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Renewable Energy and Sector Coupling Opportunities for Recirculating Aquaculture Systems in the Baltic Sea Region

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FOREWORD

While writing this report, the impacts of the Russian war on Ukraine have started to take effect throughout Europe: Sanctions towards Russia have led to energy insecurity. One consequence has been an increased prioritisation of energy security and self-sufficiency.

Even before the war began, the interest in installing local energy production to increase energy security and self-sufficiency was growing. Furthermore, many nations and companies choose to invest in renewable energy assets, given the global climate crisis. This report explores sustainable energy supply for fish farms.

Our work demonstrates the feasibility of souring electricity from local renewable energy technologies and sector coupling with local industries. By doing so, fish farms can decrease their dependence on grid electricity and external suppliers of farm inputs, such as oxygen.

By all accounts, the writing of this report is timely and necessary. We believe our results can substantially impact the future of fish farming and, so, a considerable part of the global food production footprint.

We would like to thank Ålandsbanken Abp and Fifax Abp fish farm for their vital contributions to this research.

1. INTRODUCTION

This report covers three separate studies: a background study, a case study, and a replicability study. In this work, techniques for decreasing the energy intensity of RAS were examined. More specifically, the following procedures were investigated:

- Integrate the RAS with renewable energy technologies such as wind turbines and solar panels to meet the high electricity demand of the farm with a direct supply of cost-effective, green electricity.
- Source the oxygen demand of RAS with oxygen produced locally by an electrolyser that converts green electricity and water into hydrogen, oxygen, and heat. The remaining electrolysis products could be integrated with other local industries to create a closed circular concept.
- Find off-takers of the by-products of RAS (i.e., heat, CO_2) such as greenhouses, other industries requiring heat input and district heating networks. The repurposing of the fish sludge as fertiliser is detailed in **WP2**.

The objectives were to develop a financially viable, integrated RAS, to estimate the reduction of nutrients to the Baltic Sea with the new RAS, and to produce a replication plan to achieve the reductions.

First, we present our methodology and objectives on a study-specific level. Then, we open the case and replicability studies in detail, listing and discussing our results and, finally, making recommendations based on our findings.

The conclusions of the background study are reported in separate documents.

2. METHODS AND OBJECTIVES

Our work was carried out in three steps: (1) A background study, (2) a case study with energy modelling, and (3) a replicability study. This section describes the methodology and objectives for each study.

2.1 Background study

The background study was divided into two parts: (a) **RAS and energy** and (b) **Baltic Sea aquaculture**. First, the stages and energy consumption of RAS were studied in a literature review. Second, research on current aquaculture production in the Baltic Sea region was conducted to understand methods used, species grown and nutrient emissions in selected countries.

The literature review aimed to determine the primary sources of energy consumption of existing RAS farms and discover what methods have already been employed to minimise energy consumption. The review covered papers in online publications such as Elsevier and search engines such as Google Scholar. In selecting the reviewed material, the criteria were to involve the following:

- Land-based reuse/recirculating farms
- Different fish species
- Different farm locations
- Electricity consumption data for each farm

Furthermore, sector coupling of RAS and integration with renewable energy technologies were researched to determine methods for making RAS more circular and sustainable. The first part of the background study provided the insight needed for the case study.

The second part served as background knowledge for the replicability study, focusing on aquaculture production around the Baltic Sea. The research was primarily conducted using information available in online databases such as Eurostat (2022) and EUMOFA (2022) and online publications.

2.2 Case study: Energy modelling

Following the literature review, the energy flows of a Finnish land-based RAS farm – the Fifax fish farm on Åland – which produces rainbow trout, were investigated. The investigation was carried out through sophisticated energy modelling using

Flexens' **Energy System Design Service (ESDS).** The ESDS is based on PLEXOS, a simulation-optimisation software for analysing energy systems and markets.

The fish farm's hourly electricity demand for an entire year was obtained from Fifax. Subsequently, Flexens' energy specialists concluded that this demand could be met by grid imports or onsite renewable capacity and built a simulation model for this energy system.

In the modelling, the energy system is optimised by altering the capacities of its expansion candidates. As illustrated in Figure 1, the expansion candidates in the Fifax energy system model were solar PV and wind power, lithium-ion batteries, and in some cases, cold thermal energy storage (CTES) and peak power reduction.

Cold Thermal Energy Storage (CTES) refers to storing cooling capacity in an appropriate medium at temperatures below the nominal temperature of the space or processing system. Useful in fish farms where the water needs to be cool. The main purpose of CTES is to shift electricity use from on-peak to off-peak hours, thus decreasing costs (Abdul Galil, 2013; Dorgan & Elleson, 1993).

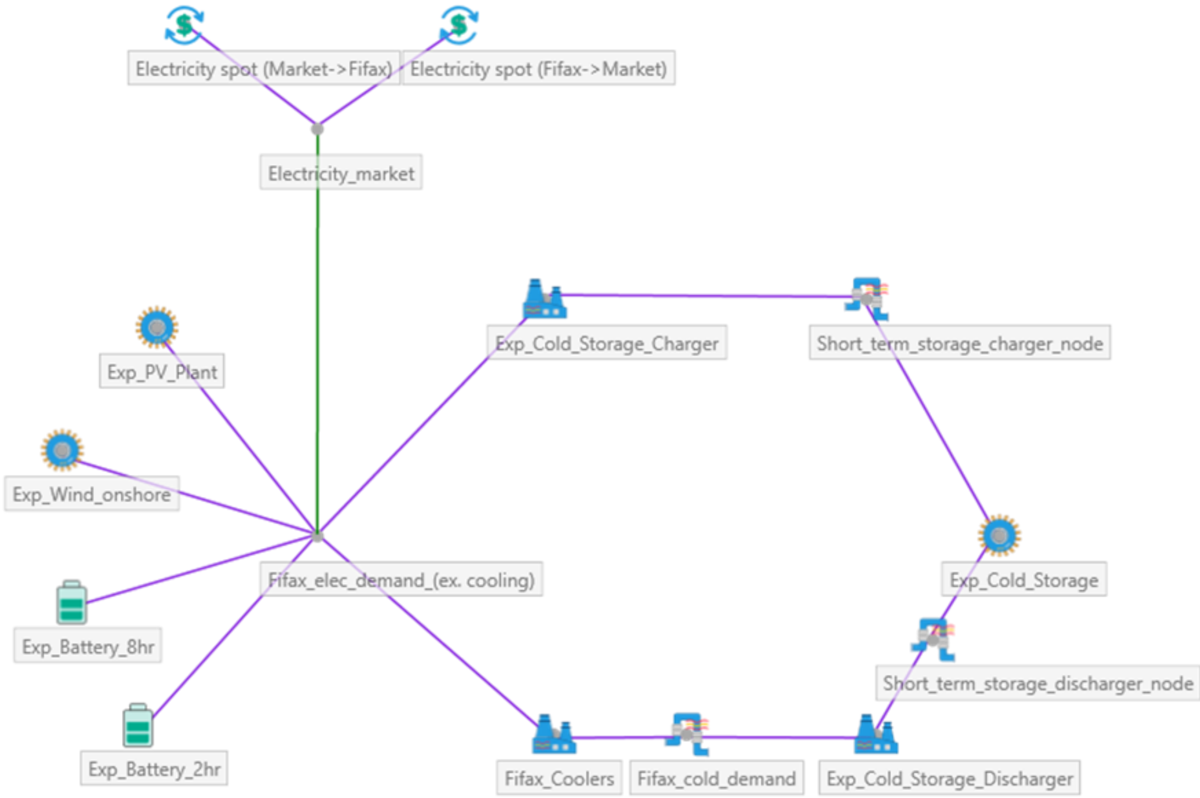


Figure 1. Energy system model for the Fifax fish farm. Made with PLEXOS.

The assumptions made for the case study were techno-economic parameters for all expansion candidates, Nord pool spot price in the SE3 area in 2021, local grid fees (night/day tariff) and estimated cooling demand from electricity demand (in discussion with the fish farm).

Four scenarios were modelled: two without CTES (Scenarios A and B) and two including CTES (Scenarios C and D). Electricity export – the fish farm selling surplus electricity to the grid – was allowed for two scenarios (B and D). Optimised costs and installed capacities were calculated and compared between scenarios. The results are detailed in Section 3.2.

Sector coupling with nearby heat sources was not explored as this farm requires cooling only. However, sector coupling with an electrolyser to source the oxygen demand of the fish was evaluated. The results are detailed in Section 3.3.

2.3 Replicability study

Based on the background and case study, a replicability study examined where RAS with the proposed integrations and modifications could be duplicated in the Baltic Sea region. That is, find land areas around the Baltic Sea where RAS could be integrated with renewable energy technologies and circular economy concepts, for example, through sector coupling.

The first objective of the replicability study was to estimate the decrease in nutrient emissions to the Baltic Sea if the integrated RAS was used to replace local offshore fish farms. Secondly, the replicability study aimed to determine locations in the Baltic Sea Region where the integrated RAS could be replicated.

The replicability study was conducted as a desktop analysis: The decrease in nutrient emissions was estimated using values from the literature reviewed in the background study and data provided by the Fifax fish farm.

For the second part of the study, the regions with the most existing offshore fish farms were the primary focus since they have the largest share of direct nutrient emissions into the Baltic Sea from aquaculture. These regions were in Finland, Sweden and Denmark as determined in the background studies. The most prospective locations for building onshore RAS were established based on the opportunities for integration with renewable energy technologies and for sector coupling on land nearby the existing offshore fish farms.

More specifically, direct integration with onshore wind turbines was evaluated. In addition, sourcing of electricity from the grid was also evaluated based on the "greenness" of the country's grid. In terms of sector coupling, coupling with electrolysers and industries requiring or producing heat were the main areas of focus. These choices were motivated by the locations of existing fish farms, the needs of the fish being farmed in the region and the author's prior knowledge of major renewable energy project developments in the region. Any additional data on electricity production, renewable energy development projects and industrial sectors within the evaluated land areas were gathered from online open sources.

The results of the replicability study are detailed in Section 4.

3. CASE STUDY: FIFAX FISH FARM

3.1 About Fifax

The Fifax fish farm is located on the Åland Islands and is one of Europe's most extensive operating RAS facilities. Fifax grows rainbow trout in large land-based tanks. The farm incorporates all production stages, from hatchery to slaughtering. The final product, adult slaughtered fish, is transported to wholesalers in the Åland Islands, mainland Finland and Sweden. In 2021, Fifax produced nearly 300 tonnes of slaughtered rainbow trout while operating at approximately 25 percent of its full output capacity and considering unusual accidents.

The water used for growing the fish is pumped from the Baltic Sea and piped to the farm, where it is recirculated in an almost entirely closed loop. The water goes through various treatment steps, including mechanical and biological filtration as well as CO_2 removal, pH regulation, oxygenation, and disinfection. Oxygen is currently imported in the form of oxygen tanks.

Fifax is an industry leader in capturing nutrients with its RAS. The facility's nitrogen and phosphorus emissions are so small that they do not require an environmental permit. Some of the nutrients exiting the farm are recovered as sludge, which is currently sent to an open composting area. See our report on reutilising this sludge as fertiliser on local farms **here.**

Operating the RAS is an energy-intensive process. The electricity is used primarily to pump and circulate the water throughout the facility. The second largest consumption of electricity is from running the cooling compressors (1600 kW_{th} capacity) which cool the circulating water to the desired temperature of 15 °C. Heating is not required for growing the fish.

The farm's annual electricity consumption was nearly 10 GWh in 2021, roughly equivalent to the consumption of around 2000 European households. The electricity is currently sourced from the grid but is certified as produced from renewable energy.

At full output capacity, Fifax expects to reach a relative electricity consumption of 5 kWh/kg live-weight fish produced. This value would be among the lowest values when compared to the electricity consumption of the farms with both hatchery and grow-out stages in the **background studies.** (Jalo, 2022). Currently, during a year with continuous normal operations at 25 percent of full output capacity, Fifax's electricity consumption is 15 kWh/kg live-weight fish produced.

3.2 Energy modelling results

This section shows the end results yielded by our energy system modelling. To reiterate: four scenarios, with varying flexibility resources in their energy system design, were investigated using the Fifax fish farm as a case study. Each scenario's (A, B, C, and D) expansion candidates (renewable power, storage units and optimal grid utilisation) were optimised in size through Flexens ESDS, finding the most economically advantageous solution for the fish farm.

While the energy modelling aimed to deliver a best-case option for each scenario, the ultimate selection between the four optimised system designs will be the essential conclusion for the fish farm. Therefore, the distinction between the scenarios is comprehensively discussed in this section.

The scenarios were explored through our sophisticated energy modelling processes, which we do not describe in detail here. For step-by-step explanations or any additional information, we encourage you to be in contact with our team.

Table 1 lists the production and storage capacities, total capital expenditure (CAPEX), annual savings, payback time, and share of energy self-sufficiency (share of production used onsite divided by total demand) for each optimised scenario.

Table 1. Detailed techno-economic outcomes of each optimised scenario.

	A	B ✓ Export	C ✓ CTES	D ✓ Export ✓ CTES
Solar + wind (MW)	3.6	7.9	3.7	8.3
Battery (MWh)	4.6	3.6	1.3	1.2
CTES (MWh)	-	-	9.8	13.3
Tot. CAPEX (M€)	4.9	9.1	4.5	9.3
Annual savings (M€/a)	0.49	1.06	0.51	1.09
Payback time (years)	14.2	11.5	11.9	11.4
Self-sufficiency (%)	67	82	67	84

These attributes are further visualised in Figure 2. Next, we raise general conclusions which can be made from these figures.

The mission of the renewed energy system would be to add value to the fish farm. Higher self-sufficiency adds to energy security and long-term savings. On the other hand, the investment outcomes should be worth the costs. Consequently, we reflect on both the affordability and gain of the energy system designs.

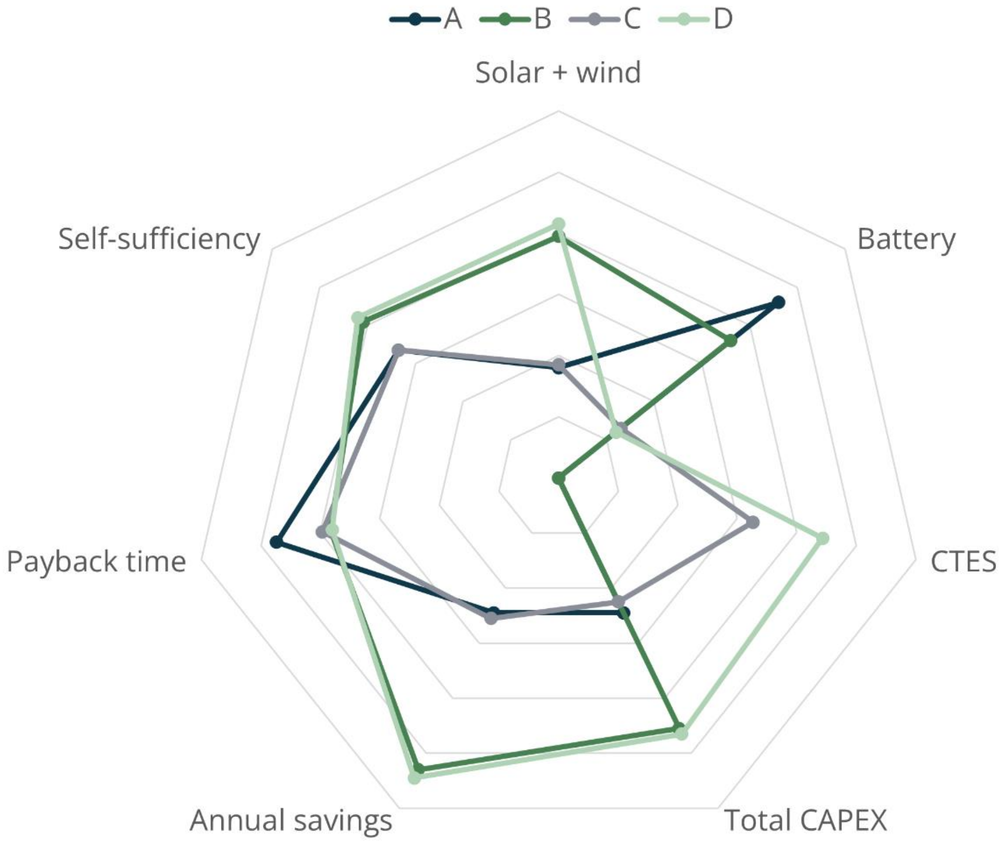


Figure 2. Graph of normalised results per scenario.

When comparing scenarios A and C with B and D, we see that doubling CAPEX does the same for annual savings. The higher expenditures in B and D are due to the added possibility of selling surplus electricity to the grid. From a techno-economic perspective, upscaling seems feasible enough due to adding self-sufficiency for the fish farm. However, the risk of being unable to export to the grid due to other obstacles makes the benefits of the investment uncertain.

In scenario A, a lithium-ion battery is the only storage unit included. If export is not allowed, adding more flexibility lowers the payback time significantly (by at least 2 years). For example, in scenario C, where only CTES is added to the energy system investigated for scenario A, the CAPEX is lower while both owned storage capacity and annual savings have increased. This is because using a smaller battery in combination with a larger CTES is more cost-competitive (in €/kWh) than using solely battery storage for cooling purposes.

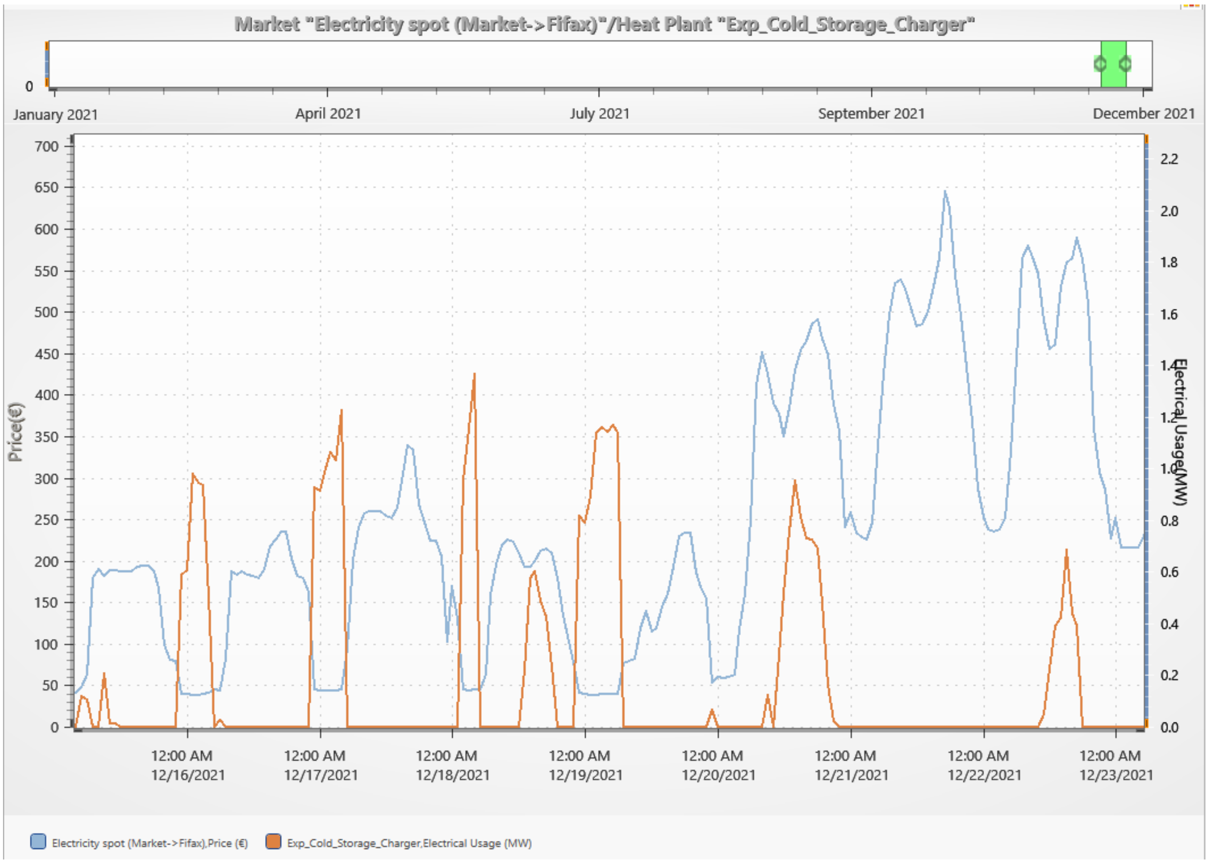


Figure 3. Electricity usage for charging CTES (orange) versus electricity prices in 2021 (blue). This graph shows that the storage is being charged during low-cost electricity hours whenever possible, which usually occurs at night-time. This effect is further enhanced by on-peak/off-peak grid tariffs. Made with PLEXOS.

As seen in Figure 3, CTES, like other storage solutions, can be incorporated to save on electricity bills. However, similarly to the consequences posed by possible grid regulations, applying novel (somewhat untested) solutions such as CTES adds a level of uncertainty to the outcomes of the energy system design. Other complications, such as long waiting times due to material shortages or political issues, should be considered when assessing the fish farm's optimal energy system design.

In conclusion, there are several aspects to oversee in selecting an energy system design for a RAS farm. The decision depends on external variables, such as electricity market prices and costs of RES, and internal variables, such as the availability of funds. Electricity prices have reached historical hights during the current energy crisis, with volatile price patterns during the day (as seen in Figure 3). We expect this price volatility to continue as the share of production from intermittent sources, such as wind power, increases. Therefore, having onsite flexibility assets and self-consumption can balance the risks and advantages of high and low electricity prices, respectively. This balance is an essential aspect of the designed system, providing more secure operational costs long-term.

Furthermore, when evaluating these results, it is important to recall that the total electricity demand will vary for each farm depending on the local parameters, as discussed in the background study. Hence, the abovementioned findings may not be directly translatable to another farm. However, the model built for this report has been done flexibly; It can be easily adjusted to fit the specific conditions of another fish farm. The model can quickly determine the potential installation of renewables onsite that are economically beneficial (payback time of approximately ten years in the modelled results in a system with a 25-year lifetime). Fish farms needing cooling or heating are possible to model in the framework built for this project.

3.3 Sourcing of oxygen from an electrolyser

As described in the background study, some companies have already investigated meeting the oxygen demand of fish farms by using by-product oxygen from electrolysis.

For Fifax, the current annual oxygen demand is slightly over 1000 tonnes/yr. To cover this oxygen demand entirely, an electrolyser of a minimum of 2 MW would be required to operate at least 5000 full capacity hours per year. The corresponding hydrogen production would be around 180 tonnes/yr (tpy) or 6000 MWh/yr. This amount of hydrogen could be used to power a small-scale boat or bus or to produce green derivatives of hydrogen, such as ammonia or methanol, in very small scale. The inputs and outputs to the electrolyser are summarised in Figure 4.

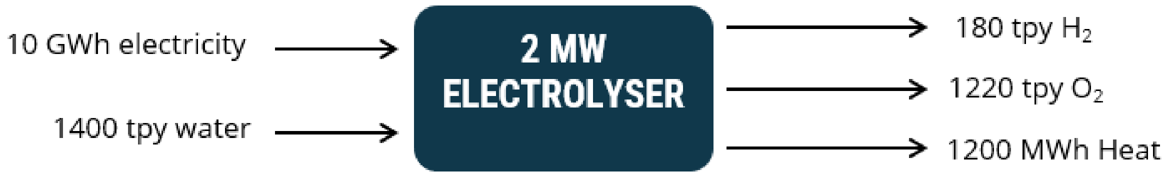


Figure 4. Example electrolyser production at 5000 full capacity hours per year.

Based on these results, the electricity consumption of the farm would roughly double if the electrolyser was located onsite, thereby incurring additional operational costs, in addition to the investment and maintenance costs of the electrolyser. However, the farm could also benefit from additional revenue streams from selling the hydrogen and waste heat from the electrolyser to other industries, thereby yielding a circular concept.

If the electrolyser is located off-site, the oxygen selling price will depend on transportation costs and the selling price of the other products from the electrolyser. Given the rising interest in green hydrogen production projects in Europe, the co-location of electrolysers and land-based fish farms should be further researched. A preliminary analysis is provided in our replicability study.

3.4 Decreasing electricity demand via optimised sourcing

Fifax has determined that one way to minimise their dependence on the cooling compressors and hence also decrease electricity consumption is to source the incoming water from a location in the Baltic Sea with cool water temperatures available even during the summertime.

The key learning from this discovery is that RAS farms can decrease their operational costs simply by locating the farms such that the surrounding conditions, whether environmental or industrial, can be optimally coupled with the parameter requirements of the farm. This local coupling is also further detailed in the replicability study.

4. REPLICABILITY STUDY: INTEGRATED RAS

4.1 Estimated potential nutrient emission decrease

To accomplish the first objective of the replicability study, the nutrient emissions from sea cages were compared to the nutrient emissions from integrated RAS.

The nitrogen and phosphorus emissions from a typical sea cage were determined by examining literature values. The results of this literature study indicated significant variations in nutrient emissions. These variations are due to the influence of many factors such as feeding habits and metabolism of the fish (Campanati et al., 2021). However, for this study, the average value of the literature values was used. These values corresponded to 4 kg P and 45 kg N released per tonne of live-weight fish production1 (Price et al., 2015).

The nitrogen and phosphorus emissions from the integrated RAS were determined based on Fifax's nutrient emission values. In 2021, Fifax emitted 91 kg of P and 847 kg of N from their RAS, corresponding to about 0.3 kg P and 2.4 kg N released per tonne of live-weight fish production. The values used in the calculations are summarised in Table 2. However, at full output capacity, Fifax expects their emission values to decrease further to 0.06 kg P and 0.5 kg N per tonne of live-weight fish production, thereby yielding an even larger difference in comparison to the emissions from sea cages (Jalo, 2022).

Table 2. Values for estimating nutrient emission decrease with integrated RAS.

Released nutrients (kg/tonne fish)	Sea Cage	Fifax RAS
Phosphorus (P)	4	0.3
Nitrogen (N)	45	2.4

To calculate the nutrient emission savings, the values in Table 2 were multiplied by the tonnes of live-weight fish produced in sea cages in 2020. This value was 32,280 tonnes/year for the Baltic Sea Region (EUMOFA, 2022). The results are shown in Figure 5.

[1] **Assumption Validation:** The validity of using the average of the literature values for the calculations for the Baltic Sea Region was checked by using these values to estimate the nutrient emissions from sea cages for 2014. For this year, the data for the total nutrient emissions to the Baltic Sea was available from the 2018 HELCOM assessment. The product of the literature values and the annual production from sea cages (tonnes live weight) in the Baltic Sea region in 2014 (EUMOFA data) yielded 0.14 kilotonnes of P and 1.54 kilotonnes of N emissions. These values correspond to 0.4 % and 0.2 % of the total P and N emissions to the Baltic Sea in 2014 (Barquet, 2021). Therefore, it was concluded that these average values are reasonable to use for the calculations since according to Asmala and Saikku, aquaculture is responsible for less than 0.5 % of total nutrient emissions to the Baltic Sea (Asmala & Saikku, 2010).

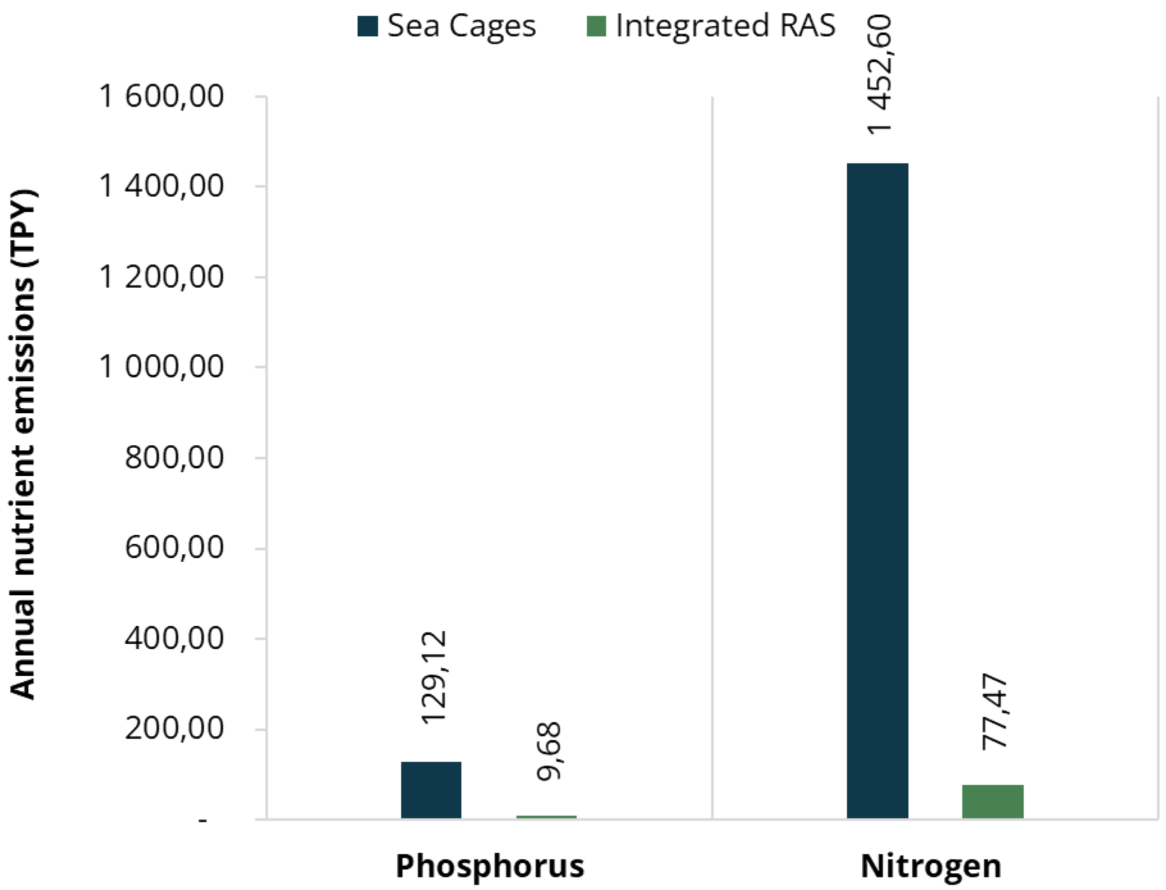


Figure 5. Annual nutrient emission savings if all fish produced in sea cages in 2020 were grown in land-based integrated RAS instead.

In conclusion, the annual nutrient emission savings would be 120 tonnes of P and 1375 tonnes of N if the integrated RAS replaced all sea cages in the Baltic Sea Region. From a large-scale perspective, this amount is not substantial, considering that aquaculture contributes minimally compared to other sources of nutrient emissions to the Baltic Sea on a regional level. However, for the areas of the Baltic Sea with the highest concentrations of sea-cages, transitioning to RAS could yield positive local environmental impacts. RAS's other benefits, such as a more controlled environment, must also be considered as motivation for transitioning fish farming inland (Bergman et al., 2020).

4.2 Scope of study for finding new locations

To achieve the emission reductions proposed in Section 4.1, new locations must be found where the integrated RAS could be constructed to replace existing offshore fish farms.

The scope of the study was the land areas nearby to the existing offshore fish farms that emit the most nutrients (nitrogen and phosphorus) to the Baltic Sea. As concluded from the background study, these offshore fish farms are located primarily in Finland, Sweden, and Denmark. The land areas investigated for replication of integrated RAS are highlighted in Figure 6.

The land areas investigated were selected based on their proximity to the existing sea cages that contribute the most direct nutrient emissions to the Baltic Sea as determined in the 2018 HELCOM Assessment. The assumption was made that finding land areas nearby to existing offshore farms would facilitate an easier transition inland for these farms. Within these designated land areas, the replicability of the integrated RAS was approached primarily from the energy and sector-coupling perspectives. Other considerations, such as financial, economic, social, etcetera, were excluded in this study.

4.3 Estimation of energy demands to determine coupling opportunities

Based on the findings of the background study and the case study, to determine the coupling opportunities, the demands for electricity, oxygen, heating and cooling of the RAS farm need to be known. In this high-level replicability study, the exact demands for each new RAS farm could not be calculated.

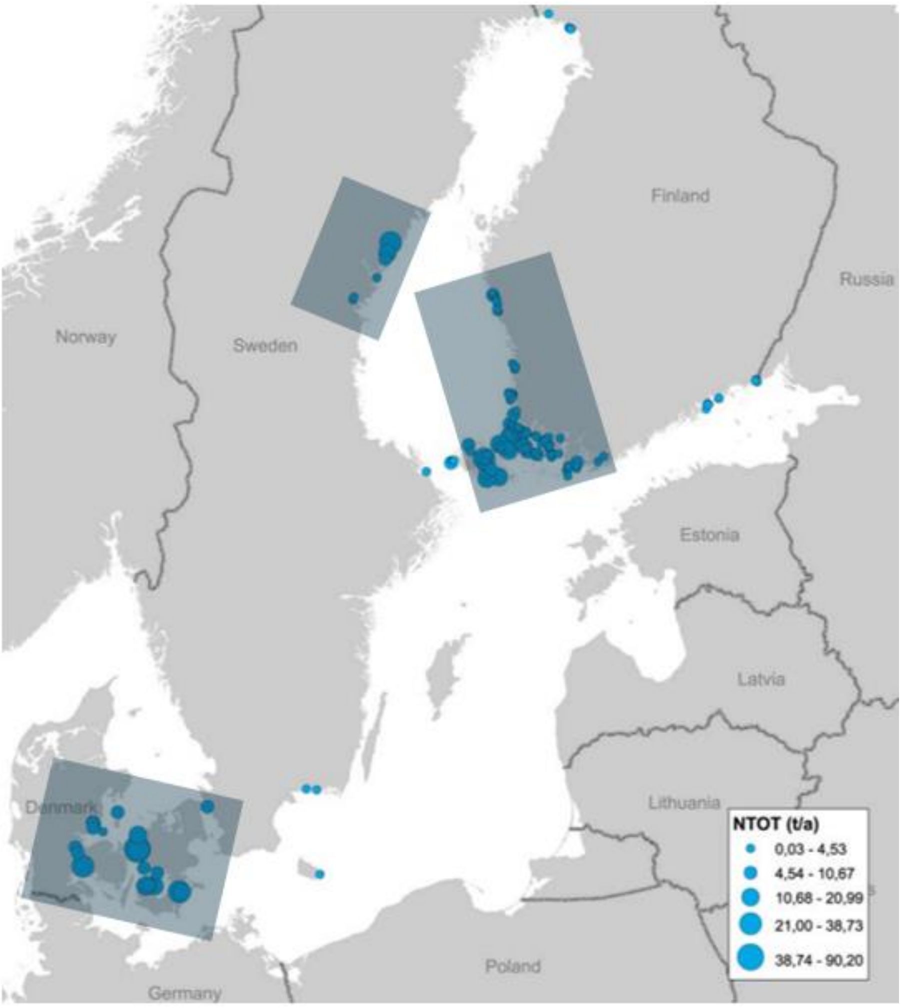


Figure 6. Land areas investigated for integrated RAS construction to replace existing offshore fish farms based on the locations with the most direct nutrient emissions from aquaculture to the Baltic Sea (HELCOM, 2018).

However, the relevance of each demand for a given location was determined based on the needs of the fish species currently being farmed in the offshore locations in that region.

According to the research in the background studies, rainbow trout composes the majority of aquaculture production in Finland, Sweden and Denmark (EUMOFA, 2022). Therefore, from the Fifax case study, it was known that the integrated RAS farms for growing rainbow trout would have both electricity and oxygen demands. The cooling and/or heating demand will depend on the source of the water to the farm. However, because rainbow trout are cold-water fish, requiring optimal temperatures of 15-16 degrees Celsius, it was assumed that in most cases the cooling demand would dominate as it had in the Fifax case study.

The demands for other types of cold-water species being grown in these regions were assumed to be the same as for rainbow trout. In other words, it was assumed that such integrated RAS farms would have electricity, oxygen and cooling demands. The other cold-water species include, for example, arctic char in Sweden and salmon in Denmark. On the other hand, both Sweden and Denmark also grow European eel, which is a warmwater fish that thrives in temperatures around 24 degrees Celsius (Jordbruksverket, 2022; EUROFISH, 2022)

While integrated RAS farms growing this species will also require electricity and oxygen, for these farms, the heating demand will most likely dominate over cooling demand. This assumption is made since all the investigated locations are in the Nordic climate. The assumption for the energy demands of the proposed integrated RAS farms in the investigated land areas, depending on whether they are growing cold or warm water species, are summarised in Table 3.

Table 3. Assumed energy demands of the hypothetical integrated RAS farms in the investigated land areas based on the type of fish being grown.

Fish species	Electricity demand	Oxygen demand	Cooling demand	Heating demand
Cold water (i.e., rainbow trout, arctic char, salmon)	Yes	Yes	Yes	No
Warm water (i.e., European eel)	Yes	Yes	No	Yes

Based on these assumed energy demands, the opportunities to integrate the RAS with renewable energy technologies and couple the RAS with nearby sectors were explored in the identified land areas. These opportunities were explored in the larger context of making the RAS more sustainable and circular.

4.4 Mapping the opportunities

4.4.1 OPPORTUNITIES FOR COUPLING BASED ON ELECTRICITY DEMAND

All land-based integrated RAS will require electricity, at least for the pumping and recirculation of water at the farm. Therefore, it was the source of electricity that was the focus of evaluation, with the aim to have the electricity produced 100% from renewables. Two options were evaluated: (1) Using certified renewable electricity from the grid and (2) Direct (behind-the-meter) connection to nearby wind turbine(s).

The CO_2-intensity of the grid electricity available in the land areas of interest is shown in Figure 7. From this figure, it is apparent that Sweden has the greenest grid electricity among the Baltic Sea countries. The region containing the land area of interest in this study had 24 gCO_{2eq}/kWh electricity produced and electricity sourced 100% from renewables (electricity price area SE2). Finland had the second greenest grid electricity with 93 gCO_{2eq}/kWh carbon intensity and approximately 50 % of electricity consumption from renewables. For the Danish locations evaluated in this study, the carbon intensity was 200 gCO_{2eq}/kWh and 121 gCO_{2eq}/kWh for the West and East, respectively (Electricity maps, 2022).

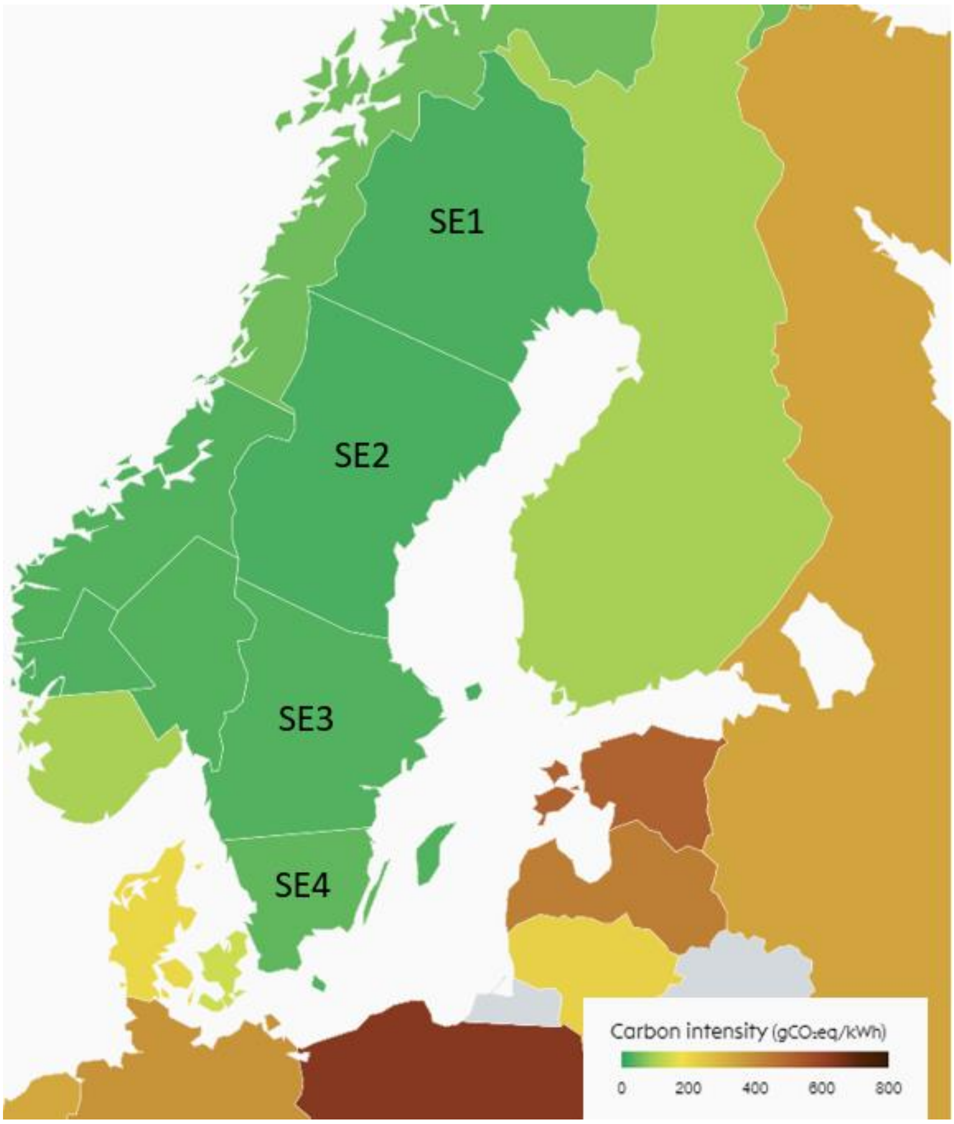


Figure 7. Carbon intensity of the grid electricity in the countries (in some cases regions within countries) evaluated in this study (Electricity maps, 2022). Data is shown for the past year as of September 2022.

Therefore, when considering the sustainability of the electricity alone, the integrated RAS farms would in most cases be able to meet their electricity demands using certified renewable electricity from the grid in Finland, Sweden, and Denmark. However, the reliability and cost of the electricity are also important factors to consider.

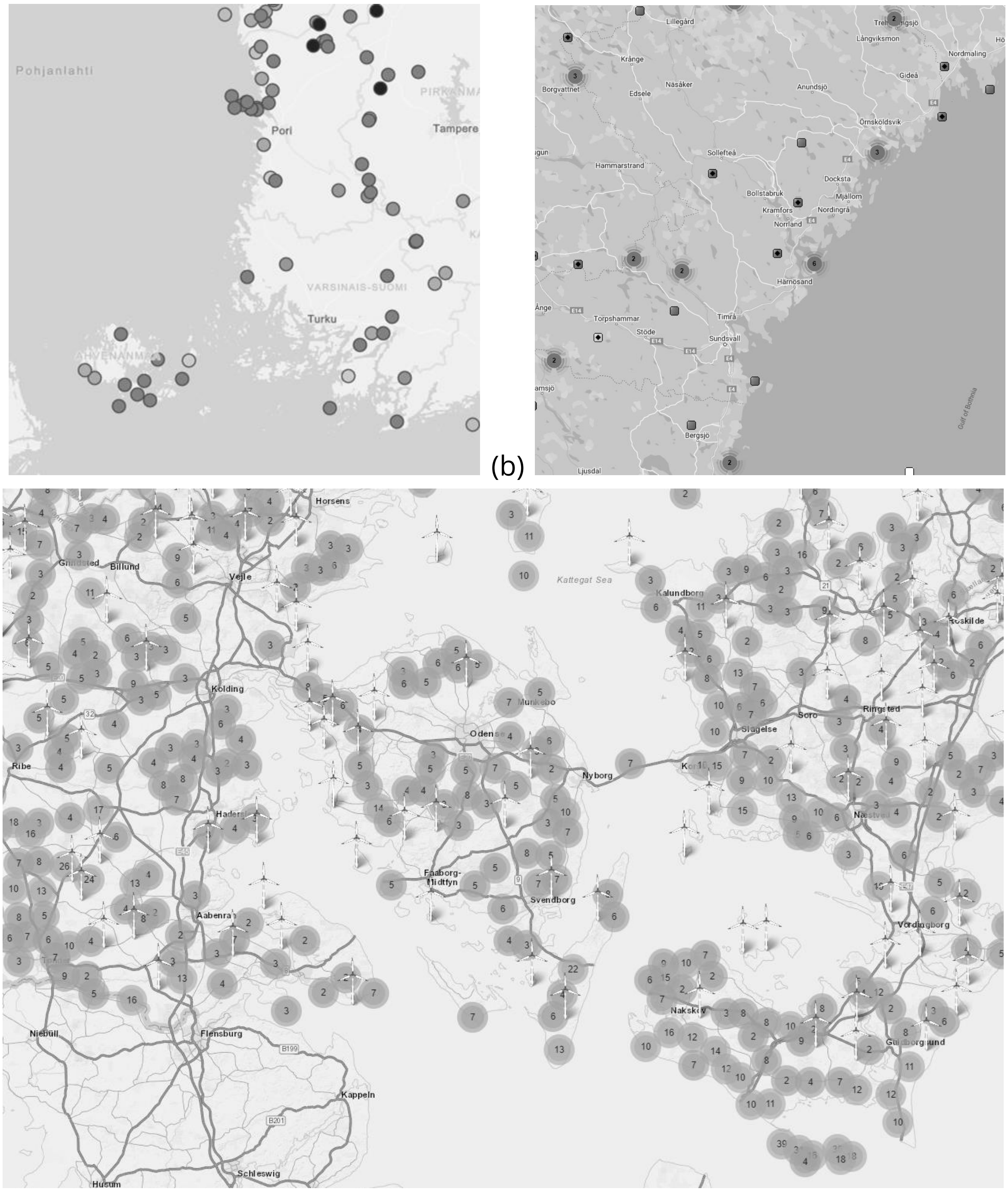
Therefore, sourcing the electricity directly from onsite renewable energy technologies, as evaluated in the Fifax case, could be a viable alternative in certain cases. In the Baltic Sea area, as in other parts of Northern Europe, wind power is the dominant source of renewable energy. Therefore, in this study, only the opportunities to integrate the land-based RAS with onshore wind turbines were evaluated.

In all three of the land areas evaluated, there are existing or planned onshore wind turbines as shown in Figure 8. Therefore, there are excellent opportunities in the evaluated land areas for new-build integrated RAS farms to source their electricity from renewables.

While in Sweden, it could make sense to source the electricity from the grid, in Finland, for example, it could make sense to directly couple the farm to a nearby wind turbine. This opportunity is also motivated by the fact that at the time of writing, Finnish TSO Fingrid has announced that grid transmission capacity in the west coast will be almost at its limit by 2024 (Fingrid, 2022). Therefore, upcoming wind turbines will be unable to connect to the grid and will need to find other off-takers for the power produced. In Denmark, direct coupling to onshore wind turbines could also make more sense as the grid electricity is more carbon intense. As of January 2022, there were over 5000 onshore wind turbines and 630 offshore wind turbines across the country, with total installed capacity of 7035 MW, yielding a high availability of options (Danish Energy Agency, n.d.) Connecting behind the meter also yields the advantage of by-passing grid fees.

4.4.2 OPPORTUNITIES FOR COUPLING BASED ON OXYGEN DEMAND

As demonstrated in the Fifax case, the oxygen demand of integrated RAS farms can be met by sourcing the oxygen from electrolysers which co-produce hydrogen and heat.



(a) (b) (c)

Figure 8. Existing and planned onshore wind turbines in (a) Finland (Finnish Wind Power Association, 2022) (b) Sweden (The Wind Power, 2022) and (c) Denmark in the land areas investigated for integrated RAS construction (Tranberg et al., 2022)

Coincidentally, the land areas identified for integrated RAS replication correspond almost exactly to the location of the hydrogen pipeline that is currently under planning in the Baltic Sea Region. This pipeline will be used to store and transport hydrogen from production sites to off-takers throughout the Baltic Sea Region and Europe.

Certain portions of the pipeline are expected to be completed as early as 2030 (European Hydrogen Backbone, 2022), The expected pipeline route is depicted in Figure 9.

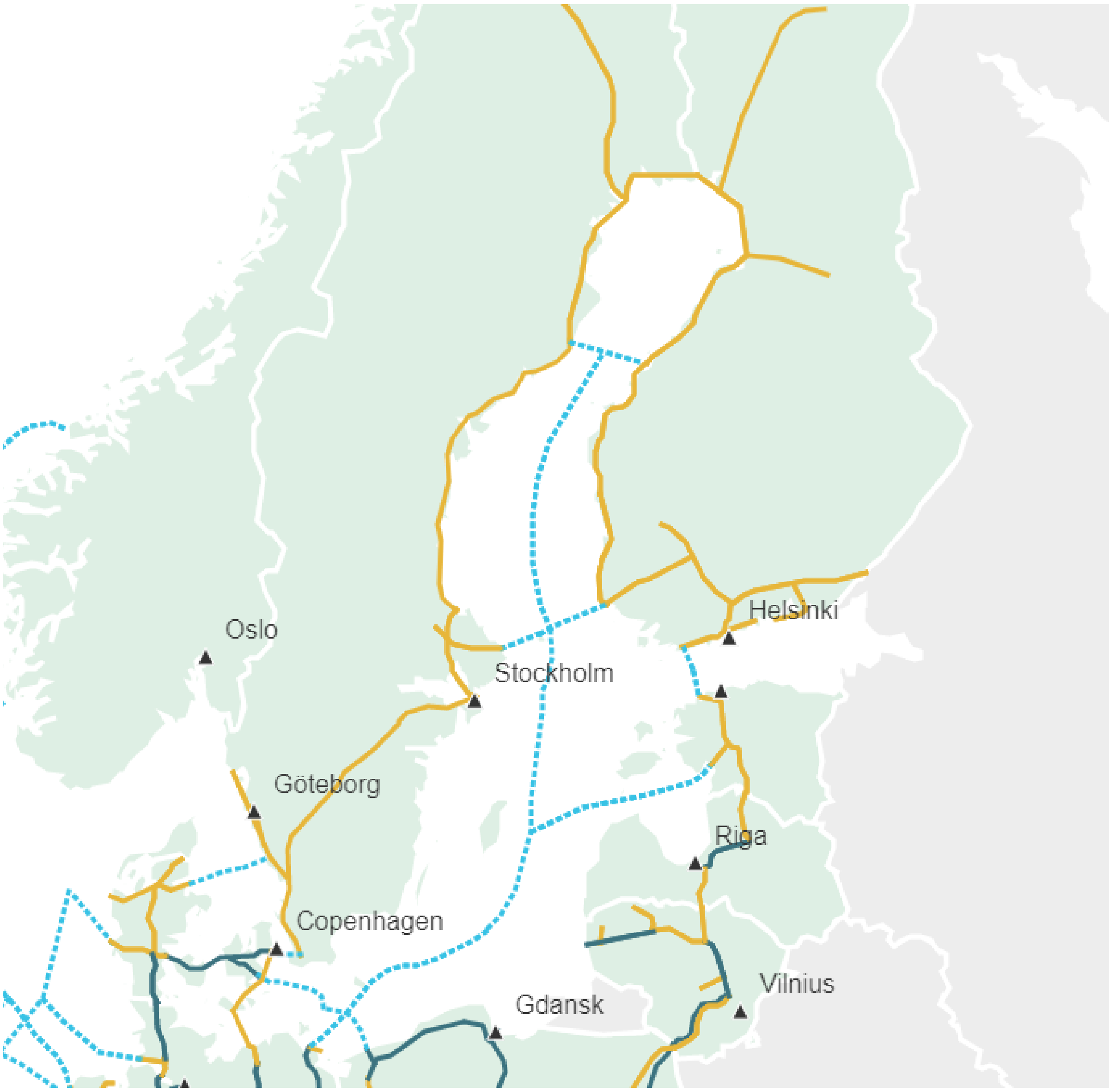


Figure 9. Planned hydrogen pipeline in the Baltic Sea region. (European Hydrogen Backbone, 2022)

More specifically, there are already some publicly announced plans for electrolysers that will be in the land areas that are investigated in this report. These electrolysers will produce green hydrogen and hydrogen derivatives, such as ammonia and methanol, and will have by-product oxygen and heat. The locations of some of the publicly announced projects in the areas of interest are shown in Figure 10.

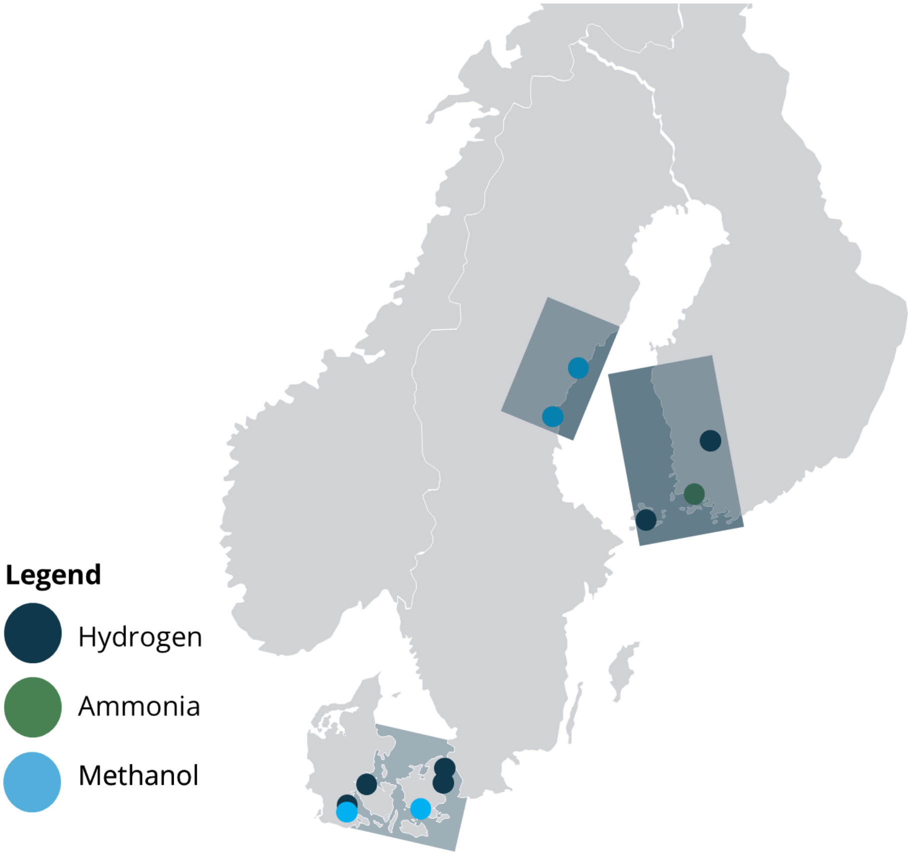


Figure 10. Map of some of the planned electrolysers in the investigated land areas. The colours denote the final product produced.

Therefore, in all areas investigated for replication of integrated RAS, there are, in theory, opportunities to utilise the by-product oxygen from the electrolysers to meet the oxygen demands of the fish grown in the RAS. However, this conclusion is based solely on this desktop analysis. The negotiations for utilisation of this oxygen would need to be carried out with the electrolyser project owners themselves.

4.4.3 OPPORTUNITIES FOR COUPLING BASED ON COOLING DEMAND

Cooling demand is anticipated to be relevant primarily for integrated RAS farms growing cold-water species, such as rainbow trout. Learning from the Fifax case study, one of the easiest and most economical ways of meeting the cooling demand of a RAS is to locate the farm nearby to a cold-water source. For the areas studied, this would mean locating the farm nearby the Baltic Sea coastline, so that the cool water can be piped directly from the Baltic Sea to the RAS.

By doing so, the RAS could take advantage of the "free cooling" from the sea, thereby minimising the electricity demand required to operate cooling compressors at the facility. If the RAS were located further inland, technologies such as CTES could also be considered to decrease the cost of electricity by shifting electricity use for cooling from on-peak to off-peak hours.

4.4.4 OPPORTUNITIES FOR COUPLING BASED ON HEATING DEMAND

The heat demand of an integrated RAS, for example, a facility producing warm water species, could be met with by-product heat from nearby industries. Some industries producing waste heat are summarised in Appendix D. These industries include iron and steel, chemical, mineral, food and beverages and paper production.

Within the land areas investigated in this replicability study, a few of these types of industries have been researched and summarised in Table 4.

Table 4. Selected industries within the investigated land areas, in accordance with the data presented in Appendix D, that produce by-product heat.

Name	Location	Industry
Orkla Foods Finland Oy	Turku, Finland	Food production
UPM Rauma	Rauma, Finland	Paper mill
Sekab BioFuels & Chemicals AB	Dömsjö, Sweden	Chemical company
SCA Sundsvall Ortvikens Pappersbruk	Sundsvall, Sweden	Paper mill
Orkla Confectionery & Snacks Finland Ab	Åland Islands, Finland	Food production
NLMK DanSteel A/S	Frederiksværk, Denmark	Steelwork manufacturer
Celsa Steel Service A/S	Ølstykke, Denmark	Steel fabricator

Nastec Steel ApS	Årslev, Denmark	Steel fabricator
HESA-TEK (Part of MARSØ GROUP)	Fredericia, Denmark	Stainless steel plant
Give Steel Aarhus	Aarhus, Denmark	Steel fabricator
Novo Nordisk A/S	Kalundborg, Denmark	Pharmaceutical company

4.5 Mapping of the most ideal sites

After evaluating the opportunities for renewable energy integration and sector coupling according to the different demands anticipated at the new integrated RAS facilities, a few of the most suitable sites within the evaluated land areas were selected. The selected locations are shown in Figure 11. and are further detailed below. In all locations, the proximity to the Baltic Sea was prioritised, to allow for the pumping of cool water to the RAS directly from the sea.

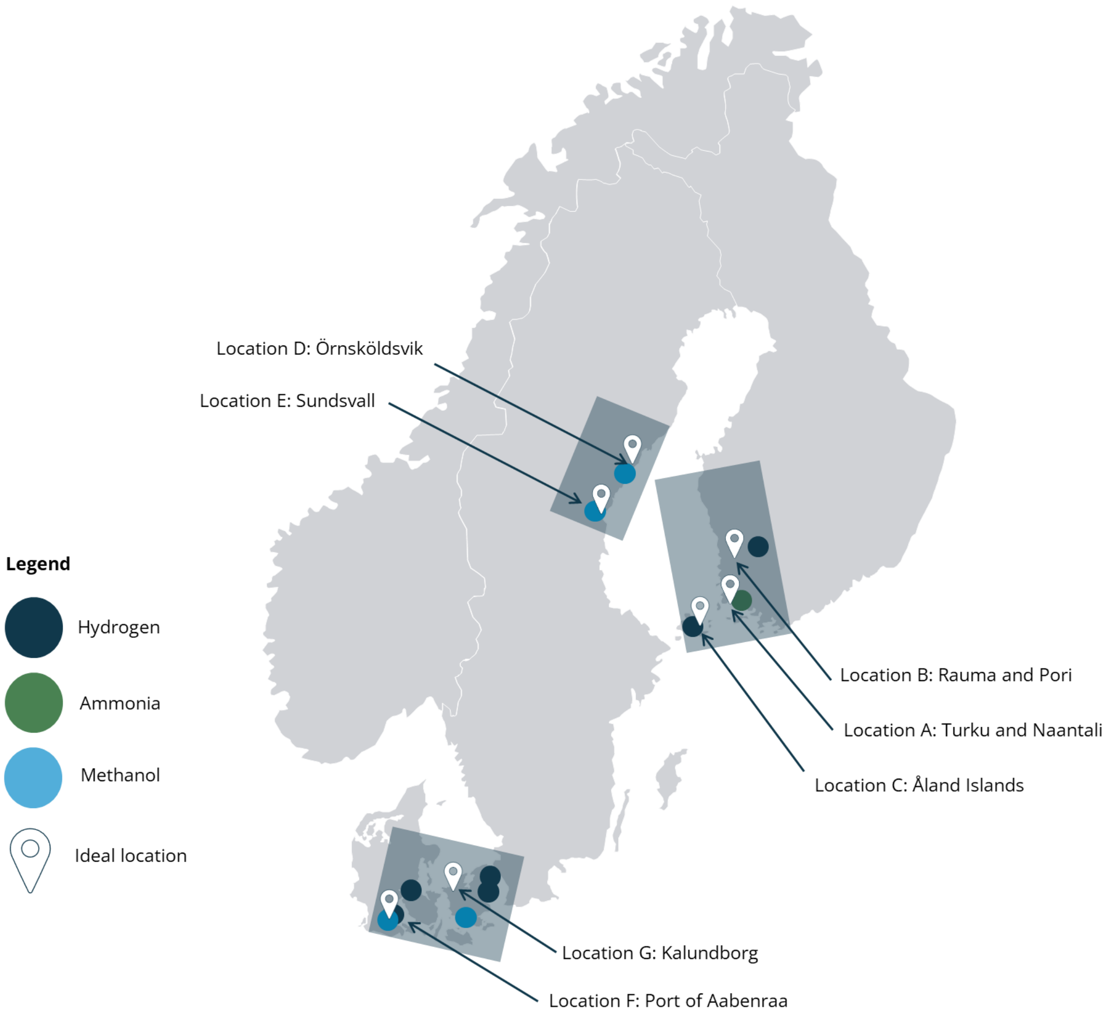


Figure 11. Overview of selected locations that were determined to be the most suitable for replicating the integrated RAS based on energy and sector coupling opportunities evaluated through this desktop study.

LOCATION A: TURKU AND NAANTALI, FINLAND

Green NorthH2 Energy is planning a green hydrogen and green ammonia production plant in Naantali, which is located nearby Turku in Southwest Finland. (Green NorthH2 Energy, 2022). The hydrogen will be supplied by a 100 MW electrolyser (50x larger than the estimated electrolyser capacity for Fifax RAS). Therefore, the by-product oxygen could be used to supply oxygen to multiple RAS nearby. While there are no wind turbines planned directly in the Turku-Naantali region, there are excellent grid connection opportunities in the area. Therefore, this area could be a viable location to transition to for the farms currently located in the waters of the Turku archipelago.

LOCATION B: RAUMA AND PORI, FINLAND

P2X Solutions is planning industrial-scale green hydrogen and renewable synthetic methane production plant in Harjavalta. The 70 MW plant will be completed in 2024. (P2X, 2022) The by-product oxygen from the plant could be used in RAS, although the oxygen would need to be transported to the fish farm as the electrolyser is planned to be further inland. There is one operational 1 MW wind turbine between Rauma and Pori and a few others just North of Pori. There is also an existing 42 MW offshore wind park by Pori and a few onshore turbines under planning in the area. Therefore, this could be a suitable land-based location for farms currently in the waters nearby Rauma and Pori.

LOCATION C: ÅLAND ISLANDS, FINLAND

Fifax is located on the Åland Islands.

In 2020, after years of previous research on hydrogen possibilities on Åland, **Flexens** started a project to materialise the first hydrogen and Power-to-X application: **Power2AX**. Power2AX aims to combine local green hydrogen production and fuel cell powered ferry operations in the Åland archipelago.

The Power2AX project acts as a demonstration of new hydrogen technologies, as well as bringing additional cross sector benefits, including, for example, future large-scale offshore wind production – a hot topic on the Åland Islands.

LOCATION D: ÖRNSKÖLDSVIK, SWEDEN

In Örnsköldvik, **Ørsted and Liquid Wind AB** are planning the FlagshipONE e-methanol project, which includes an electrolyser with a capacity of around 70 MW (same size as the one in Harjavalta). The by-product oxygen from the electrolyser could be used at nearby RAS growing cold-water fish. The project aims to begin production by 2024 (Ørsted, 2022).

There are three operational wind farms located nearby Örnsköldvik, which could potentially supply renewable electricity directly to RAS (The Wind Power, 2022 If there was heating demand at the RAS, the by-product heat from the e-methanol production could be used at the facility.

LOCATION E: SUNDSVALL, SWEDEN

Liquid Wind AB is also planning a second e-methanol production plant in Sundsvall, Sweden together with **Sundsvall Energi**. The plant, called FlagshipTWO, will produce 100,000 tonnes of e-fuel (Hydrogen Central, 2022).

Therefore, oxygen and heat (if needed) could be sourced from the plant. The local paper mill could serve as an alternative source of heat for growing warm-water species such as European eel. There are two existing wind turbines nearby Sundsvall. Alternatively, renewable electricity could be sourced from the grid.

LOCATION F: KALUNDBORG, DENMARK

While there are no electrolysers currently planned in this location, the existing **Kalundborg Symbiosis** project makes Kalundborg an attractive location to incorporate integrated RAS in a circular economy concept. In this project, 15 local industrial companies have been working towards a circular economy concept by sharing of excess energy, water and materials (Kalundborg Symbiosis, 2022). Therefore, there are excellent synergies with integrated RAS, as the energy flows of the RAS could be incorporated in the existing symbiosis. For example, by-product heat from the current industries could be used to grow warmwater species. The proximity of Kalundborg to the coastline makes it a viable location for growing cold-water species using water from the Baltic Sea as well.

LOCATION G: PORT OF AABENRAA, DENMARK

An example here is the **Port of Aabenraa**, which together with **Linde Gas A/S**, is planning a 100 MW electrolyser (same size as the one in Naantali) that will be in operation by 2025 (Danish Ministry of Climate, Energy and Utilities, 2021). As the plant will run on green electricity from offshore wind turbines, it can be concluded that there will be available renewable electricity and by-product oxygen and heat in the port area.

4.5.1 OPPORTUNITIES IN OTHER BALTIC SEA COUNTRIES

Other countries in the Baltic Sea region have already largely transitioned away from sea-based aquaculture and are currently using different methods, such as ponds, tanks, and raceways. Therefore, these countries were not as critical to evaluate for meeting the objective of minimising direct nutrient emissions from aquaculture to the Baltic Sea.

However, from an environmental impact perspective, RAS has the lowest land and water usage and should be considered in these countries. Furthermore, from the circular economy and sustainability perspectives, it is always advantageous to consider sector coupling and sourcing of electricity from renewables. Therefore, a brief analysis of the opportunities for replicating the integrated RAS in other Baltic Sea countries is also provided.

From the grid electricity carbon intensity comparison map in Figure 7 (Section 4.4.1), Poland, Estonia, Lithuania, and Germany (in descending order) had the most carbon-intense electricity consumption over the past year. Therefore, in these countries, fish farms should emphasise sourcing their electricity directly from renewable energy technologies rather than from the grid or otherwise should use certified renewable electricity from the grid.

As depicted in the background material, rainbow trout is also the dominant species produced in Estonia. Poland and Germany also have large shares of rainbow trout production in their food-fish production. Therefore, the decision-making process applied in the replicability study for Finland, Sweden and Denmark can also be used in these countries. The sourcing of oxygen from electrolysers should be considered. The hydrogen pipeline will be connecting through all the Baltic Sea countries analysed in this report. Therefore, it is expected that there will be electrolysers producing hydrogen in the other countries as well.

Unlike in the countries discussed so far, common carp (*Cyprinus carpio*) dominates aquaculture production in Latvia and Lithuania and has significant production shares in Germany and Poland. Since carp is a warm-water fish requiring around 26 degrees Celsius for optimal growth, coupling with industries producing waste heat should be considered. Carp also requires dissolved oxygen, so coupling with electrolysers is also possible.

In Table A in Appendix A, we see that Germany, Poland and Lithuania have already taken greater steps towards establishing RAS farms. These farms have included cold-water species, such as rainbow trout, and warm-water species, such as catfish and tilapia.

The decision diagram in Appendix E can be utilised to perform a high-level analysis for coupling opportunities in any location if the energy and utility demands of the RAS are known. However, these charts are simplified for the report. For example, regulatory, permitting, and financial considerations are not detailed and must be separately considered when evaluating a business case. **Flexens ESDS** can be used to model renewable energy technology and storage integrations at the existing RAS farms for optimised results on a case-by-case basis.

5. CONCLUDING REMARKS

In this report, an in-depth analysis was conducted on an existing RAS farm to determine ways to make the farm more energy and cost efficient. Using the learnings from this case study, a high-level analysis was conducted on where such RAS could be replicated in the Baltic Sea region.

The results from the energy modelling in the case study indicated that integrating renewable energy technologies with RAS yields the farmer the benefits of annual savings in operational costs and varying degrees of energy self-sufficiency. Furthermore, sector coupling, for example with electrolysers and local industries, creates circular concepts that benefit not only the environment, but also the parties involved by yielding energy savings and decreased transportation costs.

The results from the replicability study indicated that annual nutrient emissions to the Baltic Sea could be decreased by 120 tonnes of P and 1375 tonnes of N if the integrated RAS replaced all remaining sea cages in the Baltic Sea Region. Within the replication land areas studied, seven example locations were selected as ideally suited for new-build integrated RAS facilities, based on the opportunities to meet the anticipated energy and material demands of the RAS through coupling with local industries, renewable energy technologies and the surrounding environment.

As this study was conducted solely as a desktop study, significant steps would still need to be taken to actualise the integrated RAS farms that were envisioned in the study. For each individual RAS, a thorough energy modelling and business case evaluation would need to be conducted. Furthermore, the fish farmer would need to engage with the power producers, grid operators, renewable energy project developers, local industries, regulatory bodies, and other stakeholders to realise the circular concepts outlined in this report. The limitations of this study and opportunities for future work are detailed below.

5.1 Limitations

- Did not explore other methods for reducing nutrient emissions from offshore fish farms
- Excluded evaluation of coupling with solar farms in the replicability study
- Largely focused on energy aspects, rather than social and financial considerations

- Stakeholders in the replication locations were not interviewed. The conclusions from the replicability study were purely from the desktop study and authors’ prior knowledge of renewable energy developments in the region

5.2 Future work

The model built for this report has been done flexibly so that it can be easily adjusted depending on the specific conditions at another fish farm. Updating the hourly electricity demand, market prices, land availability, and other local factors enables reviving the potential installations on renewables on site that are economically beneficial (payback time of approximately ten years in the modelled results in a system with a 25-year lifetime). Both fish farms needing cooling or heating are possible to model in the framework built for this project.

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APPENDICES

Appendix A. Existing RAS production in the Baltic Sea countries

Table A. Mapping of RAS production in the Baltic Sea region, excluding Russia (EUMOFA, 2021).

Country	**Development stage**	**Enterprises (2018/2019)**	**Main species**
Denmark	Commercial stage with significant production – 34 farms including freshwater and saltwater	34	Rainbow trout, European eel
Estonia	Desk review identified RAS production with low production (no more info on the freshwater share)	n.a.	
Finland	Commercial stage with low production (less than 1000 tonnes)	5	Rainbow trout
Germany	Commercial stage (50 farms) with significant production and 26 farms for research purposes. 14% of RAS production is carried out in freshwater	76	European eel, European catfish, North-African catfish, pike-perch, sturgeons
Latvia	Commercial production with low production	n.a.	
Lithuania	Commercial stage with low production	26	Rainbow trout, north African catfish
Poland	there are 24 farms using RAS but only 8 have significant production (more than 50 tonnes per year).	24	Rainbow trout, north African catfish, tilapia

Sweden	At early stage, mainly for restocking purposes (hatcheries)	7	Rainbow trout, arctic char, sturgeons, carps, pikeperch, Nile tilapia

Appendix B. Parameter requirements for different fish species

Table B. Overview of parameter requirements for selected species produced in the Baltic Sea countries.

Name	**Water type**	**Temperature Requirements (deg C)**
Rainbow trout (*Oncorhynchus mykiss*)	Freshwater or Saltwater (2)	16 (1)
Common carp (*Cyprinus carpio*)	Freshwater (2)	26 (1)
Arctic char *(Salvelinus alpinus)*	Freshwater or Saltwater (3)	14 (1)
Atlantic Salmon (*Salmo salar*)	Saltwater (1)	14 (1)
European eel (*Anguilla anguilla*)	Freshwater (2)	24 (1)
Pike-perch (*Sander lucioperca*)	Freshwater (1)	20 (1)
African Catfish (*Clarias gariepinus*)	Freshwater (1)	28 (1)
Tilapia (*Oreochromis niloticus*)	Freshwater or Saltwater (4)	28 (1)

(1) Bregnballe, 2015
(2) EUMOFA, 2021
(3) Pettrone (2019).
(4) https://www.globalseafood.org/advocate/considerations-tilapia-farming-saltwater-environments/

Appendix C. Direct nitrogen and phosphorus loads from aquaculture in 2014

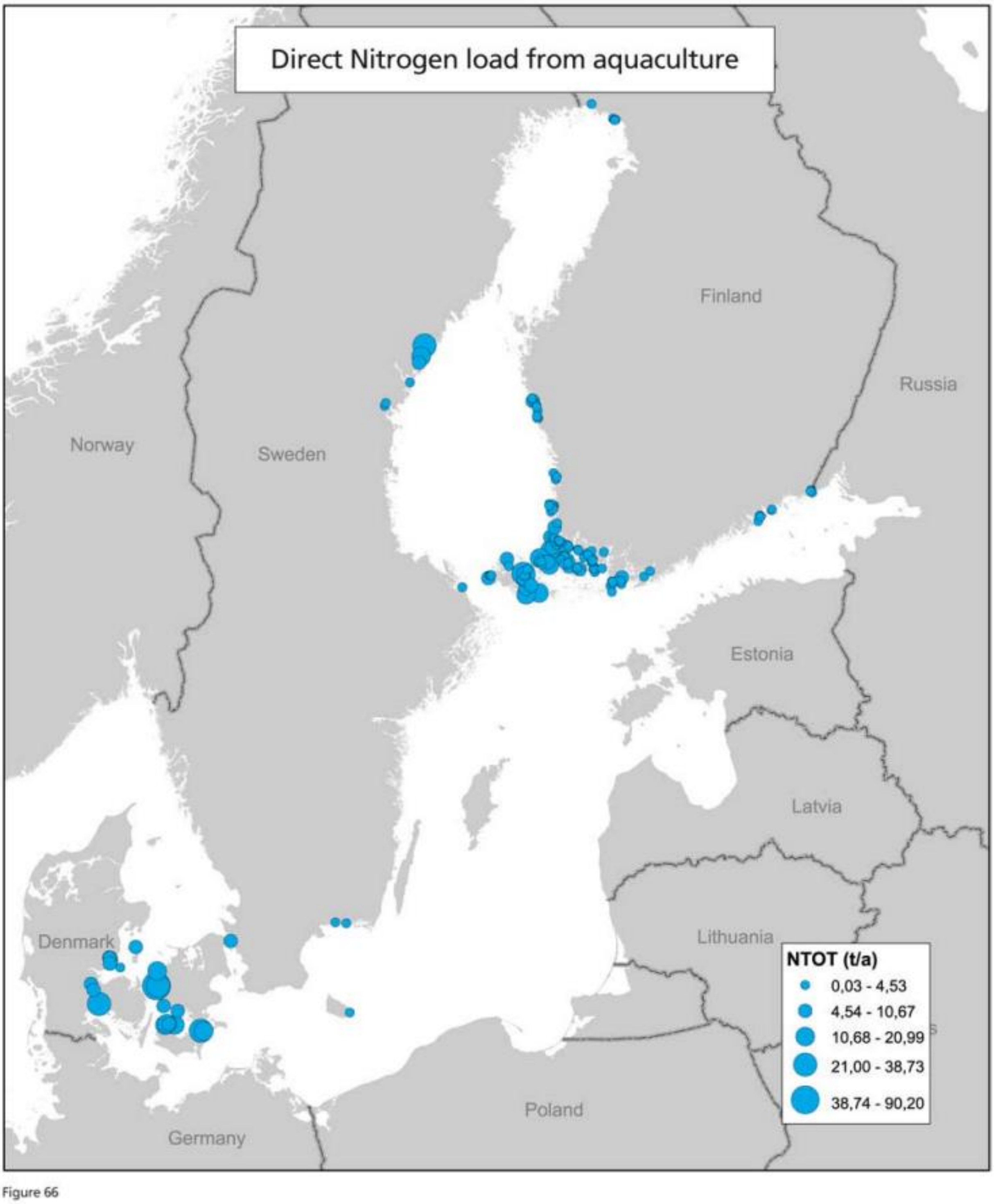


Figure C1. Direct nitrogen load to the Baltic Sea from aquaculture (HELCOM, 2018).

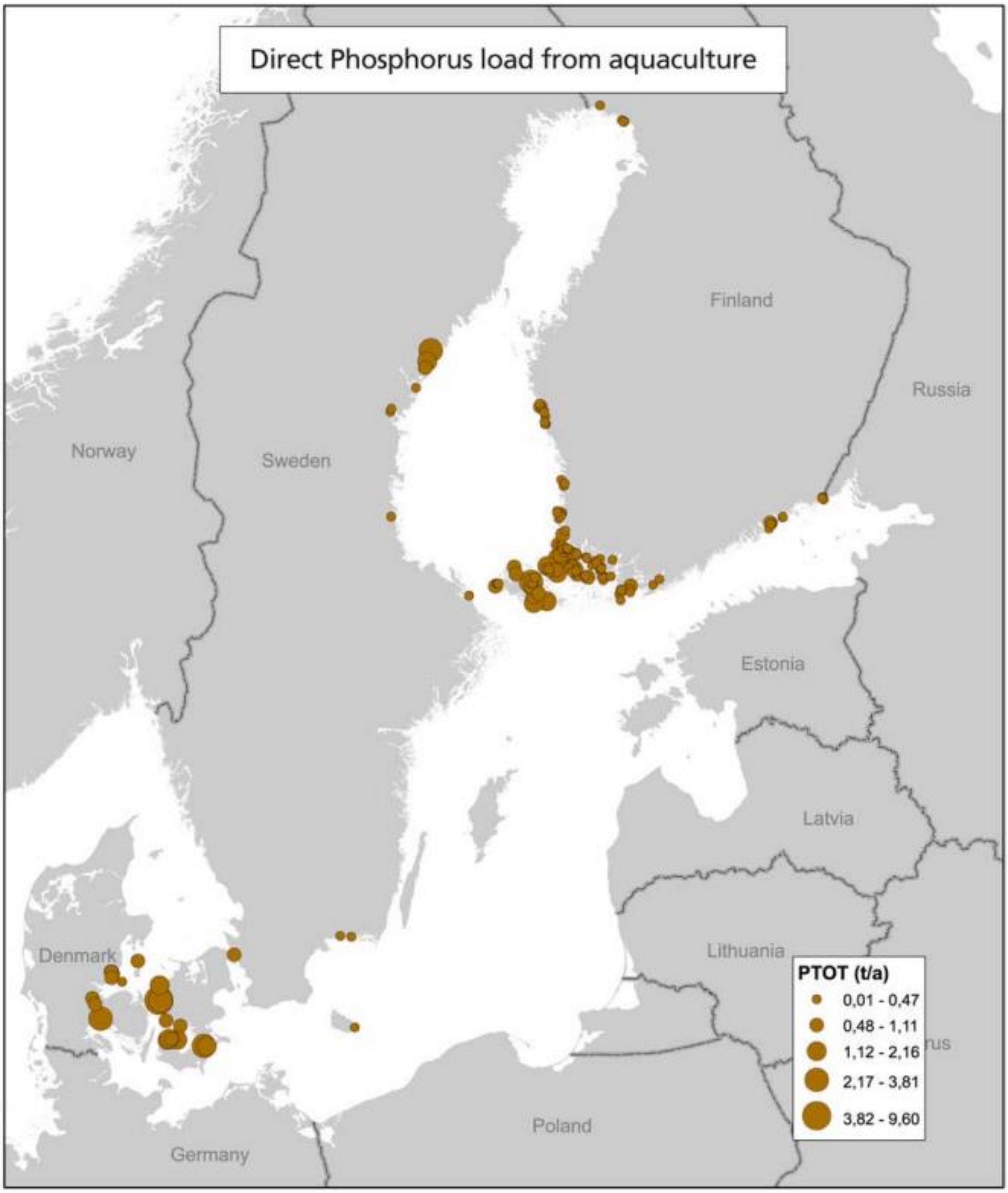
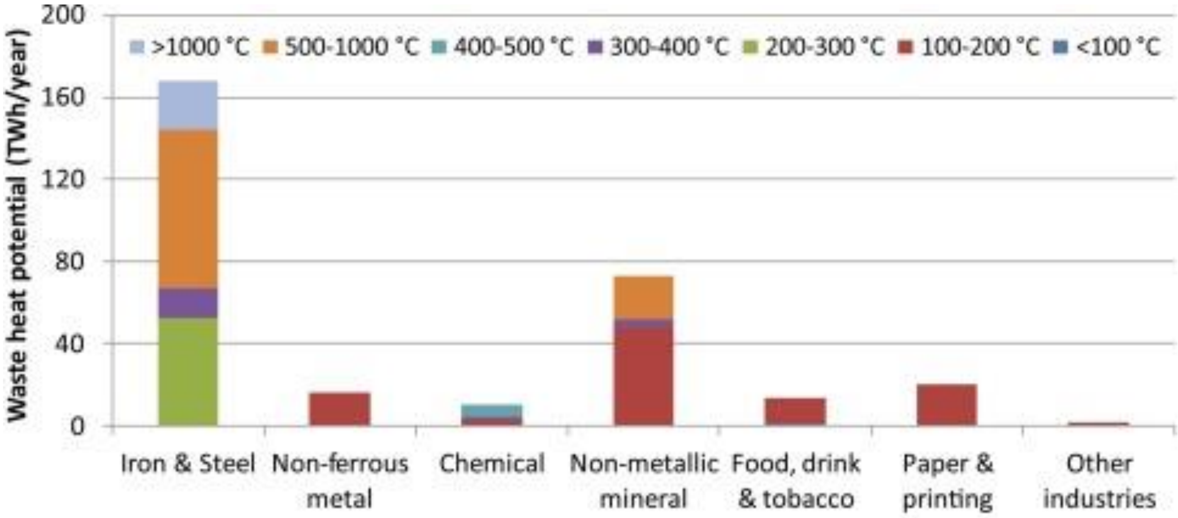


Figure 67

Figure C2. Direct phosphorus load to the Baltic Sea from aquaculture (HELCOM, 2018).

Appendix D. Industries producing waste heat

(a)



(b)

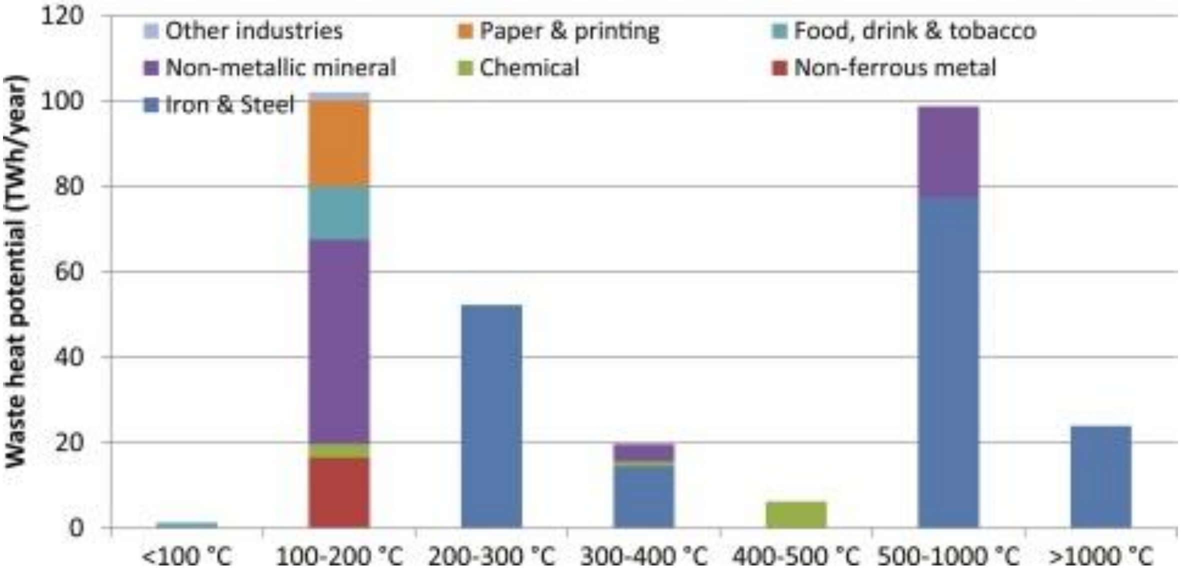


Figure D1. Waste heat potential (TWh/year) of industries in the European Union by (a) industrial sector and (b) temperature (Papapetrou and Kosmadakis, 2022)

Appendix E. Decision diagram for preliminary analysis of coupling opportunities.