Interreg
Baltic Sea Region

Co-funded by
the European Union

BLUE ECONOMY
TETRAS

BAT Report for Saltwater RAS

Best Available Technology & Business Case for Scaling Up the Solution Identified by Pilot 1: 'Saltwater from RAS – Treatment of Technical Water Used in Symbiosis', and a Future Perspective.

Project co-funded by
Interreg Baltic Sea Region

/ Business
Lolland-Falster

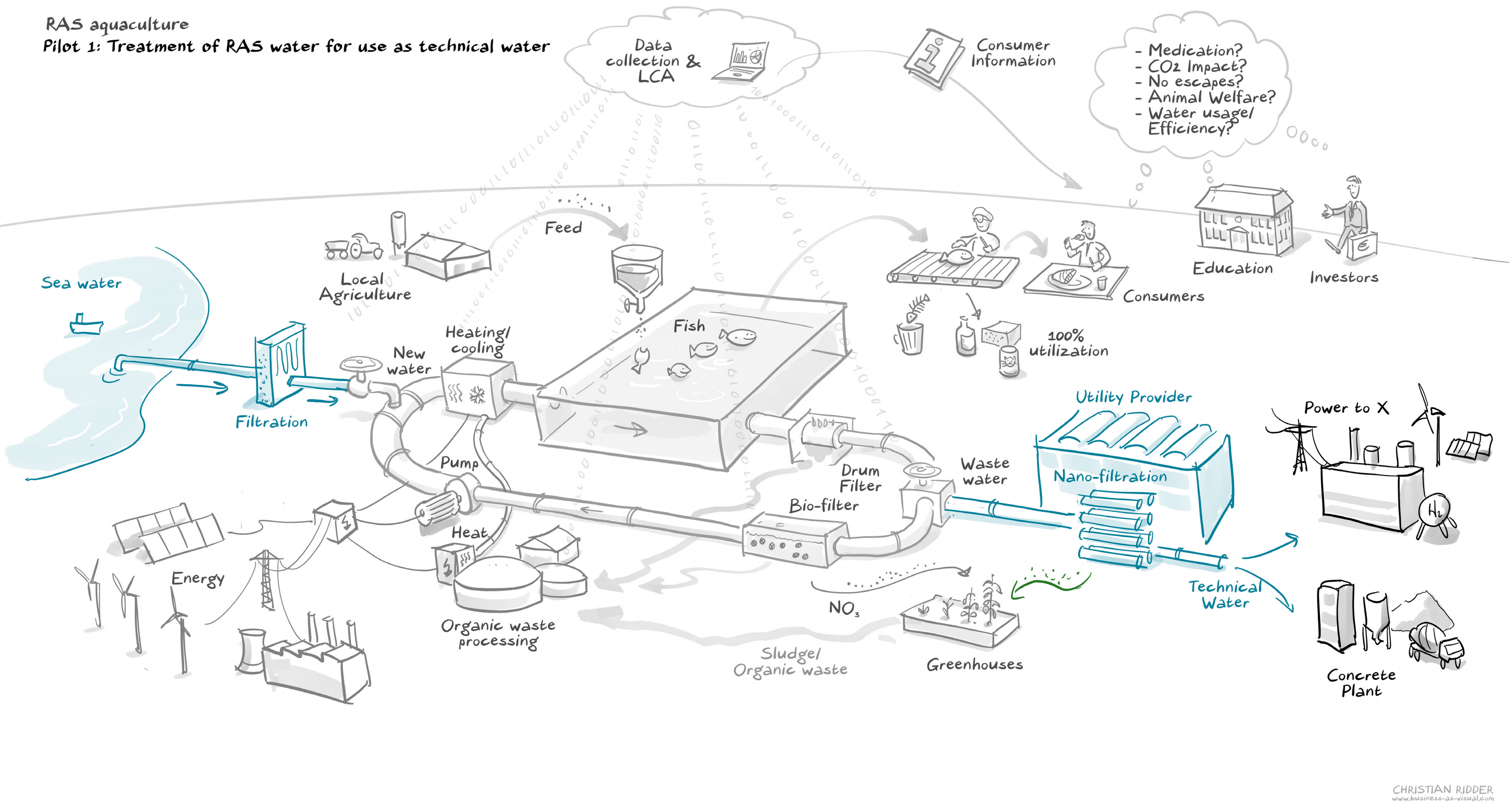
RAS aquaculture
Pilot 1: Treatment of RAS water for use as technical water
Data collection & LCA
Consumer Information
- Medication?
- CO2 Impact?
- No escapes?
- Animal Welfare?
- Water usage/ Efficiency?
Sea water
Filtration
Local Agriculture
Feed
New water
Heating/ cooling
Fish
Consumers
Education
Investors
100% utilization
Utility Provider
Nano-filtration
Power to X
Pump
Drum Filter
Bio-filter
Waste water
Heat
Energy
Organic waste processing
NO_3
Sludge/ Organic waste
Greenhouses
Technical Water
Concrete Plant
CHRISTIAN RIDDER
www.business-as-visual.com

Table of Contents

Context of the Report

This Best Available Technology (BAT) report and Business Case has been prepared as part of Pilot 1 of the TETRAS project. TETRAS is a three-year project (2023-2025) funded by Interreg Baltic Sea Region.

The project aims to improve the economic and environmental sustainability of recirculating aquaculture systems (RAS) by demonstrating new concepts of industrial symbiosis where RAS are placed strategically or combined with industrial processes to increase resource efficiency (water or energy) while producing affordable and healthy food.

The project has also developed tools and standards to assess and monitor RAS and promote investment, cluster creation, and expansion of these food systems. TETRAS is led by a consortium of research organisations, academic institutions and business organisations and is supported by Interreg Baltic Sea Region under the Water-Smart Societies programme – Blue Bioeconomy.

Discharge of nutrients from RAS systems is a barrier for growth in the RAS industry, which is why the project aims to develop a solution that supports sustainable development in the RAS industry and increase the available resource of technical water.

Pilot 1 evolves around the business symbiosis between a salmon RAS, which supplies partially purified water, a municipal utility company that processes the water from RAS to technical water, and the industry as end-users of the water. Pilot 1 has tested several technologies to demonstrate that discharged water from a RAS facility can be treated to meet the quality requirements to be used as technical water for other industries.

The study has also assessed what improvements can be expected in RAS from treatment of discharge water within a 5-year period and reviewed the existing water treatment methods for production of technical water from saltwater RAS systems, just as it has recommending areas for future study.

Executive Summary

The UN forecasts the population growth to peak at 10.4 billion in 2086. At the same time meat consumption is expected to increase by 20-40% per capita. This massive future demand for protein sources can only be met by replacing meat from land animals at least partially with protein from aquatic sources. But as wild stocks have been depleted and the oceans in general, and the Baltic Sea in particular, are under pressure, it is necessary to reevaluate how the 'blue' protein is produced.

TETRAS aims to improve the economic- and environmental sustainability of recirculating aquaculture systems, through the demonstration of new concepts of industrial symbiosis, placing the RAS strategically or in combination with other industrial processes to improve resource efficiency, while producing affordable, healthy food. Pilot 1 tests the best available technologies (BAT) to demonstrate how discharge water from RAS systems can be treated to meet the quality requirements to be used as technical water for other industries. This is crucial in a region where groundwater influx is too scarce to support a developing industry, and the ocean is too overloaded with nutrients already to accept additional discharge of nitrogen.

RAS production holds the potential of becoming the solution to future protein deficit, as well as being environmentally friendly and locally produced. Besides a feed conversion rate close to 1, it has several environmental benefits, such as waste collection, disease control and protection of wild stock through avoidance of escapes. In addition, RAS production is year-round and although energy intensive, has a very low environmental footprint.

The environmental impacts and associated running costs can be reduced by thinking RAS into industrial symbiosis, which makes it perfectly suitable for Lolland-Falster, as well as the wider Baltic Sea region. Lolland-Falster is undergoing rapid development within renewable energy- and infrastructure projects. The industrial development could prove mutually beneficial in a cluster setting which includes RAS, especially from a water re-use perspective, as it is not a given (in Denmark) that industrial customers gain access to ground water.

Just as the reduced access to groundwater could be a limiting factor, so could the restrictions associated with obtaining a discharge permit, hence the discharge water from a RAS could become a cluster commodity instead of being the limiting factor.

The solution piloted has undertaken to use membrane filtration to filtrate RAS wastewater to obtain water of drinking water quality which can then be reused for other industrial purposes or further treated to make ultra-clean water for PtX. As the challenge lies as much in finding a cost-efficient way of producing technical water as in finding ways to dispose of the residual waste stream, the pilot will also examine the reject and how to create usable side streams as opposed to waste. A particular challenge will be the salinity and treatment of reject water from the filtration processes.

The pilot team has carried out an extensive desk study of the proposed solutions from Deliverable 1.1 and shortlisted several promising technologies which are further scrutinized in this study. They all have the desired characteristics in the right configuration; however not all configurations are suitable for the symbiosis solution, which is the purpose of this pilot.

Executive Summary

The membrane filtration technology tested, was a combination of ceramic ultra filtration (CUF), and reverse osmosis (RO). In addition, membrane distillation was tested to determine if it could be an advantageous/feasible substitute for reverse osmosis, as it can utilise low temperature waste heat from, for example, PtX.

To run the tests on actual discharge water, an agreement was made with 'Skagen Salmon'. The tests were carried out at their RAS plant in Skagen, Denmark in early October 2024 and the membrane distillation tests were carried out at DTU in Lyngby during the following month. The 'feed' water for the test was diverted from the discharge water which is normally discharged to the sea (under a discharge permit).

The test results fed into a detailed techno-economic assessment of a water reclamation facility (WRF) producing technical water from the wastewater from a Recirculating Aquaculture System (RAS) using membrane technology, focusing on both the water quality of the permeate for reuse and the potential reuse options for the reject water. An economic analysis of a future full-scale WRF spans a 20- year period, from 2025 to 2044, examining CAPEX and OPEX.

The permeate water produced through CUF and RO processes was extensively assessed against Danish drinking water standards. The CUF permeate failed to meet several key drinking water standards due to high salinity and ammonia levels. However, RO permeates at 65% recovery rate (RO65) showed significant improvements. The RO65 permeate is expected to meet the ammonia limit however, the detection limit of the analysis (<1 mg/l) was far beyond the Danish drinking water limit for ammonia (0,05 mg/l). A theoretical estimation of ammonia in the RO65 suggested compliance with this limit (expected 0.037 mg/l). Other parameters, such as conductivity and chloride levels, were within acceptable limits, making RO permeate suitable for industrial applications, including industrial processes where purity is a crucial factor.

The MD experiment at DTU achieved a recovery rate of up to 80%. The distillate had an average conductivity of 0.35 mS/m, far exceeding the typical performance of single-stage RO, which achieves around 30 mS/m. Chloride levels were significantly reduced in the distillate (< 1 mg/l), compared to the reject (37,000 mg/l).

Other substances such as fluoride, nitrites, nitrates, and silicates were all below detection limits. And organic matter was reduced very effectively. The distillate was very soft, with minimal calcium and magnesium, and iron. Aluminium, barium, and lead were all below detection limits.

The reject water from the treatment processes was rich in nutrients, including ammonia, nitrite, nitrate, phosphorus, and potassium, presenting opportunities for reuse in agriculture as fertilizer. However, the high chloride concentrations and trace heavy metals make the reject unsuitable as fertilizer.

The low COD concentrations and trace heavy metals, not only make the reject water undesirable in biogas production, but high chloride concentrations also inhibit the process. Advanced treatment methods (biological systems, adsorption, advanced oxidation) are required to effectively lower contaminant levels for safe discharge to the Baltic Sea or to municipal wastewater treatment plants.

The business case prepared includes the design and costing of a future full-scale WRF capable of treating 200 m^3/h of RAS wastewater, priced with a 30% uncertainty.

The economic analysis over a 20-year period evaluated the total expenditures (TOTEX), considering both CAPEX and OPEX. The projected CAPEX for the facility was €15,847,020, and the total OPEX is approximately €42,428,288, summing up to a TOTEX of €58,275,308. The net present value (NPV) of TOTEX was estimated at €43,942,052, translating to a specific TOTEX NPV for technical water of €2.03 per m^3. By implementing optimizations due to lower salinity at Lolland-Falster, the specific TOTEX NPV for technical water is reduced to €1.97 per m^3.

The estimated costs of reject water treatment, at more than 50% uncertainty, range between €1.10 and €3.29 per m^3, reflecting a significant impact on the overall economic viability. Strategic planning for effective reject water management should be prioritized to ensure overall project permissibility and economic viability.

What is possible today is not the same as what is installed, as the operators are looking at feasibility within the limits of their environmental permit. However, the development in technology only during the course of this project clearly indicates that even solutions which are not presently feasible may become so in the near future, both due to technology advances but also because of tightening of legislation. If nitrogen and phosphorous in the future will be treated as commodities at the same level as CO_2, this would further add to the feasibility.

As it has been demonstrated in Skagen, RAS can be feasible in the right configuration and we believe that Pilot 1 is presenting a solution which holds the potential of making RAS both achievable and feasible in the Baltic Sea region, in the future.

Finally, as emphasised in the chapter on Evolution – the future is already here. The highlighted projects, startups and innovators showcase brilliant solutions to wastewater treatment, just as the next generation RAS fully integrated in industrial symbiosis is not far away.

Abbreviations

BAT	Best Available Technology
BLF	Business Lolland-Falster
CAPEX	Capital Expenditures
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
CUF	Ceramic Ultra Filtration
DC	Direct Contact
DeOx	Deoxygenation
DTU	Danmarks Tekniske Universitet (Technical University of Denmark)
FAO	Food and Agriculture Organisation (of the United Nations)
FCR	Feed Conversion Rate
GEUS	The Geological Survey of Denmark and Greenland
GHG	Green House Gasses
$GtCO_2e$	Giga-ton Carbon Dioxide Equivalent
LBCC	land-based closed containment
LCA	Life Cycle Analysis
LMH	Liters per square meter per hour
MBBR	Moving bed biofilm reactor
MD	Membrane Distillation
µm	Micron
N	Nitrogen
NPV	Net Present Value
ONP	Open Net Pen
OPEX	Operational Expenditures
P	Phosphorous
RO	Reverse Osmosis
RO65	Reverse Osmosis, 65% recovery rate
RAS	Recirculating Aquaculture System
RE	Renewable Energy
SiC	Silicon Carbide
TOTEX	Total Expenditures
UN	United Nations
US	United States [of America]
WRF	Wastewater Reclamation Facility
WRI	World Resource Institute

Glossary

Discharge	In this context, discharge is the wastewater which has been treated within the RAS plant, to a level of cleanliness on par with the most modern wastewater treatment plants.
Feed Conversion Rate	Kg of feed to produce 1 kg of meat.
Flux	The measure of a membranes performance and how much liquid can be filtered or processed, the unit used to describe flux here is Liters per square meter per hour (LMH)
Industrial symbiosis	A group of individual businesses joining forces to utilise each other's side streams.
Moving bed biofilm reactor	A vessel for organic breakdown and nitrification.
Permeate	The resulting water which has passed through the filtration (the 'clean' water).
Recipient	The receiving water body. In this context the Baltic Sea.
Reject	The sludge etc. filtered from the wastewater when treating this to meet drinking water quality.
RAS system	A recirculating Aquaculture System is a land-based fish production facility which cleans and recirculate the water utilised in the process, enabling low water usage per kg of produce.
Side streams	Products which are waste for one industry but can be utilised as a resource in other industries. Common side streams are wastewater, CO_2, oxygen, heat, nutrients.
Technical Water	Water for industrial usage. In this context recovered water of drinking water quality or near drinking water quality.
Ultra clean water	Water used for PtX which is ultra-pure demineralized water.
Volatiles	Group of chemical elements and -compounds that can be readily vaporized, in aquaculture primarily CO_2.

The Focus of the BAT Report & Business Case

This BAT report will summarize and expand on the results of the feasibility study and the pilot tests caried out as part of Pilot 1.

In conjunction with the concept piloted and this BAT report, a business case has been prepared for a full-scale water reclamation facility. The business case has examined the economics of producing technical water from RAS discharge water and endeavoured to put a monetary value on the potential side streams which can be derived from RAS production or utilised by a such.

The business case will amongst others examine:

- The cost of production of fresh water from RAS discharge.
- Size of market for fresh water and ultra clean water for industrial purposes
- Cost of discharging water to utility / recipient
- Cost to consumers for off taking fresh water
- Value of side streams derived from filtration process versus cost of disposal
- Legal implications in relation to handling discharge and reject water from RAS.
- ESG benefits in addition to monetary value of side streams

Background

It has been forecast that the demand for feed, fibre and food would increase by 70% during the first half of this century. This excludes crops intended for bioenergy production and other industrial purposes. A large part of the projected increase in feed is for animal consumption, to cover the rise in demand for animal protein.[1]

The ongoing war in Ukraine and escalating conflicts in the Middle East further exacerbate the need for self-sufficiency when it comes to securing the food supply chain.

Meat consumption is forecast to increase by 20-40% per capita by 2050, just as the global population is expected to grow another 25%, before peaking at 10.4 billion in 2086.[2] The continued population growth and the increase in meat consumption must be observed coherently to produce an accurate picture of the future demand for animal protein sources, and to assess how to meet this demand.

Just to maintain an apparent consumption of aquatic food, at an estimated average level of 20.7 kg per capita through to 2050, would require an increase in the total supply of aquatic animal foods of 36 million tonnes, or 22 percent global increase.[3]

The figures below corelates with a report indicating the demand for blue food (fish, bivalves) will have doubled by 2050 due to rising population size and increased living standards alone.[4] As wild fish stock has largely been depleted, it will be necessary to reevaluate how the blue protein is produced.

RAS production in industrial symbiosis has the potential to sustainably bridge the gap between supply and demand when it comes to animal protein sources and can in the right setting do so with minimal impact. Not only does RAS reduce the impact on the wild stock, but it also makes it possible to produce more with less, as the lower feed conversion rates (FCR) in aquaculture mean you increase protein production without increasing feed production, by swapping four-legged animals with fish.[5]

When producing salmon in RAS the FCR (kg of feed to produce 1 kg of fish) drops to around 1.1 (compared to 1.4 for salmon in open cage, and 4-10 for beef). It is even possible to reduce the feed requirement further by changing to a more 'economic' species. For instance, does the Clarias (African catfish, subject of Pilot 4) thrive with an FCR below 1.

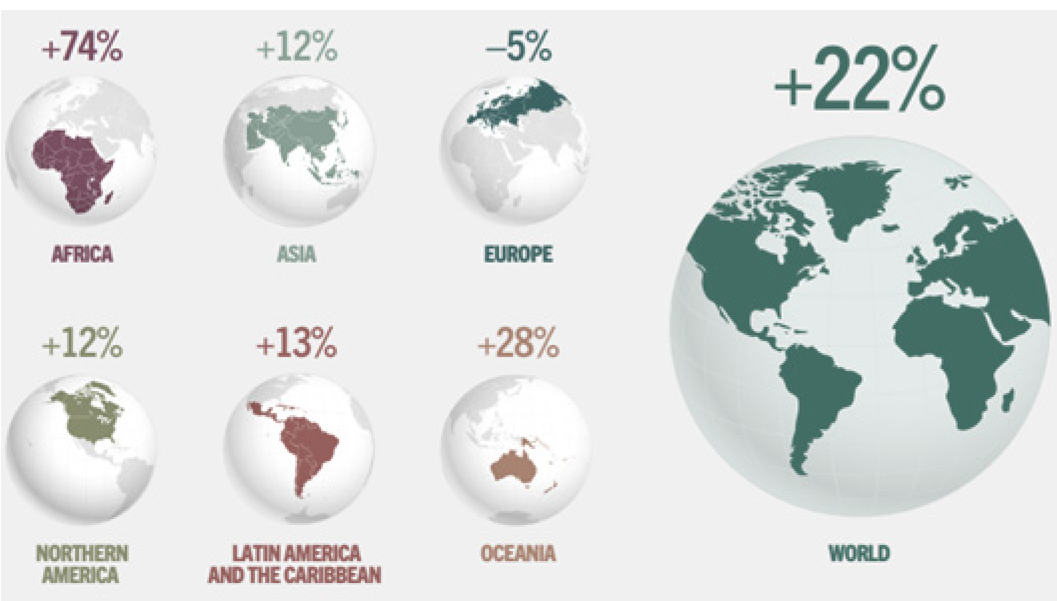

Figure 1: Estimated rise in demand for aquatic animal foods by 2050 at unchanged consumption pattern[3]

1 FAO (2009)
2 Our World in Data (2023)
3 FAO (2024)
4 Nayler et al (2021)
5 World Resources Institute (2015)

Condition of the Baltic Sea

The catchment area for the Baltic Sea is about four times larger than the Baltic Sea itself supporting an influx of fresh water which is double that of salt water, making it one of the world's largest brackish water areas. The saltwater replacement time is very long (25 years)[6], making the Baltic Sea extremely vulnerable to even minor environmental strains from the surrounding land areas. It is estimated that the degraded environmental conditions bear an annual cost of 9 billion euros to the region in terms of lost recreational benefits.[7]

Under 'normal' conditions the Baltic Sea is low on biodiversity, as marine organisms struggle with the low salinity and freshwater species have problems tolerating the saline brackish water. Because the bottom areas with the higher salt-content are close to being permanently oxygen-free, this acts as an obstacle for fish, shellfish, and other marine organisms which would under normal conditions thrive here.[8]

Traditional coastal fishing was in the 1970s partially replaced by trawlers, especially from the then Soviet Union, Poland and Eastern Germany which quickly resulted in overfishing. Sturgeon is believed to be extinct, and todays catch mainly consist of herring and sprat.[9]

Wild Salmon is only caught in very limited amounts and only smaller individuals, as the dioxin content is high and increases with size[10]; It is recommended to limit intake of Baltic Sea Salmon to 1-2 times a month (125 g).

While overfishing is only part of the problem, it is not only a problem in the Baltic Sea. Although the rate of decline has slowed, more than a third of global fish stocks are over-fished, up from 10 percent in 1974.[3]

Advantages of RAS Production

To sustain aquaculture as an industry within the Baltic Sea basin, without exacerbating the adverse impacts usually associated with aquaculture, it is obvious to turn to RAS production, which holds several noteworthy advantages, besides significantly better feed conversion rates, such as:

- Collection of waste
- Optimal sanitary conditions
- Isolation from climate related factors
- Avoidance of escapes
- Protection of wild stock
- Limits external transmission of diseases and parasites (biosecurity)
- Reduced competition for access to sea space
- Full control of production parameters
- Year-round production

Saltwater RAS within the Baltic Sea region may also benefit from the lower salinity of the sea water which could be better suited for salmon. The optimum level may be as low as 10%.[11]

6 Britannica (2023)
7 HELCOM (2022)
8 Madslund (2023)
9 Madsen et al (2025)
10 Fødevarestyrelsen (no date)
11 Emerman (2016)

Potential of Lolland-Falster

The twin islands of Lolland and Falster are situated to the South-East of the Danish Archipelago in the Western part of the Baltic Sea Region.

Lolland-Falster is a region experiencing rapid development, with the 'Fehmarn connection' (submerged tunnel to Germany) acting as a catalyst, which will bring the German consumers closer to the Danish market.

The growth in primarily 'green' industry is providing optimum conditions for the creation of business symbiosis between RAS facilities and consumers of technical water.

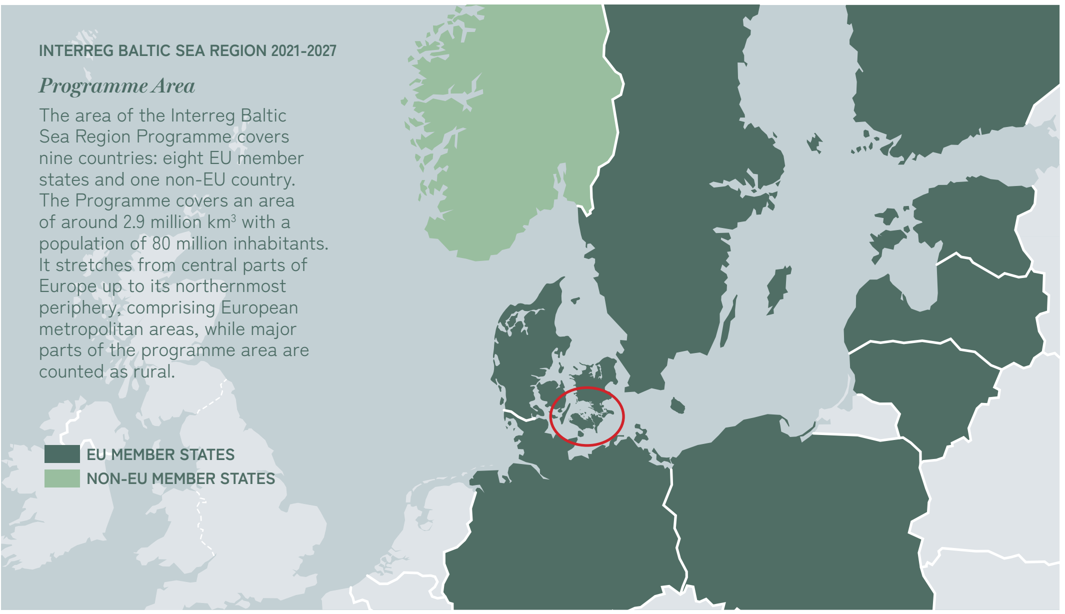

Figure 2: Location of Lolland-Falster [12]

Emerging Cluster Formation

A broad group of new and existing companies have joined forces in a working group exploring cluster potentials, because they eye the advantages in cooperation across sectors. The common denominator is their physical siting within- and around Nakskov and Nakskov harbour.

Amongst the working group participants, are the likes of European Energy, Hveiti, Nordic Sugar, Biofuel Technology, Nature Energy and Lolland Forsyning.

Water, waste heat, RE, bio waste, biogas and biogenic CO_2 are all valuable resources in demand by the companies which constitutes the future industrial symbiosis, shaped in the image of Kalundborg Symbiose.[13]

12 Interreg Baltic Sea Region
13 Business Lolland-Falster (2024)

Groundwater Generation, Utilisation and Conservation

In Denmark, drinking water is almost solely sourced from unpolluted groundwater sources. Industrial customers are however not entitled to receive ground water for production purposes, only water of a similar quality. To maintain the high quality of water supplied and to protect the natural system, the quantity made available for extraction is monitored and restricted. In 2003 the quantity available was restricted to 1 billion m^3 annually, and almost halved since 1992. Further reduction is expected in the future if pesticide pollution spreads to the deeper lying groundwater.[14]

The average annual rainfall in the eastern part of Denmark is considerably lower than the western part. Where some parts of southern Jutland experience average rainfall of above 900 mm, the average rainfall in Lolland-Falster is between 500-700 mm. At the same time, a combination of agricultural management and soil composition means that the run-off from the fields is a lot more distinct in Lolland-Falster, which further reduces the water regeneration pace of the aquifers.

In Denmark you may as a rule exploit up to 10% of the groundwater generated. However, in Lolland 30% is exploited and in Falster 52% is exploited.

Rising sea water levels also carries the risk of saltwater ingress into aquifers near the coast, potentially reducing the size of reserves.[15]

In 2023 the total extraction of water in Denmark amounted to 984.8 mil. m^3 of these only 237 mil. m^3 were for household purposes. With consumption being this close to the extraction limit it is getting critical to identify alternative supplies for industrial purposes, where the water will not be used for human consumption.

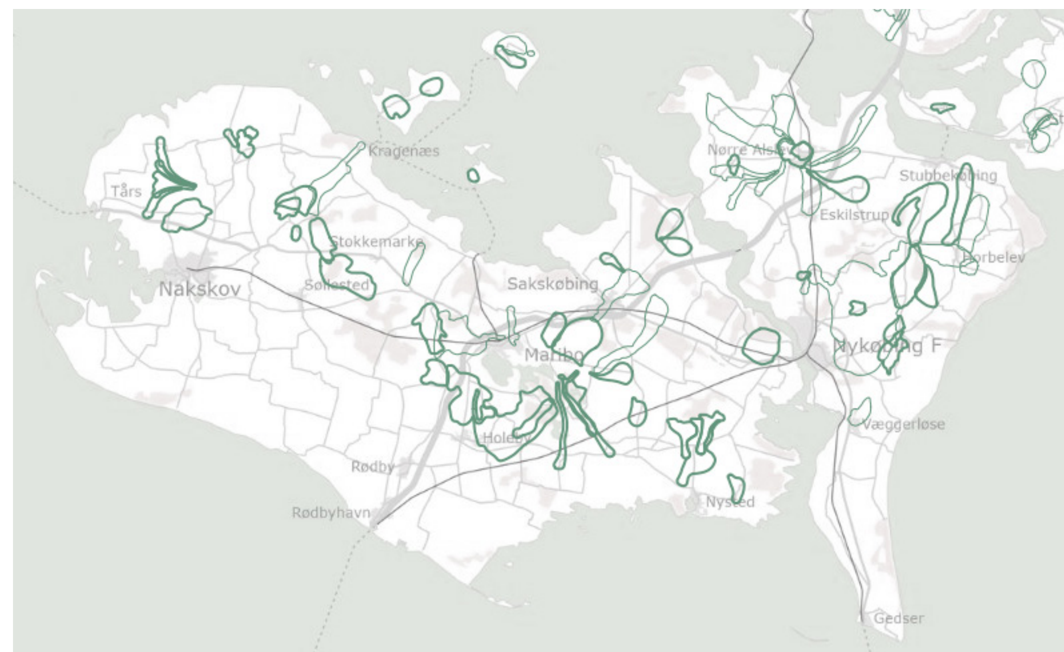

Figure 3: Aquifers in Lolland-Falster[16]

The encircled areas identified as drinking water aquifers, of interest and of special interest.
The map also highlights the lack of water, particularly in southern Lolland.

14 Danmarks Naturfredningsforening (2015), (2024)
15 Klimatilpasning (2023)
16 Miljøstyrelsen(no date)

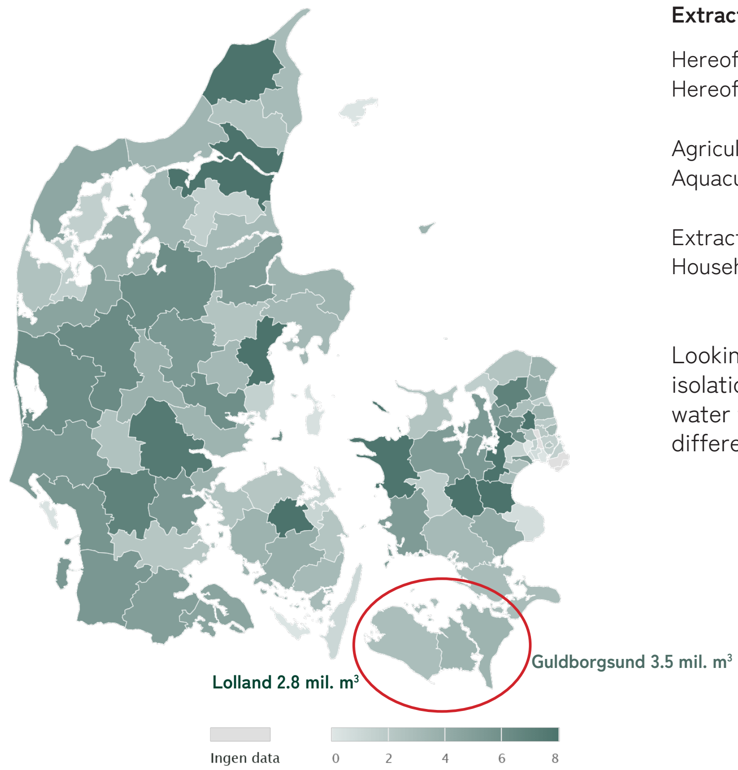

Figure 4: Total extraction in 2023[17]

Extracted in total:	**985 mil. m³**
Hereof groundwater:	753 mil. m³
Hereof surface water:	231 mil. m³
Agriculture:	290 mil. m³
Aquaculture:	261 mil. m³
Extracted by Utility (40%):	392 mil. m³
Households, DK total:	237 mil. m³

Looking at Lolland and Falster in isolation, 1 million m³ of reclaimed water from a RAS could make a big difference.

Future Demand for Technical Water in Project Area

At present, there is a projected future demand from large off takers of 970,000 m³/year in Nakskov and Rødby alone, as illustrated by the table below. Furthermore, the area surrounding the Danish side of the Femern link tunnel has just been designated as one of five industrial parks which the government wish to establish[18], which will only increase the demand.

To alleviate the strain on groundwater resources, it could also make sense to change the source of water supplies for existing non-food industrial clients.

Table 1: Potential large off takers of technical water

WHO	PURPOSE	IMPLEMENTATION STAGE	ANNUAL AMOUNT m³/year	PERIODIC OFF TAKE Y/N
European Energy	PtX, Nakskov	Planned	300.000 m³	No
Element Factory	Concrete production, Rødby	Completed	330.000 m³	No
Hveiti	Grain refinery, Nakskov	Planned	240.000 m³	No
European Energy	PtX, Rødby	Pre-planning	300.000 m³	No
Projected future industrial demand from large off-takers			970.000 m³	

17 Danmarks Statistik (2023)
18 Femern Belt Development (2024)

With a projected (waste-) water surplus around 1.7 million m3/year - of which up to 1,250,000 m³ could be made available as water of drinking water quality - a RAS facility producing 5,000 ton of salmon, could cover the internal requirement for fresh water, as well as covering the water requirements from industrial customers.

Other potential off takers of technical water could be datacentres, which use freshwater for cooling, to reduce the high energy consumption usually associated with air cooling. Several proposed locations are in play on both Lolland and Falster, but none at a stage as advanced as the projects in Table 1. It is estimated that a medium sized AI datacentre has a freshwater requirement in the region of 500,000 m³/year[19], although the exact figure is difficult to verify.

At present there is limitation in the use of 'second-hand' water when it comes to production of food and food ingredients, due to legislative restrictions. This is expected to change at European level within the foreseeable future.

RAS Production and Water Usage

Recirculating aquaculture systems (RAS) are systems which enable 'growing fish' on land. By filtering and recirculating the water, the water usage can be reduced from 30-50 m³ per kg/feed produced in a flow-through system down to 400-500 litres per kg/feed in a traditional RAS plant.

The internal water treatment in a RAS plant consists of a mechanical filter, a biological filter and aeration. The mechanical filter removes the suspended solids such as faecal matter and leftover fish feed. The filter is often a drum filter, also called a rotary filter. After the removal of solids, the water enters the biological filter, where nitrifying bacteria convert ammonia (NH4), first to nitrite (NO2) and then to nitrate (NO3). Ammonia is toxic to the fish and therefore needs to be converted into something harmless.

Lastly the water will go through aeration to ensure volatiles are stripped from the water. On top of these basic treatments, further treatment is possible such as pure oxygen enrichment, UV disinfection or ozone treatment, automatic pH regulation etc.[20]

The outlet water from this RAS will normally be distributed as illustrated in Figure 5:

- 200-250 litres of process water per kg fish feed becomes wastewater and is compensated by water replenishment.
- A side stream of 150-200 litres process wastewater per kg fish feed is treated by mechanical filtration, biological filtration (often MBBR), CO_2 stripping, ozone, skimmer and finally disinfected before recirculating to the fish tanks.

19 24Victoria (2025)
20 Bregnballe (2022)

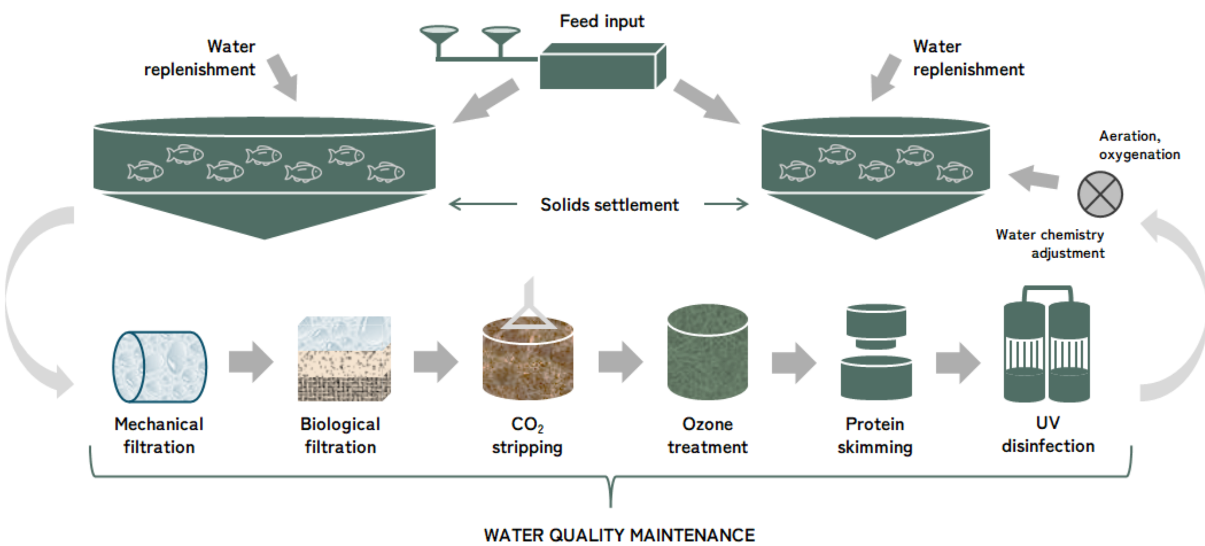

Figure 5: Schematic design of a typical RAS plant for salmon production[21]

The first two treatment steps, mechanical and biological filters, produce a stream for further treatment before being recirculated, as well as a wastewater stream which is led to sludge treatment. The sludge reject water, together with the 200-250 litres of process wastewater, is traditionally discharged (to the ocean) from the RAS plant, but will as part of this pilot study be treated for reuse.

Available technology supports water usage as low as 30 litres/kg fish produced if denitrification and phosphorus removal is installed in connection to the RAS circuit.

The composition of the process wastewater can vary a great deal and will depend, among other things, on how the plant is operated and the operators experience with management of water quality and water parameters. The species being farmed, stage of species and technologies used in the water purification within the RAS plant will also have an impact. The quality of the sludge reject water is determined by the type of sludge treatment and varies from plant to plant.

Skagen Salmon's wastewater treatment system has been configured to suit the discharge permit associated with the RAS. Operating under a stricter permit regime will require optimisation of the wastewater treatment system and impair both CAPEX and OPEX, just as increased production under the present permit is possible but would equally require system optimisation.

RAS has several environmental advantages besides reduced water consumption. But with the degree of water reusage increasing so does the need for water quality control. Nutrients and organic matter which accumulate in the system can lead to favourable conditions for growth of microorganisms which can be detrimental for the fish, is it not controlled.[22]

21 Brown, Wilson & Tyler (2024)
22 Koski et al (2021)

Carbon Footprint of RAS Production

Although the Baltic Sea region is the main objective of TETRAS, any proposed solution also needs to address the critical global need for significantly reducing GHG emissions.

At present, food production is responsible for around a third of all GHG emissions. If no transformation to the way we produce food is made, the present 18 GtCO_2e emissions annually could reach 30 GtCO_2e in 2050. A complete transformation of the food production system is not only crucial to address climate change but equally vital for safeguarding the natural ecosystems and ensuring food security for all.[23]

Comparing the CO_2 emissions per kg of produce makes it evident that the key to reducing CO_2 emissions from agriculture lies in shifting protein sources from mammals and poultry to seafood.

With beef (13.9 kg CO_2 per 1 kg product) contributing more than 10 times that of farmed trout (1.2 kg CO_2 per 1 kg product)[24], shifting to a seafood-based diet can provide 'fast' relief to the global CO_2 emission surplus and help achieving reduction goals. However, shifting to a seafood-based diet won't be possible without aquaculture, and aquaculture in a required scale will not be possible without RAS.

A life cycle analysis (LCA) performed by Liu et al (2016) on farmed Salmon indicates that salmon produced in RAS in the USA, from eggs to harvestable size of 4-5kg in land-based closed containment (LBCC) and distributed to the local market only has half the carbon footprint of salmon produced in traditional open net pens (ONP) in Norway and delivered by air to the US market.[25] If the energy intensive RAS production is fuelled by RE the carbon footprint will be further reduced. The same study highlights the production costs of RAS only being 0.52 $/kg higher than net pen production costs. This clearly indicates that the higher costs of RAS production can be offset through local production rather than import.

As growing consumer awareness calls for locally produced and environmentally friendly produce with a high level of traceability, which furthers the RAS business case, it would therefore make sense, both from a business and an environmental perspective, to install aquaculture production in RAS systems close to the consumers rather than transporting produce which can be grown locally.

This goes hand in hand with rising food supply insecurity and increased food demand from a growing population which can no longer rely on declining natural stock. A shorter distance between producer and supplier may also contribute to shifting costs from middlemen in the supply chain back to the producer, without incurring added cost to the consumer, enabling growth in local production.

23 UNEP (2022)
24 Food Nation (2023)
25 Liv et al (2016)

The challenge

The possibility of locating a RAS facility with a capacity of 5,000 ton/year in Lolland-Falster has previously been studied but stranded due to process water discharge limitations.[26] Comparisons between samples of treated water from Danish Salmon and the legal targets for Sewage Treatment Plants in Denmark, illustrates that the filtration technology already in place is on par with the national legislation for wastewater.[27]

When producing Salmon in a RAS facility it is expected that the technology presently available can remove >90% of the Nitrogen. The residual Nitrogen after water treatment amounts to 5.4-8.1 kg/ton of fish. It is and has been the general practice to discharge this process water into the sea, as it is as clean as the discharge from a high performing wastewater treatment plant. However, to make a RAS facility feasible it is necessary to operate at medium to large scale (economy of scale), with a realistic production size in the region of 5,000 ton/year.

As the Baltic Sea is already overloaded by nitrogen runoff primarily from agriculture and to a lesser degree from wastewater treatment facilities (and -overflows), discharge permits [for RAS] are unobtainable, in the Lolland-Falster region. It is therefore necessary to establish solutions which do not put any further strain on the aquatic environment.

Danish scientists and RAS businesses have for the past few years worked on optimising the end-treatment of RAS production water, from saltwater production lines, to reduce the discharge of nutrients to negligible concentrations. Applying a denitrification method during end treatment which 'blows off' the nitrate as inert Nitrogen just as phosphorous traps are reducing discharge.

26 Skagen Salmon, Blue Research ApS, BLF (2021)
27 Blue Research ApS (2022)

Outline of the Pilot Project

'Based on the use of technical water on Lolland-Falster, Denmark, a feasibility study is made of water consumption and quality requirements for the technical water used, and of water quality parameters for production water from saltwater salmon RAS.

The study also assess what improvements can be expected in RAS from treatment of discharge water within a 5-year period and review the existing water treatment methods for production of technical water from saltwater RAS.'

Proposed Solution

The limiting factor for the establishment of RAS facilities is in many places whether the process water can be discharged. Therefore, the enabling factor could be, if the discharge water can be processed into technical water and reused, as it can be challenging to obtain discharge permits, especially in the EU where Water Directives are implemented to protect water recipients.

Pilot 1 assumes that all water handling is being undertaken by a utility company, which in this proposed solution will be treated as a separate entity. The operators could be the same people, as is the case in Sotenäs where Smögen Lax (the RAS) and Rena Hav (the utility) are subsidies of the same parenting company. Or could, as is the present situation in Lolland, be undertaken by the public utility. A public utility has the added benefit of operating as a 'not-for-profit' organisation.

Pilot 1 has conducted tests of production of technical water of (Danish) drinking water quality using membrane technology, evaluating management of all water streams in the water reclamation facility (WRF) and conducted an economic analysis of the technical solution in full-scale.

The study was conducted using the discharge water from Skagen Salmon. The study specifically investigated the performance of ceramic ultrafiltration (CUF), reverse osmosis (RO), and membrane distillation (MD). CUF was tested for its ability to remove suspended solids and larger particles from the wastewater, and RO for its high efficiency in desalination and removing dissolved salts and organic matter.[28]

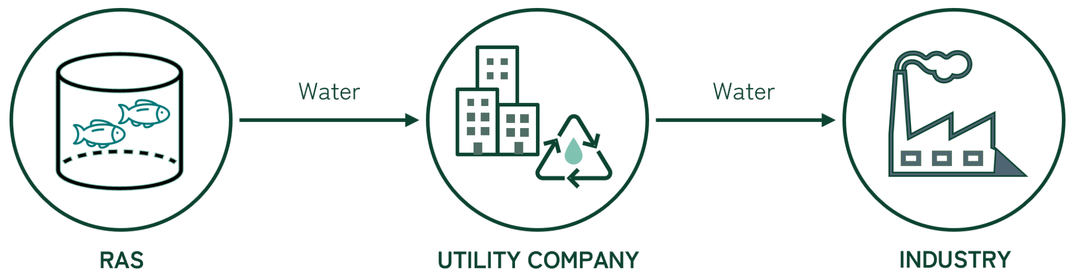

Figure 6: Proposed setup for Pilot 1 with solution anchored in the utility company.

28 Rambøll (2025)

In addition, MD was explored for its potential in utilizing surplus heat for water recovery, as it can operate effectively with low-grade heat, making it a promising solution for energy-efficient wastewater treatment, and a perfect solution in an industrial symbiosis setting with a surplus of low temperature waste heat.

When producing technical water utilizing membrane technology, two streams will be generated, a permeate stream and a reject stream. The permeate is the ‘clean’ water stream which can be further treated or directly used in industrial applications, and the reject stream is the ‘waste’ stream containing higher concentrations of the various pollutants from the wastewater, which are removed from the technical water.

The reject water therefore creates an additional challenge when producing technical water. To eliminate or at least reduce the amount of reject water to be handled, the potential for reusing the reject water in symbiosis between sectors is explored. The four scenarios that will be examined:

- Agricultural use
- Biogas production
- Direct discharge to the sea
- Direct discharge to a wastewater treatment plant

These scenarios were assessed in relation to Danish regulations, with the consideration that the regulatory thresholds may differ in other European countries. When evaluating the option of direct discharge to the sea in particular, regional differences in seawater composition must be considered.

A full-scale WRF with a capacity to treat 200 m^3/h wastewater from a RAS plant has also been designed, based on the study conducted at Skagen Salmon.

Lastly, an economic assessment based on net present value consideration of 20 years has been conducted, based on a costing of the full-scale WRF.

The full Rambøll report, test documentation and business case will be available for further examination - in the Pilot 1 section of the TETRAS deliverables page.

Skagen Salmon

Skagen Salmon is a state-of-the-art RAS plant, which delivered production water for the testing carried out in Pilot 1. Skagen Salmon commenced operation in 2020 and completed the last vessels in 2024.

The seawater-based RAS plant is producing salmon and has an annual capacity of 3,800 ton (approx. 1 million fish).

Skagen Salmon discharges saline wastewater at approximately 150 m^3/h, equivalent to a flow of 3,600 m^3/day.

The first year the fish (smolt) live in freshwater. The smolt department includes 46 vessels ranging from 7 m^3 to 122 m^3 and 5 water treatment systems.

Figure 7: The different growth stages of salmon in RAS[29]

29 Skagen Salmon

The second year the fish (grow out) live in saltwater and reach 4 kg before being slaughtered. The Grow Out department includes 30 vessels ranging from 750 m^3 to 1,200 m^3 and 6 water treatment systems.

To treat the water from all the vessels in the plant, Skagen Salmon operates 11 water treatment systems, circulating water every hour with an intake of 250-300 litres per kg of feed.

The treatment process begins with a rotary drum filter (50 µm) for solid waste removal, followed by a moving bed biofilm reactor (MBBR) for organic breakdown and nitrification, and a polisher for fine filtration. The water then undergoes deoxygenation (DeOx) to remove excess gases and ozonation for disinfection and organic matter reduction before recirculation (Figure 8).

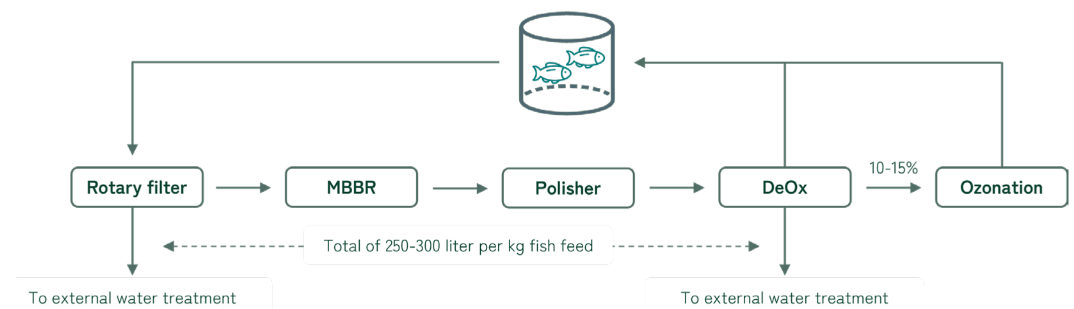

Figure 8: The internal water treatment process

As illustrated in Figure 8, water is extracted at multiple points in the process for external treatment to maintain system balance and water quality. In addition, 10-15% of the water is directed to ozonation before being returned to the system, ensuring effective disinfection and improved water clarity. These measures help optimising water reuse while minimising environmental impact.

The various wastewater streams not recirculated in the RAS plant are mixed before undergoing final external treatment, prior to being discharged to the ocean. First it passes through denitrification via conventional activated sludge and then through final sedimentation, where sludge is removed, dewatered, and sent to the wastewater treatment plant (Figure 9).

Without treatment, 48 tons of nitrogen and 6 tons of phosphorus per 1,000 tons of production would be discharged, but treatment reduces these by 90%.

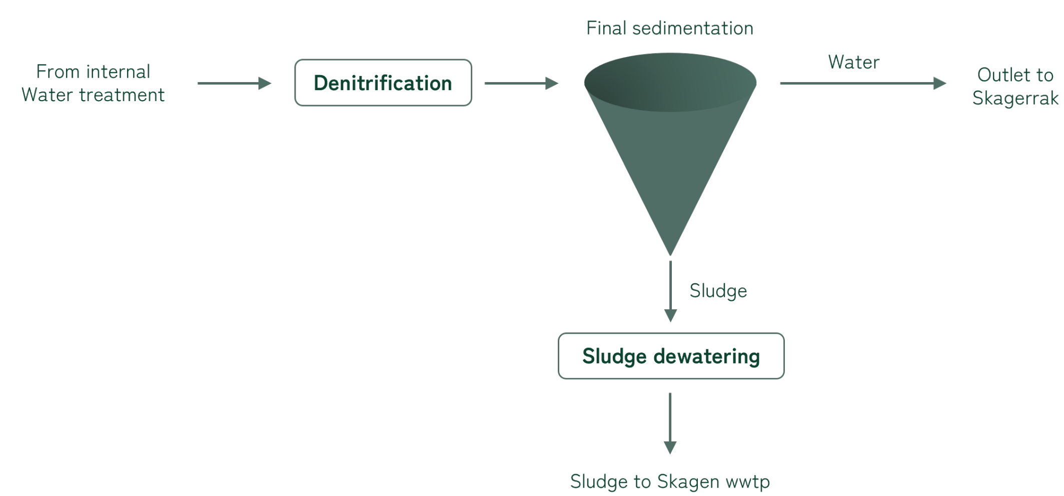

Figure 9: The external wastewater treatment process

The quality of the discharge water from Skagen Salmon is presently on par with water discharged from modern wastewater treatment plants. However, a political agreement reached in the Danish parliament earlier this year, plans to reduce the contribution of Nitrogen to Danish coastal waters by 572 ton by 2027 through stricter requirements to wastewater treatment plants.

Although most of these plants are in the top end in Europe, the new agreement requires the WWTPs removing down to 3.5 mg/l Nitrogen, a third of the present threshold, and down to 0,1 mg/l for phosphorous, a tenth of the present threshold, if discharged to water bodies adversely impacted by wastewater.[30]

These requirements will no doubt influence the permitting of new industries and will most likely also be incorporated once existing permitholders are having their permits renewed.

Water Composition & Quality

The benchmark selected for the pilot test is the Danish Drinking Water Regulation. The rationale behind this particular benchmark is, that (Danish) utilities are not obliged to provide industrial clients with ground water, 'only' with water of drinking water quality. For non-food purposes it is therefore the utility's prerogative to provide an alternative product, e.g. reclaimed water.

In reality, some industries may need to treat it further (e.g. ultra clean for PtX) and some may have more relaxed requirements.

Table 2: Quality parameters and concentration thresholds from the Danish Drinking Water Regulation (BEK nr. 1633, 2024)
**The water must not be aggressive or corrosive. This is primarily regarding water that is treated (demineralization, softening, membrane treatment, reverse osmosis, etc.).*
n.m.: not measured at given method.

	UNIT	THE DANISH DRINKING WATER REGULATION (BEK nr. 1633, 2024)
pH		7.0 - 8.5
Turbidity	FNU	1
E. coli	CFU/100 ml	n.m.
Enterococci	CFU/100 ml	n.m.
Clostridium tetani	CFU/100 ml	n.m.
Plate count at 22°C	per ml	200
Coliform bacteria	CFU/100 ml	n.m.
Ammonia, NH_4	mg/l	0.05
Nitrate, NO_3	mg/l	50
Nitrate, NO_2	mg/l	0,01
Sulphate, SO_4	mg/l	250
Bicarbonate	mg/l	*
Chloride, Cl	mg/l	250
Conductivity at 20°C	mS/m	250
Sodium, Na, total	mg/l	175
Aluminium, Al	mg/l	0.2
Iron, Fe	mg/l	0.2
Manganese, Mn, total and dissolved	mg/l	0.05

30 Miljø- og Ligestillingsministeriet (2025)

The Danish Drinking Water Regulation
The standards of the Danish Drinking Water Regulations ensure that the treated water is free from harmful contaminants and suitable for use in a variety of industrial applications.

Criteria include limits on physical, chemical, and microbiological parameters, which safeguard against risks to human health and maintain the integrity of the treated water.

In industrial equipment the removal of contaminants can be critical to avoid biofouling, scaling, or corrosion. Just as prevention of aggressive or corrosive water, highlights the importance of maintaining water chemistry, to avoid damage to infrastructure.

It is equally essential to ensure biological safety of the treated water. It is assumed that this can be achieved with a conventional drinking water disinfection system as final posttreatment. Disinfection is not included in the scope of the pilot.

Meeting the Danish drinking water standards not only ensures compliance with Danish regulations but also aligns with best practices in water treatment technology.

Discharge Water Quality
The discharge water from Skagen Salmon was sampled on 24th January 2024. The sample was taken at the overflow of the final sedimentation tank of the external wastewater treatment plant, representing the treated effluent discharged into Skagerrak.

The test result was compared with the quality requirements for drinking water, with the most critical parameters concluded to be ammonia and chloride, exceeding the thresholds by 100 and 50 times respectively. Concentrations of nitrite, sulphate and iron are around 10 times higher than the threshold, just as the content of suspended solids also is too high.

Salinity of Seawater
The seawater in the pilot test originates from Skagerrak, which is the part of the North Sea, located between Jutland, Southern Norway and Bohuslän in Sweden.

The saltwater for Skagen Salmon is extracted from 3 meters below the seabed, right on the edge of the ocean. A slight groundwater pressure from land influences the salinity which fluctuates between 28-30‰, tide and sea level dependant. The dynamic nature of the seawater must be considered when designing a RAS facility. This is particularly important around the Baltic Sea basin, where the seawater shows large seasonal variations.

- The comparison of seawater from Skagerrak (at Skagen) with seawater from Femern Belt (south of Lolland-Falster) shows that the seawater from Skagerrak has a higher salinity and mineral content which could impact the demineralization process, specifically when it comes to the energy consumption for desalination/RO in the WRF, when compared to a RAS facility using Fehmarn Belt seawater.
- The Fehmarn Belt seawater shows greater seasonal variation, which necessitates a flexible water treatment approach to accommodate fluctuations in temperature and suspended solids.
- However, both saltwater sources display similar pH levels and organic content, suggesting stable operational conditions for membrane filtration plants.

These insights are critical for designing an efficient treatment system tailored to the specific seawater conditions at Lolland-Falster.

The Pilot Tests

As illustrated in the section on groundwater (page 13) it is predicted that due to scarcity, water for industrial purposes will have to be obtained from alternative sources in the future. In Lolland-Falster it is already difficult for industries to obtain new permits for groundwater intake. Therefore, it is relevant to investigate the possibility of treating the RAS discharge water for reuse within other industrial processes. Due to the limited amount of groundwater in Lolland-Falster, this pilot test will be focusing on reuse of the discharge water rather than discharge to recipient.

Through pilot tests, desktop studies and calculations, it has been explored how to clean the discharge water to a level which enables reuse as technical water in other industries, either directly or following further specialist treatment to obtain ultra-clean water as required for PtX. It has also been explored how to achieve this while ensuring the residual waste streams can enter other value chains, for example as fertilizer and for biogas production.

The Process Specification
To carry out the pilot test, a fixed budget tender was conducted. The technical tender requirements were specified in a process specification describing two deliverables:

- Deliverable 1: Conduct a batch pilot test with the purpose of evaluating performance and design parameters of such process.
- Deliverable 2: Cost a full-scale plant including CAPEX and OPEX for a WRF with a capacity of treating 200 m^3/h wastewater.

Deliverable 1 was to be carried out using discharge wastewater from Skagen Salmon and using pretreatment, ultrafiltration (UF) and reverse osmosis (RO) for desalination to obtain Danish drinking water quality. To minimize the reject water stream, the process specification described an interest in high-recovery RO.

Deliverable 2 was to cost a full-scale WRF plant, CAPEX and OPEX, using the design and key results from the pilot test in Skagen. However, the costing was to be adjusted to the seawater composition near Lolland-Falster.

The Supplier
Out of the 8 relevant suppliers invited by Rambøll to submit a tender for execution of the pilot tests, only two chose to bid for the assignment.

After evaluating the two offers, Boll Filter was selected, as they proposed to run the trials at Skagen Salmons facility, avoiding shipping and degradation of the wastewater.

The entire trial series took 1 week and was based on both existing and new pilot units. It was suggested to treat Skagen wastewater with a mechanical filter as pretreatment before a ceramic UF unit (CUF) (compared to two polymeric UF membranes in parallel), followed by RO (65% recovery).

In addition to the original assignment, it was agreed to carry out MD of the UF permeate as an alternative to RO, given MD's potential advantages, such as lower sensitivity to fouling and its ability to utilize low-grade heat as an energy source. Waste heat is a common and abundant excess resource in most industrial applications and its utilisation adds to the symbiosis thought of TETRAS.

Treatment Technologies Applied
The test setup utilized a combination of advanced filtration technologies, as illustrated in figures 10 and 11 below.

Figure 10: On site setup (in truck); ceramic filtration (top left), reverse osmosis (front left).

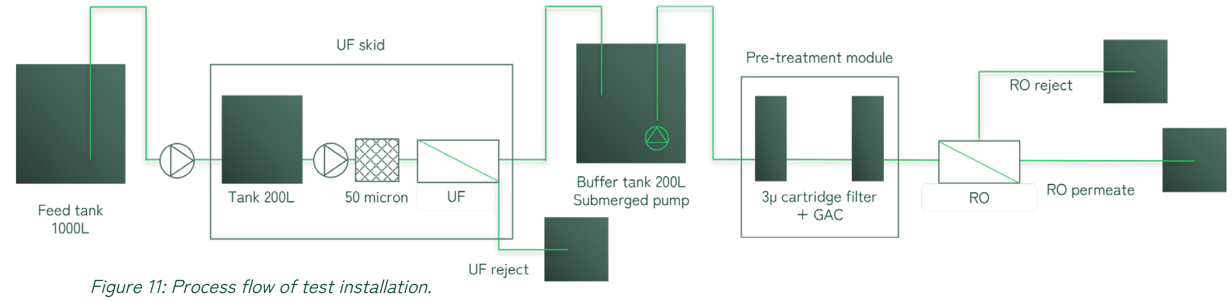

Figure 11: Process flow of test installation.

The process started with pre-filtration and ultra filtration, utilising ceramic membranes made from silicon carbide and zirconium dioxide. UF operates as a pressure-driven membrane separation process, where a transmembrane pressure gradient forces water through a semi-permeable membrane. Ceramic membranes offer exceptional chemical resistance, mechanical strength, and thermal stability, making them suitable for rigorous applications in water and wastewater treatment.

Next in the process is the pretreatment of the RO system. This included a cartridge filter for fine particulate removal and a granular activated carbon filter to eliminate dissolved organic compounds and chlorine, which could damage the polyamide RO membranes.

RO is a pressure-driven separation process where water is forced through a semi-permeable membrane under high pressure, leaving behind dissolved salts, organics, and other contaminants. RO membranes, typically made of polyamide thin film composites, are designed to achieve high salt rejection rates while maintaining low energy consumption.

Feed tanks and pumps connected the modules, enabling consistent flow and pressure management across the system, as illustrated in Figure 11. This integrated design ensured the technologies operated in coherence, providing reliable and efficient water treatment through a multi-barrier approach.

Execution of UF and RO Tests in Skagen
The pilot tests were conducted between October 1st to 3rd 2024. Bollfilter was overseeing the operation, while representatives from Rambøll and Business Lolland-Falster were present throughout the testing. Despite a few challenges such as equipment failure and electrical outages, the tests successfully demonstrated the system's operation and generated key data for further analyses.

The first day focused on setting up and test-running the equipment. The initial step involved the installation of test systems and running the UF skid with tap water to verify functionality. About 100 Liters of UF permeate were collected and used to start and evaluate the RO system, ensuring that its performance was within expected ranges.

The second day marked the start of continuous UF operation. The UF skid was operated throughout the day, producing permeate for testing. However, plans to commence RO testing were delayed due to repeated electrical outages, postponing the RO operation to the following day.

The final day focused on completing the UF and RO tests and collecting water samples for laboratory analysis. The RO operation commenced, with RO permeate and reject samples collected at recovery rates of 57%, 65% (going forward referred to as RO65), and 73%. The final recovery test at 73% was disregarded, as a failure in the non-return valve caused the RO test to end prematurely.

Execution of Membrane Distillation Laboratory Test
Membrane distillation (MD) is a thermally driven separation process that utilizes a hydrophobic microporous membrane to separate a heated feed solution from a cooler distillate stream. Unlike pressure-driven processes such as RO, MD relies on the vapor pressure gradient created by a temperature difference across the membrane. This allows only water vapor to pass through, while salts, organics, and other contaminants are retained. MD's reliance on temperature gradients, rather than high pressure, makes it advantageous in setups where low-temperature waste heat, is available, for example from PtX.

MD process offers several benefits compared to conventional desalination technologies like RO. One of the most significant advantages is its ability to achieve higher recovery rates, often exceeding 80–90%, compared to the 50–75% typically seen with RO, especially when treating challenging feedwaters.

MD can also deliver superior distillate quality, with conductivity levels as low as 0.35 mS/m. Achieving comparable water quality with RO would require a two-stage RO system. Furthermore, MD is tolerant of high salinity and fouling-prone feedwaters, such as brines or complex wastewaters, where RO would face significant performance limitations.

In this study, MD was evaluated as an alternative to RO for treating UF permeate derived from RAS wastewater. A sample of UF permeate from the pilot test in Skagen was tested in a laboratory-scale Direct Contact (DC) MD unit at the Technical University of Denmark (DTU).

The MD unit was equipped with a heat exchanger, heating the feedwater to 55°C. The heating system simulated the use of low-temperature waste heat, making it relevant for industrial applications where surplus heat is available.

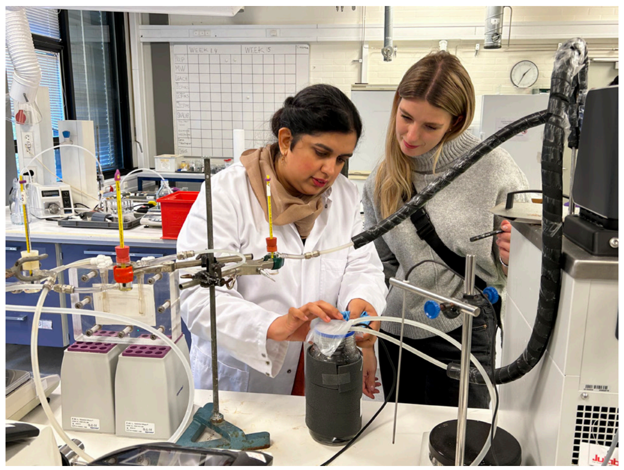

Figure 12: Execution of MD test at DTU

Figure 13: MD feedwater (left) and permeate (right)

Analysis of the Test Results and the Application Potential of Permeate
The analysis of permeates and rejects from the treatment processes both highlights their potential applications and stresses the associated challenges. The detailed analysis is available in the report prepared by Rambøll.

The RO process is designed to concentrate dissolved solids and contaminants in the reject stream while producing purified permeate as the final product. The results display that the reject contains high concentrations of salts, nutrients, and organic matter, which increase from CUF Reject to RO Reject 65%. The RO process efficiently reduces the concentration of dissolved solids and contaminants of the feed water, resulting in significantly improved water quality.

The analysis of the CUF permeate and RO permeate in relation to the maximum permissible values for drinking water shows that these permeates do not fully meet the requirements for drinking water attributable to several thresholds being exceeded.

The RO permeate show improvements in terms of water quality but still do not meet the criteria for drinking water quality in relation to ammonia. However, the conductivity for RO65 (25 mS/m) is within the drinking water limit but requires further monitoring and optimization. Chloride levels are well below the drinking water limit of 250 mg/l, indicating no concerns regarding chloride. The ammonia concentration is measured at <1 mg/l but the applied detection limit is many times higher than the Danish drinking water limit for ammonia (0,05 mg/l).

A theoretical estimation of ammonia in the RO permeate suggests compliance with this limit: an expected 0,037 mg/l ammonia in the permeate, based on a theoretical ammonia rejection of 99% for the specific RO membrane (informed by Boll Filter and DuPont).

While RO permeate shows improvement over CUF permeate in terms of conductivity and chloride levels, it still fails to meet all drinking water requirements without further treatment. However, the permeate remains highly suitable for industrial and technical applications, such as cooling systems and cleaning.

It is also important to note that the Danish requirement is 10 times stricter than the EU drinking water requirement at 0.50 mg/l ammonia. Therefore, it is recommended to perform a risk assessment of the ammonia quality of the permeate in relation to actual technical reuse.

Permeate from MD treatment, generally meets drinking water standards, though some parameters require adjustments for full compliance; A pH of 6.0 is slightly below the acceptable range of 7.0-8.5 but may be within tolerance for some technical application.

The results showed that the MD process maintained a steady flux of 7 LMH even at recovery rates of up to 80% where feedwater was heated to 55°C. The distillate had an average conductivity of 0.35 mS/m, far exceeding the typical performance of single-stage RO, which achieves around 30 mS/m.

The conductivity and chloride concentration are well within acceptable limits, making it suitable for technical use without concerns about scaling or mineral buildup. Fluoride, nitrites, and sulphates are also within safe limits. However, the ammonia concentration exceeds the drinking water limit. Despite this, the MD permeate is suitable for various industrial applications, with low levels of metals and organic contaminant.

Technical water of drinking water quality has a variety of applications, primarily in uses for technical purposes. In industry, technical water can be used in some cooling systems, where its purity prevents scaling and mineral buildup, or for cleaning machinery and equipment. In agriculture technical water can be used for irrigation, as clean water helps protect plants from harmful accumulations. Additionally, it is well-suited for cleaning processes, such as high-pressure washing, where the water's purity ensures no stains or residues are left behind. Incompliant drinking water parameters in the RO and MD permeates may potentially be exceeded in the case of technical water: pH and ammonium. The risk of ammonium concentration above 0.05 mg/l in technical water is only related to corrosion of materials in contact with the permeate. The measured concentrations of 2.1 mg/l ammonia are assessed as low enough to prevent corrosion of standard equipment at room temperatures. For use at elevated temperatures, a material compatibility assessment is recommended. In conclusion, the RO and MD permeates are of sufficient water quality for selected technical water purposes, after disinfection.

Application Potential of Rejects
Besides permeate, membrane filtration processes produce a waste stream consisting of concentrated (undesired) contaminants. This resulting concentrate is referred to as reject water. For full-scale application of membrane filtration at RAS plants, a good destination and/or further treatment for the reject water must be found.

On the back of increased global demand for water reuse from wastewater effluents, many desktop-, pilot- and some full-scale studies are currently ongoing to find sustainable ways to valorise or handle reject water rich in organics, though not containing the high amount of salt that the RAS reject water contains.

The following options can be considered in the given order of priority:

1. Can the reject stream be valorised? E.g. as biogas or in agriculture.
2. Can the reject stream be discharged without further treatment?
3. Can the reject stream be discharged after degradation of contaminants by treatment with e.g. biological systems, advanced oxidation or adsorption, and allow for environmentally safe and compliant discharge?
4. Can the reject stream be concentrated further and thermally reduced/evaporated (to medium-liquid discharge or even zero-liquid discharge)

Reject water from the treatment processes contains high levels of salt, nitrogen compounds, and other contaminants, influencing its reuse potential. The nutrient-rich reject water could be utilized as agricultural fertilizer, provided it meets Danish regulations on heavy metals and environmental substances, although high salinity and chloride concentrations pose potential risks to soil health.

Reject water is also unsuitable for biogas production due to inhibitory salt levels and low biodegradable organic content. For marine discharge, the high chloride, nitrogen, and heavy metal concentrations necessitate careful regulatory compliance, as they could impact marine ecosystems and contribute to eutrophication. While discharge into the Baltic Sea is a potential option, but probably not achievable, additional treatment would be required to meet environmental standards.

Although outside the scope of this project, potential solutions are touched upon in the chapter on evolution, later in this report.

Pilot Tests Conclusion
Local pilot trials with RAS wastewater in Skagen was successfully completed. The tests included mechanical filtration as pre-treatment before the ceramic ultrafiltration and testing of membrane distillation alongside RO as a second filtration step, showcasing innovative thinking to address potential fouling issues and utilize low-grade heat sources.

The pilot tests led to promising results regarding the quality of permeates produced through the advanced filtration processes. The pilot tests demonstrated that the RO process effectively improves the quality of RAS wastewater permeate to meet stringent Danish water standards. At a recovery rate of 65%, the RO permeate achieved significant reductions in contaminants, making it suitable for various technical applications.

The results assert that RO permeate can provide high-quality technical water, suitable for industrial processes, with potential for biological safety ensured through post-treatment disinfection.

MD offers a thermally driven separation alternative to RO, showcasing distinct advantages in water quality and recovery rates. The study highlighted several benefits of MD:

- Higher Recovery Rates: MD achieved recovery rates exceeding 80-90%, compared to 50-75% typically seen with RO, making it highly effective for challenging feedwaters.
- Superior Distillate Quality: The MD distillate showed an average conductivity of 0.35 mS/m, significantly lower than typical single-stage RO, which achieves around 30 mS/m. Achieving similar purity with RO would require additional stages and increase CAPEX and OPEX.
- Tolerance to High Salinity: MD demonstrated resilience in handling high salinity and fouling-prone feedwaters, making it particularly useful for complex wastewaters where RO faces limitations.

Overall, MD produced high-quality distillate suitable for similar applications as RO permeate, with additional advantages in recovery rates and distillate purity. This makes MD a viable alternative for scenarios utilizing low-grade waste heat. MD is not yet applied in larger scale, but it is expected to be applied in full-scale operation within the next 2-3 years.

The Business Case

There are many initiatives which are already reusing wastewater for industrial purposes, just as utilising saline water for freshwater production is widely applied. The innovative solution piloted in TETRAS Pilot 1, attempts to combine both, reusing saline wastewater for industrial purposes. The feasibility study highlighted a number of examples, but this report will only draw attention to the progress made in Israel, as it underlines a thesis put forward by an external expert of the project about economy of scale. It is noteworthy that in Israel the cost of producing fresh water from sea water has dropped to €0.50. Prices this low are only achievable when producing a very large amount of fresh water as costs drop exponentially with increase in production.

Fresh Water Production in Israel[31]
Water scarcity and increased usage has forced Israel to think innovatively. This has resulted in reuse of wastewater reaching 87% (of 500 million m^3) in 2015, 40% hereof was used for irrigation purposes.

Over the last 15 years, to avoid further strain on aquifers, five mega desalination plants based on seawater reverse osmosis (SWRO) have been constructed on the Mediterranean Coast with a total capacity of 585 mil. m^3/year. They provide 85% of the domestic urban consumption and 40% of the country's total consumption.

Large scale desalination has enabled Israel to reduce the cost of desalination down to only US$0.54 (€0.50) per m^3 at the most recent plant, which is amongst the lowest in the world. The low price per m^3 is also linked to both energy efficiency and low cost of electricity.

Costing & Economic Analysis of a Full-Scale WRF[27]

In addition to conducting the pilot tests evaluating the performance and design parameters of a RAS WRF, the external expert was tasked with providing a cost assessment for a full-scale WRF capable of treating 200 m^3/h of RAS wastewater.

Based on this assessment, an economic analysis has been made. The economic analysis was prepared to cover a 20-year lifespan evaluating the total expenditures (TOTEX), considering both CAPEX and OPEX.

The detailed analysis and the assessment forms part of Rambøll's report.

Full-scale Water Treatment Installation
The full scale WRF is based on a fully automated installation, designed to monitor and adjust operating pressure and capacity independently. Cleaning of the UF and RO membranes will involve a combination of back pulse, backwash, and chemical cleaning-in-place (CIP), all initiated automatically.

The membranes, control cabinets, electrical cabinets and chemical dosing should be placed inside a building, just as the system layout features four primary outdoor tanks:

- 200 m^3 UF permeate tank.
- 200 m^3 UF concentrate tank.
- 200 m^3 RO permeate tank.
- 200 m^3 concentrate tank.

It is assumed that the UF feed water comes from the clarifier from the RAS systems activated sludge water treatment system, and therefore the cost for a UF feed water tank is not included. Any piping, pumping, and other infrastructure from the permeate and concentrate tanks are not included in the costing, since these costs are very project specific. The recovery of the UF-membranes is 95%, and the recovery of the RO-membranes is 65%, resulting in a technical water production of 123.5 m^3/h.

The system is designed with a redundancy on both the UF- and the RO-membranes, meaning that the system can uphold full production with one UF- or RO-skid not in operation during CIP or maintenance. It is therefore assumed that there is no downtime, which means that 123.5 m^3/h of technical water can be produced all year round, resulting in a yearly production of 1,081,860 m^3. The process flow diagram of the system is seen in Figure 14.

31 World Bank Group (2017)

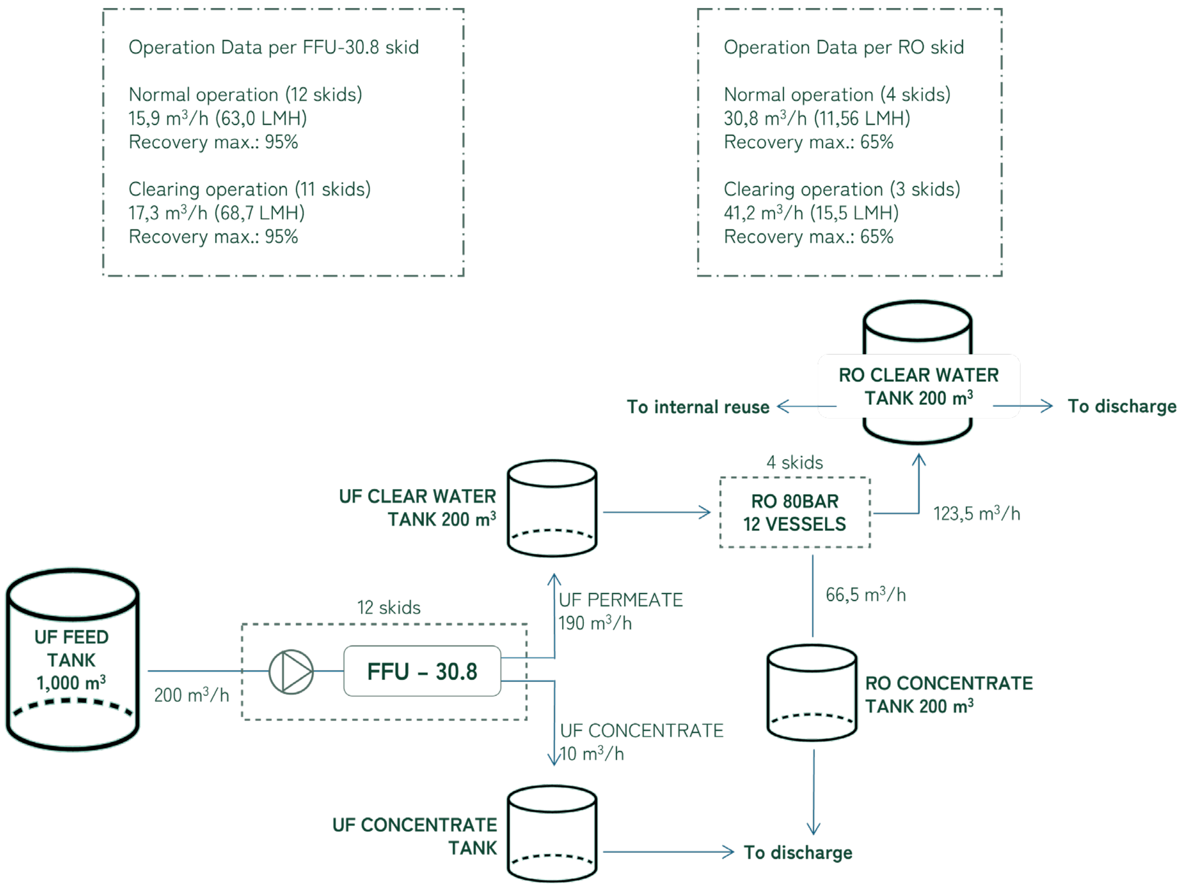

Figure 14: Process flow diagram of the full-scale water treatment system. The UF feed tank and piping, pumping, and other infrastructure from the permeate and concentrate tanks are not included in the costing.

CAPEX

All costs of the equipment are provided by Bollfilter, however, the costs for building and fortified area, consultancy and miscellaneous expenses are estimated by Rambøll. The complete economic analysis is included in Rambøll's report.

The total estimated CAPEX for the project is EUR 15.63 million, with a margin of error of +/- 30%. The building costs are based on a light building of 1,050 m² priced at 1,675 EUR/m² complete with electrical work, sewerage, foundations etc.

For the outdoor fortified area, with the storage tanks, the area is estimated to be 400 m², and priced at 670 EUR/m², complete with sewerage/manholes, paving etc. Consultancy and Miscellaneous and unforeseen expenses have been estimated by Rambøll based on experience, at 10% and 14% respectively. Bollfilter's basic site lay-out is included below. Additional details, including equipment datasheets, are available in Rambøll's report.

The key components contributing to the CAPEX are summarized in Table 3:

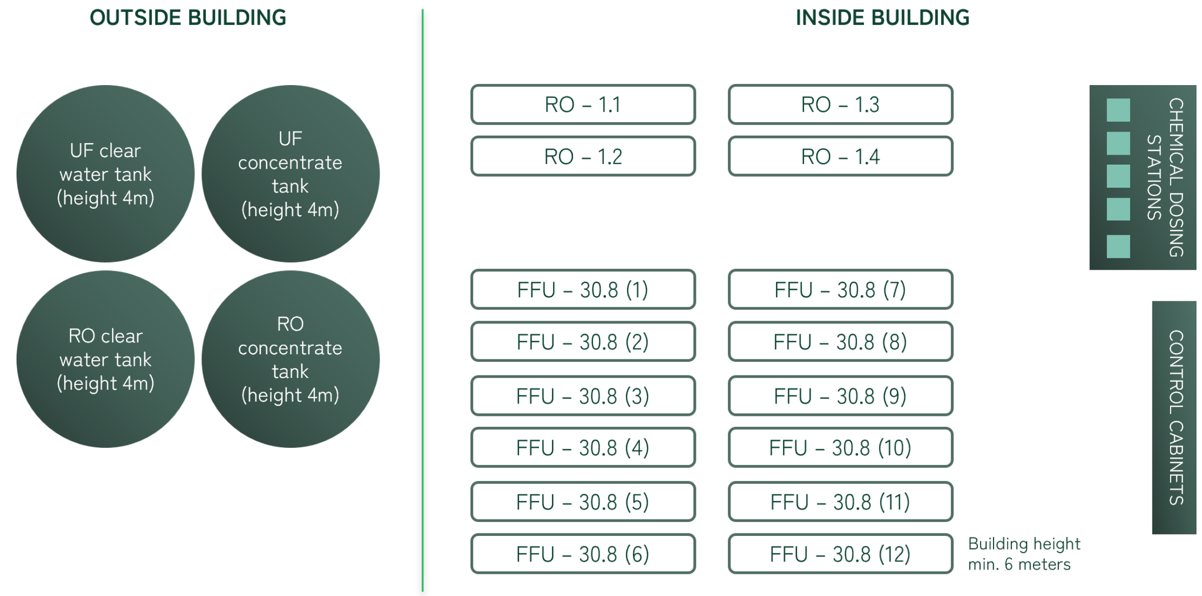

Figure 15: Basic lay-out drawing of a full-scale water treatment facility.

Table 3: CAPEX – Overview of components and costs

CAPEX			
Category	**Description**	**Quantity/Size**	**Cost (EUR)**
Tanks	UF permeate tank	200 m³	
	UF concentrate tank	200 m³	
	RO permeate tank	200 m³	
	RO concentrate tank	200 m³	
	Total Tanks		**€ 550,000**
UF system	Pre-filter (pre-UF)		
	BOLL Fine Filter Unit 30.8 UF-skids		
	Total UF-system		**€ 7,500,000**
RO system	RO pre-treatment		
	BOLL RO-skids		
	Total RO-system		**€ 2,500,00**
Light building (1,050 m²) and fortified area (400 m²)			**€ 2,027,00**
Consultancy		10% of total CAPEX	**€ 1,509,240**
Miscellaneous and unforeseen expenses		14% of total CAPEX	**€ 1,760,780**
Total CAPEX			**€ 15,847,020**

OPEX

OPEX are closely tied to the energy required for crossflow operation, membrane cleaning frequency, and membrane lifespan. The crossflow operation on the UF-membranes requires a large energy consumption.

The electricity price is assumed to 0.134 EUR/kWh. A detailed breakdown of the annual OPEX components is provided in Table 4.

The cost of operation and maintenance is estimated by Rambøll. Chemicals for membrane cleaning and scale prevention represent a smaller portion of OPEX but remain essential for maintaining long-term performance.

Table 4: OPEX – Overview of Operating Costs – annual expenses.

OPEX Annual			
Category	**Description**	**Quantity/Size**	**Cost (EUR)**
Electricity	UF: ~5,500 mWh/year (crossflow)	11,000 mWh/year	€ 1,474,531
	RO: ~5,500 mWh/year		
	Assumed price: EUR 0,134/kWh		
Chemicals	BollClean 1550 (acid-based cleaning agent)	6,000 L/year	€ 24,000
	BollClean 3300 (alkaline cleaning agent)	6,000 L/year	€ 24,000
	Antiscalant (fosing)	5 m ml/m^3	€ 74,898
	Caustic soda (50%)	80 L/year	€ 200
	Sulfuric acid (96%)	30 L/year	€ 200
Operation and maintenance		7% of total OPEX	€ 111,848
Total OPEX			**€ 1,709,677**

The lifespan of the membranes is 10 years and 4 years for the UF- and RO membranes respectively, as seen in Table 5. This means that every 10 years, there is an additional cost of 11.760 EUR to replace the 12 UF-membranes and every 4 years an additional cost of 3.920 EUR to replace the RO-membranes (2025 prices).

Table 5: OPEX – membranes

OPEX - Membranes		
Category	**Interval**	**Cost/membrane (EUR)**
Membrane replacement (UF)	10-year lifespan	€ 980/UF membrane
Membrane replacement (RO)	4-year lifespan	€ 980/RO membrane

With the total annual OPEX and the additional cost for membrane-replacement, the total OPEX for a 20-year period is 42,428,288 EUR.

The OPEX does not include any costs associated with the discharge of reject water from the UF- or RO membranes.

Economic Optimizations
Conservative engineering assumptions in sizing and material selection have been adopted, which on one hand adds robustness to the design but on the other hand increase the investment costs. For example, crossflow UF membranes were dimensioned for 3.0 m/s velocity to ensure fouling control, and the system was automated to allow minimal operator intervention. However, further optimization through extended piloting could yield significant savings, potentially reducing CAPEX and OPEX by up to 25%.

To further reduce both CAPEX and OPEX, Bollfilter have proposed several system-level and component-level optimizations:

1. UF Alternatives: The electricity demand is primarily driven by the UF system's use of high velocity crossflow operation. As this is a major contributor to OPEX transitioning from crossflow SiC tubular membranes to flat sheet dead-end membranes can reduce energy consumption by up to 75%, however, this will probably result in lower permeability and potentially higher surface area requirements.
2. RO Energy Recovery Devices: Implementing pressure exchangers or closed-circuit RO (CCRO) configurations could reduce RO energy usage by up to 35%.
3. The lower salinity at the Lolland-Falster site compared to the Skagen pilot location will positively impact energy efficiency and RO membrane performance. Simulations with reduced feed salinity (21,800 mg/L vs. 29,000 mg/L) show potential for reducing RO pressure by 12 bar and energy use by approximately 600 MWh/year — a substantial economic benefit that constitutes a potential saving of 80,400 EUR/year.
4. Membrane Distillation (MD): In scenarios where waste heat is available, suppliers highlight MD as a future alternative capable of producing ultrapure water with significantly lower OPEX and higher recovery.
5. Just as membrane distillation holds the potential of utilising low temperature waste heat from other industries in a cluster setting, negotiating PPAs and establishing direct power connections from producers (which are expected within a cluster setting) could equally reduce OPEX.

Cost of Reject Water
At present, treatment and discharge of the treated reject water to marine recipients is the most likely scenario. The cost estimates below are extrapolated from a recent report about reject water treatment in the context of water reclamation plants for Power-to-X, from different types of feedwater sources, including groundwater, surface water, treated municipal wastewater and seawater.[32]

The estimated capacity of the 1 GW Power-to-X plant, for which these costings were done, is within the same range as the RAS facility this study is based upon, which allows for extrapolation (Table 6).

The RAS reject water is expected most comparable to reject water from treated municipal wastewater, however, contains more salts. Therefore, the costs are extrapolated based on volume and calculated with a +/- 50% uncertainty and should be regarded as an indicative cost range only.

The detailed calculations are included in the appendices of Rambøll's report.

Table 6: Assumptions for extrapolation of reject treatment plant cost estimate from Miljøstyrelsen

Parameter	Unit	Value
Technical water plant feed volume	m^3/year	1,728,000
Reject water plant feed volume	m^3/year	660,960
PFAS removal from reject water	-	No

32 Miljøstyrelsen (2024)

The cost estimates are extrapolated from reject water treatment cost estimates that include a full train of treatment units in series selected and combined for the treated reject water to comply with Danish national guidelines for marine recipient discharge, except for PFAS.

They include chemical precipitation/coagulation, oxidation, advanced biological treatment, filtration and adsorption. The technologies are dimensioned to treat reject water and comply with Danish national guidelines for marine recipients for phthalates, phenols, arsenic, PAHs, heavy metals and phosphor.

It is not sufficiently treated to comply with PFAS regulations (>75% compliance) and nitrogen discharge regulations (< 75% compliance).

The different treatment steps in the reject water treatment plant are described in more detail in the Rambøll report.

Table 7: Estimated costs associated with a RAS reject water treatment plant

Estimated costs associated with reject water treatment plant (+/- 50%)	Minimum	Maximum
CAPEX (mio. EUR)	2,03	6,09
OPEX (mio. EUR)	0,54	1,63
TOTEX (mio. EUR)	0,72	2,17
Specific TOTEX cost (EUR/m^3 reject water)	1,10	3,29

Table 7 sums up, that the costs for cleaning the reject water may vary between 1.1 – 3.3 EUR/m^3.

It is important to notice that the costs are extrapolated from another feasibility study and subject to minimum 50% uncertainty, just as additional costs related to disposal of reject streams are not included.

Economic Analysis
An economic analysis has been conducted to evaluate the long-term financial viability of the proposed full-scale water treatment installation treating 200 m^3/h RAS wastewater.

This analysis considers both capital investments and operational expenses over an expected 20-year project lifespan, from 2025 to 2044, using a standard discount rate of 4% to reflect the time value of money. The CAPEX and OPEX costs are 2025-values, and they have been projected with a net price increase of 2% p.a.

TOTEX

Table 8 sums up the total CAPEX and OPEX (TOTEX) for the next 20-year period.

Table 8: CAPEX, OPEX and TOTEX in 2025-values projected with a 2% net price increase.

Total CAPEX and OPEX		
Category	**Interval**	**Cost/membrane (EUR)**
CAPEX	Year 0	€ 15,847,020
OPEX	Sum of the 20-year period	€ 42,428,288
TOTEX		**€ 58,275,308**

Net Present Value (NPV)
In Table 9 the NPV for the CAPEX and OPEX is presented.

It is assumed that the CAPEX is incurred in year 0 (2025), and OPEX incurs from year 1 to 20 (2026-2045).

Table 9: NPV of CAPEX, OPEX and TOTEX and cost of technical water.

NPV TOTEX		
Category	**Interval**	**Cost/membrane (EUR)**
CAPEX, NPV	Year 0	€ 15,847,020
OPEX, NPV	Sum of the 20-year period	€ 28,095,032
TOTEX NPV		**€ 43,942,052**
Specific TOTEX NPV technical water (EUR/m^3)		**€ 2.03**

The total production of technical water for the 20-year period is 21,637,200 m^3.

That means that the NPV of technical water in the WRF is 2.03 EUR/m^3.

As previously suggested, the lower salinity of the seawater around Lolland-Falster may result in a reduced electricity consumption of 600 MWh/year.

Taking this into account, the NPV OPEX is reduced to 26,682,504 EUR in the 20-year period, resulting in a specific TOTEX NPV of 1.97 EUR/m^3 of technical water, as indicated in Table 10.

Table 10: NPV of CAPEX, OPEX and TOTEX and cost of technical water, due to lower salinity around Lolland-Falster.

NPV TOTEX		
Category	**Interval**	**Cost/membrane (EUR)**
CAPEX, NPV	Year 0	€ 15,847,020
OPEX, NPV	NPV of the 20-year period	€ 26,682,504
TOTEX NPV		**€ 42,529,524**
Specific TOTEX NPV technical water (EUR/m^3)		**€ 1.97**

The remaining optimization suggestions have not been considered, as the corresponding CAPEX is not known. However, it is expected that the suggestions would result in a significant reduction in TOTEX.

Impact of Reject Water Cost
The cost of discharging the reject water is not included in the economic analysis, since the costing of managing the reject water is not conducted to the same level of detail as the full-scale WRF.

However, it is important to note that the previous estimations revealed high costs associated with treatment of the reject water upon discharge.

They are estimated to vary between 1.1 – 3.3 EUR/m^3 of reject water, which corresponds to 54 to 162% of the NPV costs for the technical water plant. It should be noted that the costs are extrapolated from another feasibility study and are subject to minimum 50% uncertainty.

Utility Charges
For large industrial customers there is usually a potential for discounted payment terms, but listed below are the official prices of the local utility. CAPEX costs are not included.

The cost of wastewater treatment in Guldborgsund is dependent on the amount discharged to the WRF, with a large discount available for large customers.

Table 11: Ladder model for cost of wastewater discharge in Guldborgsund municipality applied to our business case figures[33]

Wastewater treatment at WWTP - Ladder model			Cost w/o VAT	W/o reclamation 200 m³/h	With reclamation 76.5 m³/h (RO reject)
				1,752,000 m³/year	670,140 m³/year
Step 1: up to 500 m³		Per m³	52.48 DKK / 7.04 EUR	3,520 EUR	3,520 EUR
Step 2: 501-20,000 m³	20% discount	Per m³	42.24 DKK / 5.67 EUR	110,565 EUR	110,565 EUR
Step 3: above 20,0001 m³	60% discount	Per m³	21.77 DKK / 2.92 EUR	5,057,440 EUR	1,885,406 EUR
Total cost				**5,171,525 EUR**	**1,999,491 EUR**

The cost of drinking water supply is a flat rate, but it is assumed the rate is negotiable for a large customer.

Table 12: Theoretical value of permeate from RO and MD respectively[34]

Water supply from utility	Cost without VAT	Unit	Potential sale of RO permeate (123.5 m³/h)	Potential sale of MD permeate (152 m³/h)
Annual water production			1,081,860 m³	1,331,520 m³
Water value	17.34 DKK / 2.33 EUR	Per m³	2,520,734 EUR	3,102,442 EUR

Business Case Conclusion
The economic analysis over the 20-year project horizon reveals a substantial investment requirement with a projected CAPEX of €15,847,020 and total OPEX of €42,428,288, summing up to a TOTEX of €58,275,308. The net present value (NPV) calculations indicate a specific TOTEX NPV for technical water at €2.03 per m³.

By implementing optimizations due to lower salinity in Lolland-Falster, a potential saving in energy consumption can reduce the specific TOTEX NPV for technical water to €1.97 per m3. These figures underlines the financial implications of establishing and operating the full-scale WRF. Bollfilter has provided several optimization possibilities, to reduce both the CAPEX and the OPEX. The CAPEX is estimated to be reduced by up to 25% by extended pilot testing. The OPEX, which primarily consists of electricity consumption for the crossflow on the UF membranes, can be reduced by up to 75% through replacing the type of membranes. Implementing pressure exchangers or closed-circuit RO (CCRO) configurations could reduce RO energy consumption by up to 35%. In scenarios where waste heat is available, MD can be a future alternative capable of producing ultrapure water with significantly lower OPEX and higher recovery.

The costs associated with reject water treatment further emphasize the need for strategic planning and innovative management. The preliminarily estimated range of €1.10 to €3.29 per m³ shows the related uncertainties regarding reject water management can have a significant negative impact on the feasibility requiring more efforts to optimize treatment processes and explore valorisation opportunities.

33 Guldborgsund Forsyning (2025a)
34 Guldborgsund Forsyning (2025b)

Limitations & Recommendations

There is no doubt, that the more industries which could be included in a cluster formation, the more feasible a land-based fish production facility would become, just as there may be added benefits to other cluster industries. These may not necessarily be financial, but a greener profile through reduced waste streams, resource conservation etc. is part of the storytelling which is good for business.

As this study has highlighted, the real issue in producing technical water from wastewater does not lie in producing water of drinking water quality, but what to do with the reject streams, especially when handling saline water, as from a RAS production of a saltwater species. Large scale tests with bioaugmentation could be a game changer, not only for RAS but for wastewater handling in general, providing an efficient low-cost solution while generating a new value stream.

In 2020 1.5 million tonnes of salmon was produced in Norway. The salmon consumed 2 million tonnes of feed, highlighting the need for the industry (and government) to develop new sustainable feed ingredients and sustainable production methods, as Norway is aiming towards a potential future production reaching 5 million tonnes a year.[35]

How to sustainably meet the future feed demand is outside the scope of this study but a recommended area for further investigation. Micro algae from the bioaugmentation could hold the potential of replacing fish meal and oils, making feed more sustainable.

Further studies should investigate feed production and especially the reduction in feed when producing fish in RAS as opposed to ONP. With the expected rise in demand for (sustainable) seafood, feed reduction as well as change to feed sourcing is essential.

The Expected Evolution

The future is already here. The upscaling and commercialisation are what is missing, but what is expected over the coming years.

As previously mentioned, a future game changer could be membrane distillation, of which full scale application is yet to be seen, but showed promising results during pilot testing, even at 80% recovery, which is far superior to the 65% obtained with RO. In industrial symbiosis MD furthermore has the benefit of utilising waste heat and has during the pilot test been tested at 50 degrees C. It is expected that full scale applications will emerge within the next two to three years.

Outside the scope of this report is of course the O&M of the RAS plant, where financial optimisation also could be done on the power costs, as mentioned in the business case section, through negotiating PPAs and direct supply from producers, just as the bioaugmentation solution proposed for the reject streams, potentially could be applied earlier in the treatment process (within the RAS plant) and reduce costs for other treatment methods.

Bioaugmentation is also expected to play a larger part of wastewater treatment in the future. The technology has been proven, what is missing is the scaling-up to match the RAS production. Already several companies are using RAS wastewater for micro algae production, such as Swedish Algae Factory[36] and Maripure.[37] Locally a promising start-up has started pilot projects with the utility and the sugar factory, using bacteria for wastewater treatment.

Within the TETRAS project, Pilot 2 has utilised a turbular microalgae photobioreactor for testing suitability of shrimp process water for saltwater microalgae cultivation and nitrate removal. The outcome can be further examined in the Pilot 2 result report.

Looking into the crystal ball, a future solution implementing the technologies expected to be available for large scale solutions could look like the proposal in Figure 16 below.

35 SINTEF (no date)
36 Swedish algae factory (no date)
37 Maripure (no date)

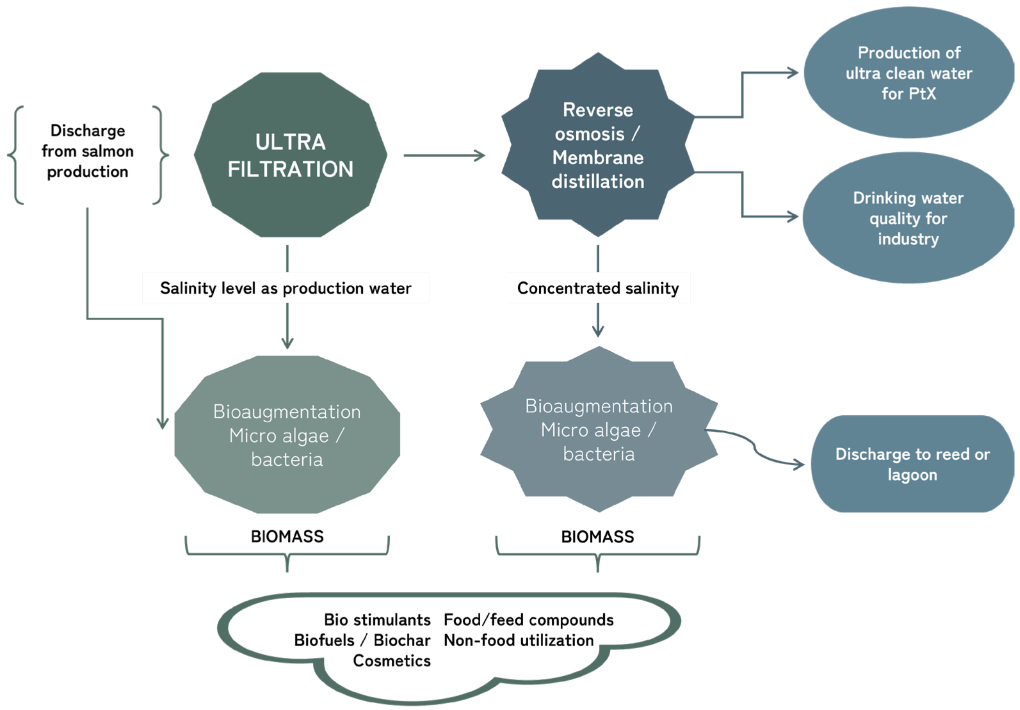

Figure 16: Proposed future solution for handling of reject from RAS, and production of technical water.

Ongoing Projects
AQUAPHOENIX[38] is a Horizon Europe project working with collection and utilisation of sludge from open net pens. The partners will test technology for capturing waste and hereby limit emissions and valorise these waste streams into new products such as feed, fertiliser and energy.

As the reject from water treatment is the bottleneck in advancing RAS production in the Baltic Sea area, the solutions emerging from AQUAPHOENIX has great potential in RAS, if it can solve the problem with saline sludge and reject.

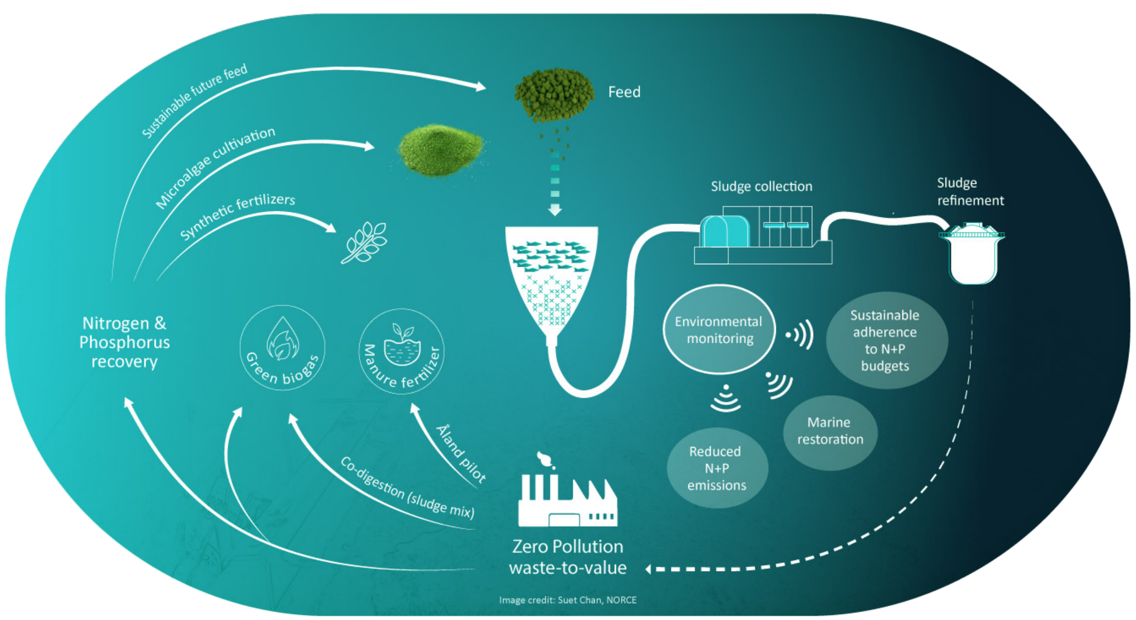

Figure 17: The AQUAPHOENIX solution

38 Aquaphoenix (2025)

Startup and Innovation
French startup Agriloops has recently launched its first commercial scale saline aquaponics facility[39] which combine shrimp farming with vegetable cultivation in a single ecosystem.

At their facility which comprises 2,000 m^2 aquaculture and 5,000 m^2 greenhouses, water usage is reduced by 90% as wastewater is used to produce both shrimps and vegetables, just as fertilizer usage is minimal. The salty water adds to the tastiness of the vegetables.[40]

Danish Swiss startup Bio Clean Carbon has patented a strain of cyanobacteria to be utilised for wastewater treatment. Although wastewater treatment plants are their no 1 target, their solution holds large potential for industrial clients with in-house wastewater treatment, such as RAS facilities. The initial pilot tests on ‘fresh’ wastewater shows promising results, and as the bacteria is tolerant of saline water up to a certain degree, could be interesting to test as primary treatment for a ‘Baltic Sea RAS’. Their 100% nature-based-no-chemical solution boasts CO_2 capture seven times greater than algae-based solutions, absorption of 80% of Nitrogen and 50% of Phosphorous. The biomass produced is converted to biochar and utilised for soil improvement.[41]

French startup Magma Seaweed plans to revolutionise seaweed production with their pioneering land-based seaweed cultivation solution. As with aquaculture, land-based production in a controlled environment enables year-round production. MAGMA is looking at integrating seaweed- with shellfish production, to optimise resource utilisation and diversify the income potential for shellfish farmers.[42] Large-scale seaweed production for wastewater treatment is one of the potential solutions we investigated during our feasibility study.

Swedish food-tech company Big Akva is next generation RAS producer. Receiving their environmental permit July this year, they intend to produce 6,000 ton of Rainbow Trout annually. Their RAS facility will form part of an industrial cluster, utilising excess heat and oxygen from hydrogen production. Waste from the RAS production will be utilised for production of biochar, fertilisers and microbial proteins. Operation is planned to commence already in 2026 with full capacity expected to be reached by 2029.[43]

Conclusion

The development in technology only during the course of this project clearly indicates that even solutions which are not presently feasible may become so in the near future, both due to technological advances but also because the tightening of legislation makes it a necessity. If nitrogen and phosphorous will be treated as commodities in the future at the same level as CO_2, this would further add to the feasibility.

As it has been demonstrated in Skagen, RAS can be feasible in the right configuration and we believe that Pilot 1 is presenting a solution hich holds the potential of making RAS both achievable and feasible in the Baltic Sea region, in the future.

As highlighted in the chapter on Evolution – the future is already here. The highlighted projects, startups and innovators all showcase brilliant solutions to wastewater treatment, with Big Akva leading the way for the next generation RAS systems, fully integrated in industrial symbiosis.

39 Barbier (2025)
40 Agriloops (2025)
41 Bio Clean Carbon (2025)
42 Magma Seaweed (2025)
43 Big Akwa (2025)

References

Agriloops (2025). ‘Ultra-Fresh Shrimps, sustainable and produced in France’. https://www.agriloops.com/homepage-agriloops

Aquaphoenix (2025). 'Technology'. https://aquaphoenix.eu/technology

Barbier E. (2025). ‘Saline solution: rethinking shrimp farming in France’. https://thefishsite.com/articles/saline-solution-rethinking-shrimp-farming-in-france

Big Akwa (2025). ‘Can WE & YOU bring the process and food industry together?’. https://bigakwa.com/en/

Bio Clean Carbon (2025). ‘Turning waste into Clean Assets: Carbon Capture & Water Purification in One Solution’. https://www.biocleancarbon.com/

Blue Research ApS (2022). ‘Production of Atlantic Salmon in Recirculated Aquaculture System (RAS)’. Københavns Universitet.

Bregnballe, J. (2022). 'A guide to recirculation aquaculture – An introduction to the new environmentally friendly and highly productive closed fish farming systems'. Rome. FAO and Eurofish International Organisation. https://doi.org/10.4060/cc2390en

Britannica (2023). ’Baltic Sea’. https://www.britannica.com/place/Baltic-Sea

Brown, A.R., Wilson, R.W., Tyler, C.R (2025). ‘Assessing the Benefits and Challenges of Recirculating Aquaculture Systems (RAS) for Atlantic Salmon Production’. Reviews in Fisheries Science & Aquaculture, 33:3, 380-401, https://www.tandfonline.com/doi/full/10.1080/23308249.2024.2433581

Business Lolland-Falster (2024). ‘Grøn industriklynge på vej i Nakskov’. https://businesslf.dk/groen-industriklynge-paa-vej-i-nakskov/

Business Lolland-Falster (no date). ‘Teknisk vand – infrastruktur til ptx‘. Teknisk vand - Infrastruktur til PtX | Business Lolland-Falster (businesslf.dk)

Danmarks Naturfredningsforening (2015). ‘Sådan ligger landet… tal om grundvand og drikkevand 2015’. https://aktiv.dn.dk/media/4321/dn-saadan-ligger-landet-2014-grundvand-og-drikkevand.pdf

Danmarks Naturfredningsforening (2024). ’Se kortet: Så ofte bliver der fundet pesticidrester i drikkevandsboringer i din kommune’. https://www.dn.dk/nyheder/se-kortet-sa-ofte-bliver-der-fundet-pesticidrester-i-drikkevandsboringer-i-din-kommune/

Danmarks Statistik (2023). ’Forbrug af vand’. https://www.dst.dk/da/Statistik/emner/miljoe-og-energi/groent-nationalregnskab/vand-og-spildevand

Emerman, J.D. (2016). ‘Establishing the optimal salinity for rearing salmon in recirculating aquaculture systems’. University of British Columbia. https://dx.doi.org/10.14288/1.0225868

FAO (2024). 'In Brief to the State of World Fisheries and Aquaculture 2024'. https://doi.org/10.4060/cd0690en

FAO (2009). ‘How to feed the world in 2050’. https://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/

How_to_Feed_the_World_in_2050.pdf

Femern Belt Development (2024). ‘Stor international erhvervspark på vej i Rødbyhavn’. https://www.femern.info/da/news/stor-international-erhvervspark-paa-vej-i-roedbyhavn

Food Nation (2023). ‘Denmark is a Leading hub for Sustainable production and Innovation within fisheries and aquaculture’. https://foodnationdenmark.com/seafood-digital-white-paper/

Fødevarestyrelsen (no date). 'Dioxin'. https://foedevarestyrelsen.dk/kost-og-foedevarer/alt-om-mad/kemi-i-maden/uoensket-kemi-i-mad/dioxin

GEUS (2024). ‘Forekomst af pesticidstoffer i de almene vandværkers boringskontrol for perioden 1/1-2023 til 31/12-2023’. https://www.geus.dk/Media/638405778743622866/Forekomst%20af%20pesticidstoffer%20i%20de%20almene%20vandv%c3%a6rkers%20boringskontrol%201.1.2023-31.12.2023.pdf

Guldborgsund Forsyning (2025a). ’Prisliste Spildevand’. https://www.guldborgsundforsyning.dk/prisliste-spildevand/

Guldborgsund Forsyning (2025b). ’Prisliste Vand’. https://www.guldborgsundforsyning.dk/prisliste-vand/

HELCOM (2022). ‘HELCOM Thematic assessment of economic and social analyses 2016-2021.Baltic Sea Environment Proceedings No. 188’. https://helcom.fi/wp-content/uploads/2023/03/HELCOM-Thematic-assessment-of-economic-and-social-analyses-2016-2021.pdf

Klimatilpasning (2023). ’Climate change impact on the water’. Climate change impact on the water (klimatilpasning.dk)

Koski M., Gregersen K.J.J., Riisager-Simonsen C., Gallemi A.P., Lisbjerg D., Pedersen L-F. (2021). ’Towards biocide-free recirculating aquaculture systems’. https://www2.mst.dk/Udgiv/publications/2021/09/978-87-7038-342-4.pdf

Liu, Y., Rosten, T.W., Henriksen, K., Hognes, E.S., Summerfelt, S., Vinci, B. (2016). ’Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (Salmo salar): Land-based closed containment system in freshwater and open net pen in seawater’. Aquacultural Engineering, Volume 71, Pages 1-12. https://doi.org/10.1016/j.aquaeng.2016.01.001

Madsen, B.L., Valeur, B., Worm, B., Buch, E., Christiansen, E., Jensen, K., Houmark-Nielsen, M., Ventegodt, O. (2025). ’Østersøen’. https://lex.dk/%C3%98sters%C3%B8en

Madslund, H.S. (2023). ’En sjettedel af Østersøen er død’. Vid&Sans. https://vidogsans.dk/en-sjettedel-af-oestersoeen-er-doed/

Magma Seaweed (2025). ‘Macro algae made with amour’. https://www.magma-seaweed.com/

Maripure (no date). 'Biosolutions for an emission free future'. https://www.maripure.com/

Miljø- og Ligestillingsministeriet (2025). ’Ny aftale for spildevand: Markant reduktion i kvælstofudledningen skal forbedre vandet i 16 fjorde og kystvande’. https://mim.dk/nyheder/pressemeddelelser/2025/april/ny-aftale-for-spildevand-markant-reduktion-i-kvaelstofudledningen-skal-forbedre-vandet-i-16-fjorde-og-kystvande

Miljøstyrelsen (2024). ’Rensning af processpildevand fra rentvandsfabrikker til Power-to-X’. https://mst.dk/media/oxqp5pwj/bilag-1-rensning-af-processpildevand-fra-rentvandsfabrikker-til-power-to-x.pdf

Miljøstyrelsen (no date). 'Kortlægningsresultater'. https://mst.dk/erhverv/rent-miljoe-og-sikker-forsyning/drikkevand-og-grundvand/grundvandskortlaegning/kortlaegningsresultater

Naylor R.L., Kishore A., Sumaila U.R., Issifu I., Hunter B.P., Belton B., Bush S.R., Cao L., Gelcich S., Gephart J.A., Golden C.D., Jonell M., Koehn J.Z., Little D.C., Thilsted S.H., Tigchelaar M., Crona B. (2021). ’Blue food demand across geographic and temporal scales’. Nature Communication 12, 5413. https://doi.org/10.1038/s41467-021-25516-4

Our World in Data (2023). ‘World Population Growth’. https://ourworldindata.org/population-growth

Rambøll (2025). ‘TETRAS – Pilot 1, Water reclamation from landbased RAS-plant’. Business Lolland-Falster. TETRAS

SINTEF (no date). ‘This is why we need sustainable feed’. https://www.sintef.no/en/sintef-research-areas/biomarine_resources/this-is-why-we-need-sustainable-feed/

Skagen Salmon, Blue Research, BLF (2021), ‘Production of Atlantic Salmon in Recirculated Aquaculture System (RAS) at Lolland-Falster’

Skagen Salmon (2025). 'Innovativt og skånsomt lakseopdræt'. Skagensalmon.com/opdraetsmetode

Swedish Algae Factory (no date). ‘Advanced materials from algae’. https://www.swedishalgaefactory.com/

24Victoria (2025). ‘Ny rapport: AI datacentre presser vores vandforsyninger’. https://24victoria.dk/artificial-and-intelligence-deep-tech/ai-datacentre-2

World Bank Group (2017). ‘Water Management in Israel’. https://documents1.worldbank.org/curated/en/657531504204943236/pdf/Water-management-in-Israel-key-innovations-and-lessons-learned-for-water-scarce-countries.pdf

World Resources institute (2016). ‘Animal-based Foods are More Resource-Intensive than Plant-Based Foods’. https://www.wri.org/data/animal-based-foods-are-more-resource-intensive-plant-based-foods

/ *Business*
Lolland-Falster

+45 7022 8901 · INFO@BUSINESSLF.DK · BUSINESSLF.DK