAS farms vastly depend on selected technologies. Water use intensity plays an important role in the nutrient capture efficiency: the more intense the water use is, the higher are the concentrations of nutrients in the water and sludge streams, which enables higher nutrient reductions. In Table 2, nitrogen and phosphorus discharge estimates for cage farming, Danish model fish farming and intense RAS are provided. It should also be noted that the division between different model fish farm generations is not in use anymore in Denmark. Since particle-bound phosphorus is more easily removed than soluble nitrogen, reduction efficiencies are typically better for phosphorus. Model fish farm data by Jokumsen and Svendsen (2010) is probably outdated and Danish model fish farms currently have higher nitrogen removal percentages, due to the increasingly common denitrifying woodchip reactors. This data could be available, but as of writing this report, we have not received information to provide estimates on the current discharge treatment efficacies. Nutrient reduction efficiencies at intense indoor RAS can vary considerably. At some farms, RAS discharge is led to municipal or industrial wastewater treatment units, where nutrient reduction efficiencies can be above 90%. However, performance data of such systems cannot be found in public.

Table 2. Typical phosphorus and nitrogen discharge estimates for cage farming, Danish model fish farming and intense RAS. Discharge reduction efficiencies are compared to cage operations. Data sources are provided in footnotes.

	Cage farming [1]	Model fish farm 3[2]	Intense RAS[3]
P, kg/tn production	4–5		
Reduction, %		76	70–90
N, kg/tn production	35–40		
Reduction, %		50	30–90

[1]Data from the regional authority statistics (Centre for Economic Development, Transport and the Environment, Southwest Finland)
[2]Jokumsen and Svendsen (2010)
[3)] Estimate based on various sources

Fish sludge captured in RAS has nutrients with value outside the aquaculture value chain, agriculture as the most apparent example. However, the term “sludge” has become problematic from the regulation point of view, since it equates this valuable RAS side-stream to municipal sludge, which is strictly regulated due to obvious potential health hazards. Using term “fish manure” would allow less strict regulation of RAS nutrients re-use. Recently, Federation of European Aquaculture Producers (FEAP) has brought this dilemma up in discussion with the EU Commission (FEAP, Pless-Jesner, pers. comm.).

CO_2 emissions (carbon footprint) are higher in RAS production compared to flow-through and cage farming operations. This is due to energy intense technologies, especially water pumping, temperature control of the water and building, and other technologies. Few carbon footprint estimates for RAS production are available, and the values depend on system borders and allocations, as well as details of the RAS design such as water lifting heights and local climate. Furthermore, the country of production and consumption of the fish makes a large difference. Liu et al. (2016) compared carbon footprint of salmon consumed in USA, either produced in RAS in US or produced in cages in Norway and transported by air freight to US. At producers’ gate, carbon footprint of salmon in Norway is half of that compared to RAS salmon using average fossil fuel based electricity. This is due to energy intense processes in RAS farms. However, carbon footprint of RAS salmon produced and delivered in US was less than half of that for salmon produced in traditional open net pen systems in Norway and delivered to the US by air freight. In that study, the most climate friendly alternative of US salmon consumption is to ship frozen salmon from Norway with a modern container ship to US. However, frozen product is not directly comparable with a fresh fish, since they have partially different uses in the markets (Liu et al. 2016).

5. Cost structure of RAS farming

In this chapter, most important cost items of RAS operation are presented. The data is from feasibility studies, which have been used at a general level to evaluate the potential of RAS sector, for business case evaluation, and to analyze the importance of single cost items for further improvements by research and development.

Investments include land property, buildings, tanks, water treatment systems, automation, measurement and feeding systems, possible processing facilities and several other items. Investments range from appr. 10 to over 20 euros per kg estimated yearly production. Various investments have different true depreciation times, ranging between 5 to 30 years, and interest rates vary.

Feed is usually the main variable cost factor. RAS feeds should not contain certain feed ingredients such as regular soybean meal causing loose fecal material and are therefore few percentages more expensive than feeds for open system farming. The price of fingerlings becomes relevant factor for profitability especially in the production of portion size fish where the market size of fish is small. The larger the fish are farmed, the less significant becomes the fingerling purchasing cost, because less fingerlings are needed for producing the same tonnage. Other variable costs consist of electricity, oxygen, and pH control and sludge thickening chemicals, cleaning chemicals, laboratory systems etc. In comparison to open system farming, RAS production is more labour intensive and requires more maintenance work and repairs.

Insurance can become a fairly large cost factor due to higher technological risks compared to open system farming. Licensing costs are typically related to the size of operation. In Norway, RAS licences are free whereas cage farming licenses have very high prices. Transport and administration costs are similar between traditional and RAS farming. However, for oversea markets, local RAS production can avoid high air cargo costs (Liu et al. 2016).

Bio-economical productivity factors, especially growth rate, mortality and feed efficiency influence the efficiency of production and thus costs. In some feasibility studies, variation on these parameters is included as sensitivity analysis.

Tables 3–5 present cost structures for various RAS cases. The products vary from live rainbow trout juveniles to heads on gutted large salmon. In Table 3, production costs for large salmon are estimated within the range €3.5–5.0 per kg (HGO, head on gutted). Marttinen (2020) built a real-case scenario for juvenile production RAS, which would be located in the coastal city of Kaskinen, Finland (Table 4). Higher cost of over €6 per kg live fish can be partially explained by the necessary vaccination and by the production cycle of rainbow trout for further on-growing. Due to spiking summer temperatures and freezing winter conditions, fish can be transferred to the sea only during the Spring months and for second time in the Autumn. This leads to uneven biomass at the farm and therefore more inefficient use of investments, since RAS systems need to be dimensioned according to the peak feeding. Furthermore, Marttinen (2020) included several cost items often neglected in feasibility calculations, such as property tax and energy costs of other activities than water pumping. Finally, Table 5 presents three other cases for rainbow trout production in RAS in Finland (2 kg HOG, 500 g HOG and 500 g for further ongrowing in sea cages.

Table 3. Production cost structure estimates for RAS farming of 4–5 kg Atlantic salmon.

	Summerfelt et al. (2013), USA	Warrer-Hansen (2015), Ireland	Liu et al. (2016), USA	Bjørndal and Tusvik (2017), Norway
Feed	€2.08 / 59%	€1.52 / 42%	€1.71 / 34%	€1.58 / 42%
Eggs or juveniles	€0.1 / 3%	€0.26 / 7%	€0.11 / 2%	€0.03 / 1%
Electricity	€0.25 / 7%	€0.24 / 7%	€0.3 / 6%	-
Personnel	€0.28 / 8%	€0.08 / 2%	€0.47 / 9%	€0.23 / 6%
Oxygen	€0.16 / 5%	€0.08 / 2%	€0.13 / 3%	-
Chemicals	-	€0.1 / 3%	€0.08 / 2%	-
Fish health	-	€0.03 / 1%	-	€0.04 / 1%
Insurance	-	€0.07 / 2%	€0.16 / 3%	€0.08 / 2%
Maintenance	-	€0.02 / 1%	€0.42 / 8%	-
Administration	€0.08 / 2%	€0.05 / 1%	-	€0.08 / 2%
Other	-	€0.1 / 3%	€0.55 / 11%	€1.11 / 29%
Depreciation	€0.57 / 16%	€0.44 / 12%	€0.52 / 10%	€0.65 / 17%
Interests	-	€0.62 / 17%	€0.58 / 12%	-
Production cost, €/kg	€3.52 / 100%	€3.61 / 100%	€5,04 / 100%	€3.79 / 100%

Table 4. Cost structure for RAS production of rainbow trout growing from eggs to 360 g fish for further cage farming (from Marttinen 2020). Investment subsidy 40% is assumed.

	€/kg live fish
Eggs	€0.128 / 2%
Feed	€1.522 / 24%
Electricity	€0.739 / 12%
Personnel	€0.721 / 12%
Oxygen	€0.222 / 4%
Chemicals	€0.356 / 6%
Vaccination	€0.440 / 7%
Insurance	€0.080 / 1%
Maintenance	€0.200 / 3%
Waste disposal	€0,060 / 1%
Property tax	€0.042 / 1%
Depreciation, 20 yrs	€0.875 / 14%
Interests, 5%	€0.875 / 14%
Production cost, €/kg	**6.260/ 100%**

Table 5. Cost structure for three RAS cases in Finland. Data from Vielma et al. (2006), Kankainen et al. (2014) and Sinisalo et al. (2020). For portion size and juvenile cases, energy costs are included in other operating expenses.

	Large rainbow trout	Portion size rain-bow trout	Rainbow trout juvenile for cage farming
Feed	1.21	1.41	1.21
Eggs/fingerlings	0.35	0.74	0.13
Other operating expenses	0.22	0.7	1.01
Personnel	0.68	0.47	0.7
Depreciation	0.98	0.76	1.13
Subsidy impact	0.32	0.33	0.75
Other expenses	0.22	0.18	0.70
Energy	0.57		
Financial expenses	0.18	0.19	0.26
Production cost, €/kg (present value)	**4.73 (5.76)**	**4.80 (4.96)**	**5.98 (5.98)**

6. Economic performance of existing RAS farms in the Baltic Sea area

This section compiles information on economic performance of existing RAS farms in the Baltic Sea area, especially in Denmark and Finland, where such data is publicly available.

Statistics Denmark presents yearly summaries on the production and economics of all types of aquaculture companies. Data on traditional pond farms, model fish farms and cage farms are presented in the publicly available databases. Second part of the economic performance evaluation contains publicly available single company financial statements from Denmark and Finland.

In Picture 4, revenue and net margin of traditional pond farms, model fish farms and cage farms in Denmark during 2016–2019 is presented. In 2019, combined revenues of the traditional pond and cage farming was 123 million euros, while that of model fish farms was 57 million euros. Combined net result for the traditional farming was 11 million euros, whereas net result for model farms was 1.3 million euros loss.

For Finland, revenue and net margin of traditional juvenile production, raceway and pond production of large consumer size fish, cage farms and RAS farms during 2016–2020 is presented in Picture 5. The vastly different net results of cage and RAS farms is apparent. Financial analysis of Finnish RAS farms follows in the next chapter.

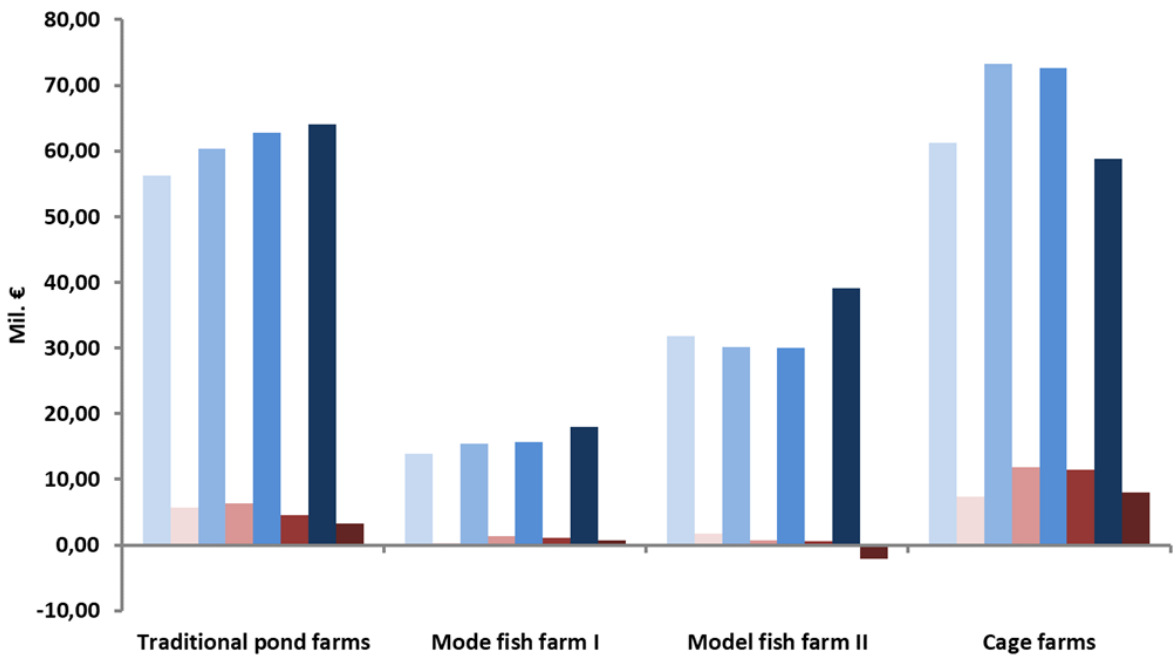

Figure 4. Revenue (blue bars) and netmargin (red bars) of traditional pond farms, model fish farms and cage farms in Denmark from 2016 (on the left) to 2019 (on the right). Data from Danmarks Statistik, www.dst.dk.

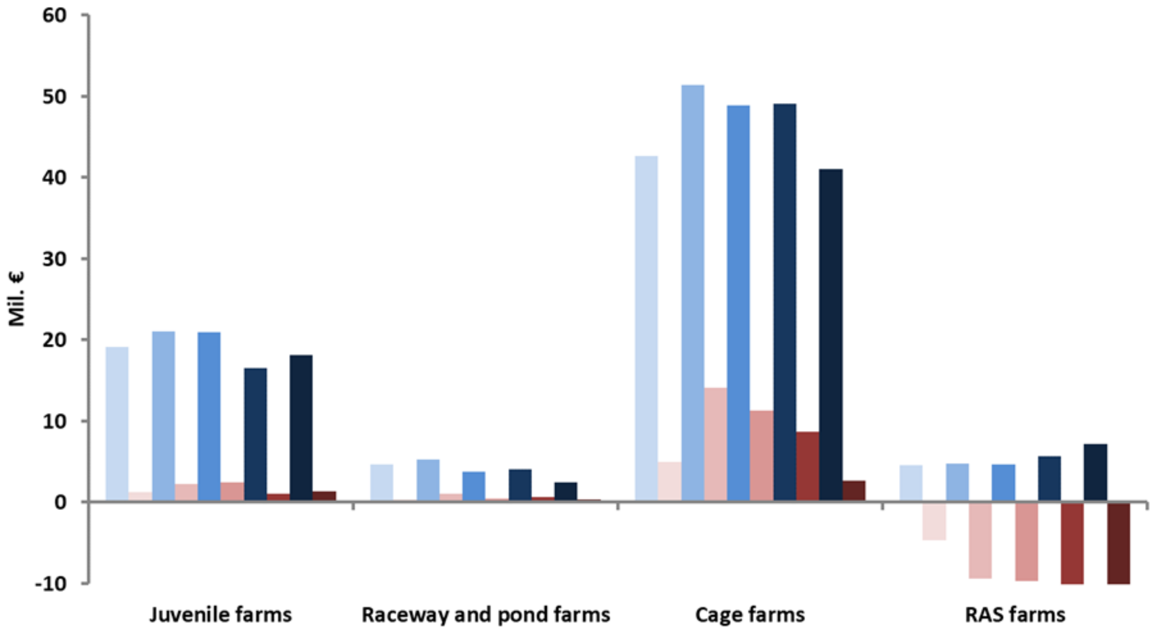

Figure 5. Revenue (blue bars) and net margin (red bars) of Finnish juvenile farms, inland raceway farms, Baltic Sea cage farms and RAS farms from 2016 (on the left) to 2020 (on the right; Kärnä et al. 2018, 2019 and 2020). Values for 2020 are preliminary.

7. Financial statement analysis

Financial statement analysis shows cost structure of true business operations. Table 6 contains financial statements of several RAS companies in Finland, while Table 7 and 8 contain net results from Finnish and Danish RAS farms. The information is available in public databases. In the following, we discuss what costs are included in each cost category and how that particular cost category is reflected in the economic performance.

Turnover of the investigated RAS farms have been lower than expected. The reasons are not detailed in the financial statements, but from publicly available sources such as news and seminars it is apparent that production target has not always been achieved due to unexpected mortalities or some other reasons.

Purchasing costs include material and services that are needed to run the operations. In RAS, this category consists of e.g., feed, electricity, oxygen, chemicals and eggs/fingerlings. At some farms purchasing costs exceed the turnover and can be as much as three times higher than the revenue.

Variation in stock or inventory change should be taken into account if a company is increasing its fish biomass with same material and other expenses. In the long run, this cost category's impact on profit should be of fairly low importance.

External services in RAS may include e.g., sludge treatment and logistics, water treatment by external service providers, and maintenance services. Parent company interventions can also be included as external services. In some companies, external services such as various maintenance and technical work tasks are high, which could be explained by "service interventions" by other related companies.

At the investigated companies, **personnel costs** are high compared to turnover, and can make over 40% of the income at some companies but has been as high as than 2.5 times the turnover.

Investment deprecation is the share of investment value that is annually decreased from the profit account, thus showing the cost impact of investment without interest. Deprecation periods vary between items. The rule of thumb is that investment's value should be decreased to zero during its operational lifetime. Real estates such as land for RAS farm normally have long deprecation periods of e.g., 20 years, buildings and robust construction items such as fish tanks 10 years and more sensitive technologies such as pumps, sensors, ozone generators etc. 5 years. In the accounting, company can to certain extent adjust how much it decreases the value of investments.

Subsidy can impact the investment deprecation, if public subsidies are included in the balance sheet by decreasing the value of investment. Role of subsidies is further discussed in the next chapter.

Other operating expenses include costs such as marketing, management, rents and agreements, energy costs and licenses. Thus this category can include costs that vary with the production volume but mainly these costs have fixed character. Feasibility studies show that the energy cost in RAS can be a significant factor.

Financial expenses depend mainly on the interest rate and the deprecation period. With long depreciation period yearly deprecation is small but financial expenses large. For years, interest rates have been low, but have lately increased due to uncertainties in international economics and politics. If a company wants to improve the short term profit, it can delay the investment deprecation period. If company uses own equity in investments, the cost of interest is lower. Obviously, production volume has a significant effect as the dominator of the financial expenses.

Profitability can be examined at different levels of the financial statement. Gross margin determines whether turnover covers material costs. In almost all Finnish RAS farms material costs exceed the loss level. If further variable costs such as energy is added to this cost category, it can be argued that each produced fish increases the loss in these RAS systems.

Operational profit should cover all costs for the operational business when loans are paid. Therefore, in case of negative result there is no tax to pay for the community nor for the shareholders from **Profit before taxes**.

Regarding the two existing companies producing rainbow trout for the consumer markets, financial statements indicate that calculated production cost are still 3–7 times higher than the market price. Two Finnish RAS companies have had a profitable year. These companies specialize in the production of high value species such as Arctic charr and European whitefish.

Table 6. Financial statements of three RAS companies in Finland. Two of them are producing rainbow trout for consumer markets while one is producing higher valued species for consumer markets. Negative financial results are shown in red font.

RAS company	Company A		Company B			Company C			
Year	2018	2019	2018	2019	2020	2017/16	2018/17	2019/18	2020/19
Turnover	1 181 536	2 660 584	332 271	701 211	1 241 616	864 024	1 066 196	972 566	728 435
Other income	25 802	35 703		17 014		234	19 599	202 970	137 139
Material costs									
Purchasing	-1 686 548	-2 419 766	-2 237 184	-2 745 302	-3 022 823	-367 827	-430 503	-370 035	-291 253
Variation in stocks	92 091	-176 618	398 333	555 542	-256 019	59 284	13 354	-197 911	62 630
External services	-965 196	-860 150	-22 351	-41 547	-76 597	-23 246	-13 359	-43 171	-28 649
Personnel costs	-567 486	-1 008 216	-919 782	-1 012 745	-1 381 398	-214 277	-244 456	-243 532	-226 200
Investment depreciation	-511 591	-702 917	-819 688	-1 004 013	-1 150 420	-55 349	-53 964	-59 666	-60 301
Other operating expenses	-1 531 957	-1 758 400	-2 071 441	-2 757 949	-2 644 635	-237 080	-252 941	-264 133	-277 522
Operating profit/loss	**-3 963 349**	**-4 229 780**	**-5 339 842**	**-6 287 789**	**-7 290 276**	**25 763**	**103 926**	**-2 912**	**44 279**
Financial expenses	-187 337	-281 788	-734 452	-750 833	-1 104 710	-65 830	-81 379	-75 266	-70 179
Profit (before apropriation and taxes)	**-4 150 686**	**-4 511 568**	**-6 074 294**	**-7 038 622**	**-8 394 986**	**-40 067**	**22 547**	**-78 178**	**-25 900**
Total Costs (TC)	-5 358 024	-7 207 855	-6 406 565	-7 756 847	-9 636 602	-904 325	-1 063 248	-1 253 714	-891 474

Table 7. Net results of Finnish RAS companies based on financial statements. Negative results are shown in red fonts.

Company	2011	2012	2013	2014	2015	2016	2017	2018	2019
A	-602 000	-1 246 000	-954 000	-1 085 000	-648 000	-589 221	-663 672	-462 000	-844 000
B	-242 118	-769 555	-218 297	-219 728	-947 000	192 000			
C	-85 000	-265 000	-350 000	-86 700	-10 000				
D	-193 000	-230 000	-282 000	-179 000	-122 000	-121 000	-40 000	23 000	-78 000
E	-406 000	-382 000	-322 000	-649 000	-1 176 000	-594 205	-1 300 000	-273 000	-1 017 000
F			-35 000	-327 000	-492 000	-3 080 000	-4 425 000	-6 088 959	-7 038 633
G					-11 000	-57 000	-393 000	-2 985 287	-4 532 691
H							199	99	123

Table 8. Table 8. Net results of Danish RAS companies based on financial statements. Negative results are shown in red fonts.

Company	2011	2012	2013	2014	2015	2016	2017	2018	2019
A	-111 990	-270 437	-842 086	-2 123 173	-1 123 506	-1 565 925	-2 535 479	-2 800 748	-5 550 843
B		-36 568	-134 401	-1 948 191	-3 700 042	-1 527 215	-426 365	17 906	-336 015
C			-4	-13 798	218 699	453 778	1 167 467	1 954 025	1 321 458
D						-116 988	-277 874	-1 686 555	-1 296 091
E				-141 948	-752 275	-485 235	-608 972	-1 020 268	-629 887

8. Discussion

8.1. General

The major observation of this report and of utmost importance for the HELCOM BAT discussion is, that economic performance of RAS companies is much poorer than estimated in feasibility studies. Despite the European Maritime and Fisheries Fund support for the investments, RAS farms are heavily on red and several have terminated their activities or are bankrupt. The only form of RAS production, which systemically seems to be able to have positive net results, is the Danish model fish farming. Subsidies vary between countries and individual business cases but are likely around 20–40% of the investment.

There are several potential reasons behind the economic losses. To our best knowledge, the main reason is that RAS farms have not reached the nominal production capacity used in the business planning phase. Causes of lower production are manyfold, and include faults in the technical design, unexpected technical failures of critical systems, inadequate quality and quantity of intake water and fish diseases. Although management and operative workers at farms do their best to reach full capacity, the technology is sensitive and still developing, and biology has brought about surprises.

8.2. Competitiveness

Economic result is very much connected to the competitiveness of the selected business idea of each RAS project. Besides the technical and operational issues, several factors influence competitiveness, such as choice of product, economics of scale, location and subsidies.

Fish markets are integrated (Kankainen et al. 2007), meaning that import products affect the value of domestic products. Baltic Sea region is no exception and, therefore, local production should be competitive in comparison to the imported production. If that is not the case, substitute products will enter the markets, causing market prices to decrease, which eventually will decrease the profitability of less competitive production methods. For example, Danish model farms produce portion size rainbow trout, which is also produced in large quantities in Turkey and imported to the North European markets. As a result, Turkey imports have caused pressure on the profitability of the Danish production, although on 25 May 2021, the EU Commission decided to extend the countervailing duty on imports of portion size trout from Turkey by a further five years. In that very case, Danish products need to demonstrate a better quality or some other attribute if it wishes fetch higher prices and maintain economic sustainability. Similarly, Norwegian salmon is a substitute for large rainbow trout produced in Finland, Sweden and Denmark, and changes in Norwegian and global salmon price influence large rainbow trout farming profitability. During the last few years, salmon and trout price has been high but RAS companies have still reported significant losses. Better competitivity and higher net income margins is needed especially during lower global salmon prices.

It has been argued that specialization is one of the solutions towards profitable business and competitive advantage of RAS. However, only a limited volume of production can be based on niche products. If preliminary high value production volumes are increased significantly, value of the product in market will decrease. This is especially possible at limited domestic markets such as the case of European whitefish in Finland (Kankainen et al. 2007). As a global example, caviar market prices have decreased due to increased production in countries such as China. A further heavy hit was caused by the COVID-19 pandemic drastically decreasing caviar demand at premium restaurants and airport shops and forced one Finnish company to shut down the activities. It is apparent that RAS profitability in the Baltic Sea region will be influenced by global fish markets.

Global RAS projects are getting bigger and, apparently, the main reason is the economics of scale. The scale needed for profitable production depends on the product of choice. Smaller operations may be profitable for high value products such as juvenile fish or niche consumer product. There are no recent analyses using latest RAS cost structure on the economics of scale for producing a substitute product for the Baltic Sea cage farming. In our discussions with managers of a global RAS technology company, profitability may need some 5,000 tn production. That is still 2–5 times higher production than any of the companies operating in the Baltic Sea area have reached so far. It should also be noted that we have not got access to details of such profitability analyses and cannot make conclusions on the robustness of such an estimation. 5,000 tn operations would require appr. 100 million euro investments and such business needs significant financies outside the traditional Baltic Sea aquaculture sector. Finally, and very importantly, although economic of scale improves the efficiency of fixed costs, non-volume depended variable cost should first be covered by revenues.

Environmental effects of fish farming depend not only on the production technologies, but also on the location. Nutrient discharges of a large RAS farm can have local environmental effects due to point source discharges, whereas large offshore cage operations may not have measurable impacts outside the farm vicinity. Therefore, RAS projects located at sensible areas may need to invest in very advanced discharge control technologies, further decreasing the profitability.

EU member countries have been able to support RAS investments through maritime and fisheries funding scheme. Member countries are preparing the next funding period 2021–2027 and certain level of support can be expected for RAS investments during the next few years. However, considering some large RAS projects that are in pre-planning phase, available fund may not be adequate for high percentage investment subsidy for the largest projects. Therefore, estimating capital costs of future RAS projects is not completely clear.

8.3. Can RAS be considered as BAT for farming salmonids for consumers?

According to article 15(2) of the EU Industrial Emissions Directive, emission limit values and the equivalent parameters and technical measures in permits shall be based on the best available techniques, without prescribing the use of any technique or specific technology. The directive includes a definition of best available techniques in article 3(10):

- "Best available techniques" means the most effective and advanced stage in the development of activities and their methods of operation which indicates the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where that is not practicable, to reduce emissions and the impact on the environment as a whole.
- "Techniques" includes both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned.

- "Available" means those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used
- or produced inside the Member State in question, as long as they are reasonably accessible to the operator.
- "Best" means most effective in achieving a high general level of protection of the environment as a whole.

Based on best available information, economic performance of RAS farms producing consumer size Atlantic salmon or rainbow trout in Denmark and Finland is alarming. Only the Danish model fish farms have been economically viable to date. Model fish farm technology is simpler compared to the technology at intensive RAS farms. The transformation from intensified pond and raceway farms has been gradual and model farms are run by experienced aquaculture entrepreneurs in Denmark. Furthermore, the incentives in the Danish regulation have played an important role in the gradual modernization of the aquaculture sector.

Most expectations have been laid on the newest large scale RAS companies. Still, several years after operation, companies make large losses. It has been expected that long experience in RAS farming, synergies with other industries, niche product, and active marketing would improve profitability.

Regarding BAT definitions, one approach is that a single whole production system shouldn't be considered BAT for e.g. market size salmonid production. Rather, BAT definitions should be targeted separately for each production system and technologies therein. Clearly this is an issue worth wider open debate among policy makers and stakeholders, and outside the scope of the present report.

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