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TETRAS – Pilot 1

Water reclamation from landbased RAS-plant

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Water reclamation from landbased RAS-plant

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Contents

Appendices

Appendix 1
Process Specification - TETRAS

Appendix 2
Boll Filter test report incl. appendix

Appendix 3
Economic assessment of full-scale plant

Appendix 4
Reject water cost estimate Process Specification - TETRAS

1. Executive summary

The report conducts a detailed techno-economic assessment of a water reclamation facility (WRF) that makes 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.

Ramboll invited eight suppliers for tenders to conduct pilot trials using Ultrafiltration (UF) and Reverse Osmosis (RO) on wastewater from the RAS facility Skagen Salmon. EnviroWater Group and Boll Filter chose to submit an offer, and Boll Filter was chosen to conduct the pilot. The pilot test was executed at Skagen Salmon in Skagen over a three-day period using Ceramic Ultrafiltration (CUF) and RO. In addition to the CUF-RO pilot, a Membrane Distillation (MD) laboratory test was carried out on a sample of the CUF permeate from the pilot study, to compare the feasibility of MD to RO.

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 showed significant improvements. The RO 65% permeate is expected to meet the ammonia limit, however, the detection limit of the analysis (<1 mg/l) was orders of magnitude higher than the Danish drinking water limit for ammonia (0,05 mg/l). A theoretical estimation of ammonia in the RO permeate at 65% 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, aluminum, 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 expected required to effectively lower contaminant levels for safe discharge to the Baltic Sea or to municipal wastewater treatment plants.

A future full-scale WRF capable of treating 200 m^3/h of RAS wastewater was designed and priced with a 30% uncertainty. The economic analysis over a 20-year horizon 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 for

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 permittability and economic viability

2. Background

A RAS (Recirculating Aquaculture System) system is an aquaculture system that, through the use of water purification, achieves a very high degree of recycling of the production water. The TETRAS (Technology Transfer for Thriving Recirculating Aquaculture Systems in the Baltic Sea Region) project demonstrates how land-based fish production facilities in a RAS facility can be strategically located and/or combined with other industrial processes.

The TETRAS project is a project under the INTERREG BSR (Baltic Sea Programme) that runs from 2023 to the end of 2025, and is a collaboration between partners from Denmark, Germany, Poland, Lithuania and Estonia.

The TETRAS project consists of four pilots:

- Pilot 1 aims to test the best available 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.

- Pilot 2 is focused on investigating the potential symbiosis between geothermal resources and RAS. The aim is to assess the feasibility of utilizing resources for the heating and mineralization of marine-brackish RAS to lower operating expenses and achieve energy efficiency.

- Pilot 3 will develop a feasibility study to analyze the use of available resources (water and energy) at the Estonian Industrial Symbiosis Agropark (EISAP) and strategies for optimal water use and management for designing a commercial RAS farm with greenhouses, other industries, and offices. The pilot will result in a business case ready to be presented to investors.

- Pilot 4 will establish a RAS and aquaponics demonstration facility at CELF (Center for Vocational Education Lolland Falster), where there is an opportunity to communicate about fish and plant symbioses, circular bioeconomy, water quality and resource efficiency. The aims are to increase public understanding of recirculating aquaculture through a small-scale RAS combined with aquaponics by providing a clear example of how they work and their associated benefits and a more profound understanding of the nutrient cycle.

This current project will address TETRAS' Pilot 1, by conducting a pilot test 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 by conducting an economic analysis of the technical solution in full-scale.

Pilot 1 is owned by Business Lolland-Falster (BLF) and focusses on Lolland-Falster in Denmark. It is BLF's ambition that the participation in TETRAS will provide technical solutions that can lead the way for investments in sustainable aquaculture in Lolland-Falster.

Lolland Municipality is a municipality with a very limited groundwater resource – so limited that there are challenges in supplying sufficient drinking water in the future. At the same time, the municipality is experiencing large growth of both inhabitants and companies. The municipality has therefore announced that companies will not be able to have unlimited access to groundwater resources in the future – as it must be ensured that there is sufficient drinking water for citizens. Companies that will be affected by the above are for example the planned PtX plants, the concrete element factory in Rødbyhavn but also other water consuming industries that would like to settle in the area.

For the establishment of RAS facilities, it can be crucial whether process water is to be discharged, or the process 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.

Therefore, this study examines how to produce technical water of Danish drinking water quality from RAS wastewater, using membrane technology. The study is conducted using the discharge water from a RAS facility in Skagen, Skagen Salmon. The study specifically investigates the performance of ceramic ultrafiltration (CUF), reverse osmosis (RO), and membrane distillation (MD). CUF is tested for its ability to remove suspended solids and larger particles from the wastewater, while RO is used for its high efficiency in desalination and removing dissolved salts and organic matter. MD is 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.

When producing technical water utilizing membrane technology, there will be produced a permeate and a reject stream, where the permeate is the produced technical water stream, and the reject stream is the stream containing higher concentrations of the different pollutants from the wastewater, which are removed from the technical water.

The reject water therefore creates an additional challenge when producing technical water. To minimize 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 in this report include:

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

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

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

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

3. Description of RAS

A RAS plant is a water recycling fish farming system. RAS stands for Recirculation Aquaculture Systems and covers all types of aquaculture facilities with a significant degree of water reuse using water treatment. RAS systems can be both freshwater systems (using groundwater or fresh water from lakes) or a saltwater system (using seawater).

A fish farming plant without water treatment (called flow-through systems) will generally need 30,000-50,000 liters of new water per kg of feed added. In a RAS system the amount of water that can be reused is determined by the water treatment used. A traditional RAS system with mechanical, biological, and degassing unit can consume down to 400-500 liters of new water per kilogram of feed. If a lower water intake is wanted, the plant must be expanded with denitrification, which can reduce the water intake to 50-100 liters per kilogram of feed.

In a traditional RAS plant, where you have 400-500 liters of water per kilogram of feed, the outlet water from the RAS will normally be distributed as in Figure 1:

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

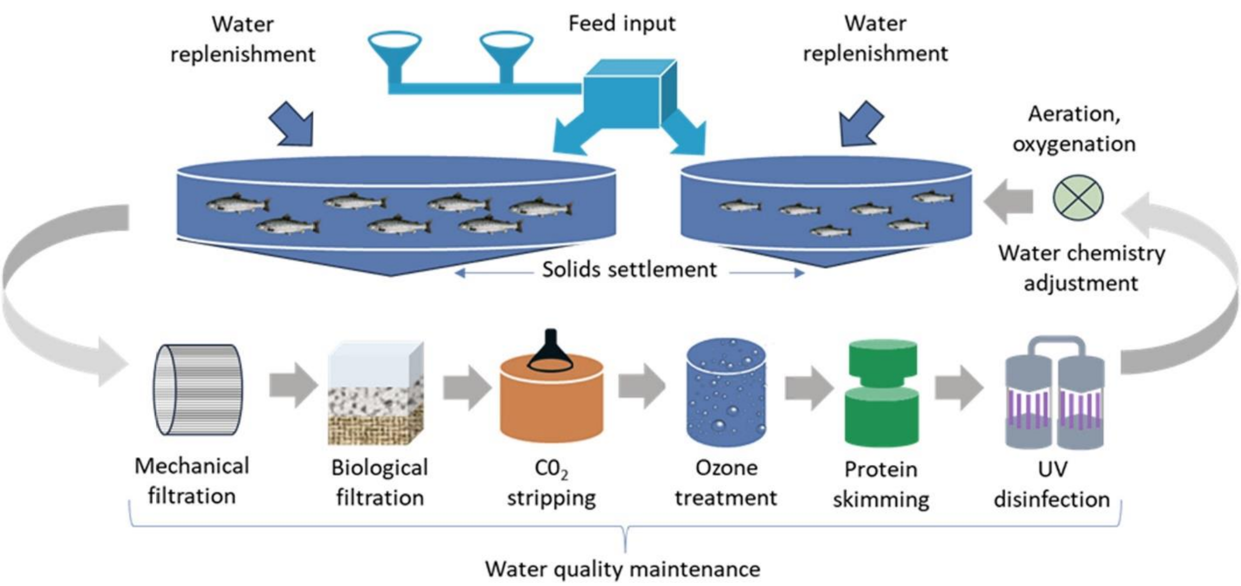

Figure 1: Schematic design of a typical RAS plant for salmon production (A. R. Brown, 2024).

The first two treatment steps, mechanical and biological filters, produce a stream for further treatment, as well as wastewater stream which is not recirculated. Instead, this stream is led to sludge treatment. The sludge reject water, together with the 200-250 liters of process wastewater, is traditionally discharged from a RAS plant, and to be treated for reuse as part of this pilot study.

The composition of the process wastewater from a traditional RAS plant can vary largely and will depend, among other things, on who operates the plant as well as their wishes and experience with water quality and water parameters. In addition, the species being farmed, stage of species and technologies used in the water purification in the RAS plant itself will also have an impact. The quality of the sludge reject water is affected by the type of sludge treatment, varying from plant to plant.

The basic principle of 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 fecal 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, NH_4, to nitrite, NO_2, and then to nitrate, NO_3. This is done as ammonia is toxic for the fish and therefore needs to be converted into something harmless. Lastly the water will go through aeration to make sure any detrimental gasses in the water are removed. This is done aerating the water thereby stripping the water from detrimental volatiles.
On top of these three basic treatments, further treatment is possible such as oxygen enrichment and UV disinfection (Bregnballe, 2015).

Experience shows that process wastewater from RAS has a high content of nitrogen in the form of nitrate. If the plant is a saltwater RAS, the process wastewater has a very high content of salts such as chlorides. Traditionally, the first stages of salmon (up to smoltification) will be grown in land-based freshwater facilities, after which the fish are transferred to a seawater facility, with gradually higher salt concentrations.

3.1 Skagen Salmon

Skagen Salmon delivers production water for the pilot testing in pilot 1. Skagen Salmon is a newly established state-of-the-art RAS plant that was launched in 2020 and is in the process of completing the last vessels. Skagen Salmon is a seawater-based RAS plant producing salmon, with a full capacity of 3,800 tons salmon per year (approx. 1 million fish). Skagen Salmon discharges saline wastewater at approximately 150 m^3/h or a daily flow of 3,600 m^3. The plant is divided into two departments: Smolt and Grow Out.

Smolt (blue circle in Figure 2) is where eggs hatch and fish gradually adapt to seawater. It includes:
- A room with trays for hatching
- 8 starting vessels (7 m^3 each)
- 30 fry vessels in groups of 10 with the sizes of 11 m^3, 22 m^3 and 40 m^3
- 8 pre-grow vessels (122 m^3 each)
- 5 water treatment systems

Grow Out (red circle in Figure 2) is where fish reach 4 kg in seawater. It consists of:
- 18 vessels (750 m^3 each)
- 12 vessels (1.200 m^3 each)
- 6 water treatment systems

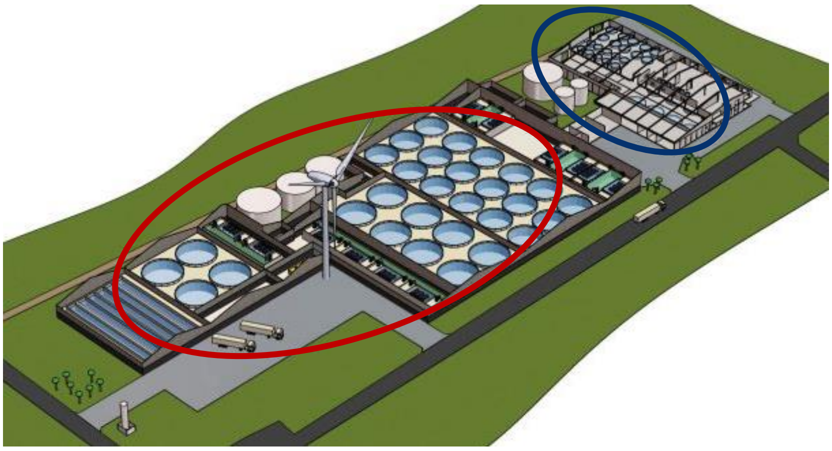

Figure 2: Skagen Salmon RAS plant. The red circle is Grow Out while the blue circle is Smolt (Tornsberg, 2022).

The plant receives approximately 320,000 eggs 4-5 times a year. Eggs hatch in freshwater, and as the fish grow, they are moved to larger vessels with increasing salt concentrations and changing light conditions to simulate seasonal transitions.

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 liters per kg of fish 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 3).

As shown in Figure 3, water is extracted at multiple points in the process for external treatment to maintain system balance and water quality. Additionally, 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 optimize water reuse while minimizing environmental impact.

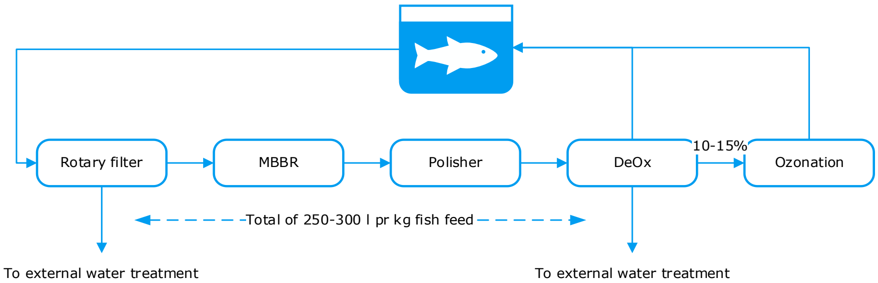

Figure 3: The internal water treatment.

The water not reused in the RAS plant undergoes final external water treatment before discharge to Skagerrak. It first passes through denitrification via conventional activated sludge and then final sedimentation, where sludge is removed, dewatered, and sent to the Skagen wastewater treatment plant (Figure 4).

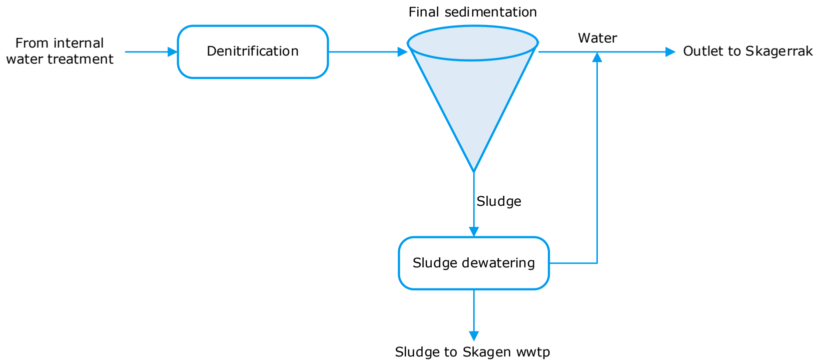

Figure 4: The external wastewater treatment.

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%. The different parts of the wastewater from the production are mixed before being send to the external activated sludge treatment plant.

4. Water quality

In this section, the required technical water quality of drinking water that meets Danish standards is accounted for. The discharge water quality at Skagen Salmon's RAS plant is examined, in relations to meeting the desired water quality. Furthermore, the seawater characteristics from Skagen are compared with those of Fehmarn Belt to assess the expected water quality for a future RAS facility in Lolland-Falster.

4.1 Water treatment requirements

The technical water will be treated to meet Danish drinking water quality standards. This enables that the technical water is suitable for most industries, depending on the necessary quality demands in the company in question. Meaning that some industries will need to treat the technical water further, and some industries will need a water quality with more relaxed requirements.

These standards ensure that the treated water is free from harmful contaminants and suitable for safe use in a variety of industrial applications. These criteria include limits on physical, chemical, and microbiological parameters, which safeguard against risks to human health and maintain the integrity of the treated water. Quality parameters and concentration demands from the Danish Drinking Water Regulation (BEK nr. 1633, 2024) are listed in Table 1.

Table 1: Quality demands for drinking water (BEK nr. 1633, 2024).

	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
Nitrite, 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
Aluminum, Al	mg/l	0.2
Iron, Fe	mg/l	0.2
Manganese, Mn, total and dissolved	mg/l	0.05

**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: Non measurable at given method.

In industrial equipment the removal of contaminants such as ammonium, nitrate, nitrite, and metals like iron and manganese is particularly critical to avoid biofouling, scaling, or corrosion. Furthermore, the prevention of aggressive or corrosive water, as outlined in the declaration, underscores the importance of maintaining water chemistry that avoids damage to infrastructure and ensures long-term usability. Finally, ensuring biological safety of the treated water is essential. It is assumed that this can be achieved with a final conventional drinking water disinfection system as a final posttreatment of the water. Disinfection is not included in the scope of this report.

Meeting the Danish drinking water demands not only ensures compliance with Danish regulations but also aligns with best practices in water treatment technology. This underscores the importance of a robust and efficient treatment system that integrates advanced filtration, chemical conditioning, and disinfection processes to achieve the desired water quality.

4.2 Discharge Water from Skagen Salmon

A water quality analysis of the final discharge from Skagen Salmon's RAS plant was conducted on 24 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.

Table 2: Discharge water quality from Skagen Salmon.

	Unit	Value
pH	pH	7.6
Temperature at pH-measurement	°C	21
Suspended solids	mg/l	100
Alkalinity, total	mmol/l	6.8
Ammonia-N	mg/l	3.6
Bromide (Br), filtered	mg/l	35
Chloride, filtered	mg/l	12,000
Fluoride, filtered	mg/l	0.45
Total phosphor	mg/l	2.8
Hydrogen carbonate	mg/l	415
Nitrate-N, filtered	mg/l	0.48
Nitrite-N	mg/l	0.084
Silicon (Si)	mg/l	3.4
Sulphate, filtered	mg/l	1,600
Hardness, total	°dH	210
Total Nitrogen	mg/l	7.4
BI5 (with ATU)	mg/l	4.9
BI5 filtered (with ATU)	mg/l	5
COD, chemical oxygen demand	mg/l	210
DOC, dissolved organic carbon	mg/l	14
NVOC, non-volatile organic carbon	mg/l	17
VOC, volatile organic carbon	mg/l	<0.5
TOC, total organic carbon	mg/l	17
Aluminum (Al)	mg/l	0.033
Barium (Ba)	mg/l	0.0095
Lead (Pb)	mg/l	<0.0002
Calcium (Ca)	mg/l	310.0
Chromium (Cr)	mg/l	0.0014
Iron (Fe)	mg/l	1.8
Potassium (K)	mg/l	220.0
Copper (Cu)	mg/l	0.0035
Magnesium (Mg)	mg/l	680.0
Manganese (Mn)	mg/l	0.11
Sodium (Na)	mg/l	2,900.0
Nickel (Ni)	mg/l	0.0024
Strontium (Sr)	mg/l	1.9
Titanium (Ti)	mg/l	<0.5

To assess the difference in quality of the Skagen Salmon discharge water to drinking water quality, Table 1 and Table 2 shall be compared. The most critical drinking water parameters are concluded to be ammonia and chloride, which exceed the drinking water thresholds ca. 100 and 50 times respectively. The concentrations of nitrite, sulphate and iron are about 10 times too high. The discharge water is also too high in suspended solids for the drinking water standard to reach as low as 1 FNU in turbidity.

4.3 Comparison of Fehmarn Belt vs. Skagen

To evaluate the seawater quality for a potential RAS facility in Lolland-Falster, the Fehmarn Belt seawater is compared with the seawater used at Skagen Salmon's RAS facility. The Fehmarn Belt data is primarily based on DTU analyses (Ramboll, 2023) and previous environmental impact assessments (Femern Sund Bælt, 2013). The Skagen seawater data is derived from literature studies and site-specific analyses.

At Skagen Salmon, the seawater is taken in through drains located approximately 3 meters below the sand, right at the water's edge. A slight groundwater pressure from the land influences the salinity, which fluctuates between 28 and 30‰ depending on the tide and sea level. This dynamic nature of the seawater needs to be considered when designing a RAS facility.

Table 3: Content of seawater from Fehmarn Belt, Lolland-Falster, and seawater quality from Skagerrak, Skagen.

	Unit	Analysis of seawater from Fehmarn Belt		Skagerrak, Skagen
		Minimum	Maximum	
Temperature[1]	°C	2.5	20	2.5-18[4]
TOC[1]	mg/l	0.3	0.8	-
TSS[1]	mg/l	2	29	25[5]
pH[2]	-	7.36	7.9	-
Calcium[2]	mg/l	94.4	161.1	386.6[6]
Magnesium[2]	mg/l	241.5	444.4	1,206.9[6]
Natrium[3]	mg/l	-	7,100	10,164[6]
Potassium[2]	mg/l	87.2	158.5	377.1[6]
Chloride[3]	mg/l	-	18,000	18,244[6]
Sulphate[2]	mg/l	620	620	2,555.1
Conductivity[2]	mS/m	1,588	2,900	-

[1]*Literature study from Ramboll report* (Ramboll, 2023).
[2]*Data from DTU analysis from Ramboll Report* (Ramboll, 2023).
[3]*Data from VVM (estimated quantities)* (Femern Sund Bælt, 2013).
[4]*Analysis from Skagen Salmon*
[5]*Based on data from Hirtshals* (Nielsen, 2010-2021)
[6]*Based on an average salinity of 33‰. A conversion from g/kg to mg/l assumes that the density of seawater is the same as fresh water (1,00 kg/l).* (CI task, u.d.) (Bendtsen, Gustaffson, & Christiansen, 2015)

A direct comparison indicates that:

- Skagen seawater has higher salinity and mineral content, which may impact the demineralization process before reuse, particularly affecting the energy consumption for desalination/RO in the WRF, compared to a RAS facility using Fehmarn Belt seawater.
- Fehmarn Belt seawater shows greater seasonal variation, necessitating a flexible water treatment approach to accommodate fluctuations in temperature and suspended solids.
- Both sources exhibit 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.

5. The pilot test

This section provides an overview of the pilot test conducted as part of the supplier selection process. It includes the process specification, detailed objectives and requirements of the pilot test, the test methodology used in Skagen, and the raw data collected during the test.

5.1 The process specification

To carry out the pilot test, Ramboll conducted a tender with a fixed budget. 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.

The process specification can be seen in Appendix 1.

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. The composition of the water sample from Skagen Salmon presented in Table 2, was to be used as a process design basis for the pilot test. The batch volume was restricted to 2-10 m^3 of discharge water from Skagen Salmon.

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 as described in section 4.3. The costing of the full-scale WRF is seen in section 7.

5.2 The suppliers

Ramboll invited 8 relevant suppliers to submit tenders for the execution of the pilot trials, all of whom based in Northern Europe. The suppliers were chosen based on Rambolls good experience with collaboration, technical solutions, and/or pilot trials. In addition, it was deemed important that the individual supplier has a department in or close to Denmark, so that the trials could either be run in Skagen or the storage of the wastewater between sampling and off-site trials could be minimized. The process specification was sent to Krüger, BWT, Eurowater, H+E, EnviroWater, Boll Filter, DuPont and Waterleau. Two suppliers chose to bid for the job: EnviroWater Group and Boll Filter.

EnviroWater Group is a large German company with more than 1,000 employees with locations in a.o. Denmark, Finland, Sweden and Norway. The company was established in 1976 and currently consists of the three subdivisions EnviroFalk, EnviroProcess and EnviroChemie. EnviroChemie specializes in wastewater, cooling water and process water, and has a few full-scale water reuse plant references.

Boll Filter is a large German company with more than 1,000 employees globally including Denmark. Since 2019 Boll Filter has been supplying ceramic UF plants for marine desalination plants. In 2024 Boll Filter has acquired the Luxembourg-based membrane system supplier APATEC, who have experience with wastewater recycling and marine desalination in the Baltic Sea on Öland. Boll Filter Denmark is currently developing a membrane distillation plant for integrated reuse of water and residual heat from hydrogen production.

Based on Ramboll's process specification and a clarifying meeting with Ramboll, the suppliers submitted their pilot test description and tender. The two suppliers both showed high engagement in the project and integrated their previous experience in their offers. Hence, the two offers differ slightly from the process specification and from each other. The key aspects of both offers are summarized below.

EnviroWater offered to run the pilot trials at their test center in Darmstadt, Germany. The trials were based on shipped wastewater from Skagen and seawater from Lolland-Falster. The entire trial series would take 3 to 4 weeks and would be based on existing pilot units in their test center. They suggested to treat Skagen wastewater with ozonation and flocculation as a pretreatment before ceramic UF unit, followed by high-recovery RO. They suggested to run additional RO trials with seawater samples from Lolland-Falster, to avoid estimating costs based on theoretical TDS assumptions and hence limit uncertainty on the full-scale cost estimates. The EnviroWater offer included a limited scope of water analysis, bringing along additional expenses for the project.

Boll Filter offered to run the pilot trials in Skagen, avoiding shipping and wastewater degradation during shipping time. The entire trial series would take 1 week and would be based on both existing and new pilot units. They 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). They also offered the possibility to test membrane distillation (MD) as an addition to the project. The Boll Filter offer included all water analysis requested in the process specification.

Due to the included analysis and the fact that the pilot was carried out directly at Skagen Salmon, Boll Filter was chosen as the supplier for the pilot test.
In addition to the original assignment, it was agreed to also 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.

5.3 Treatment technologies applied in the pilot setup

The test setup utilized a combination of advanced filtration technologies. A diagram and picture of the test setup can be seen in Figure 5 and Figure 6.

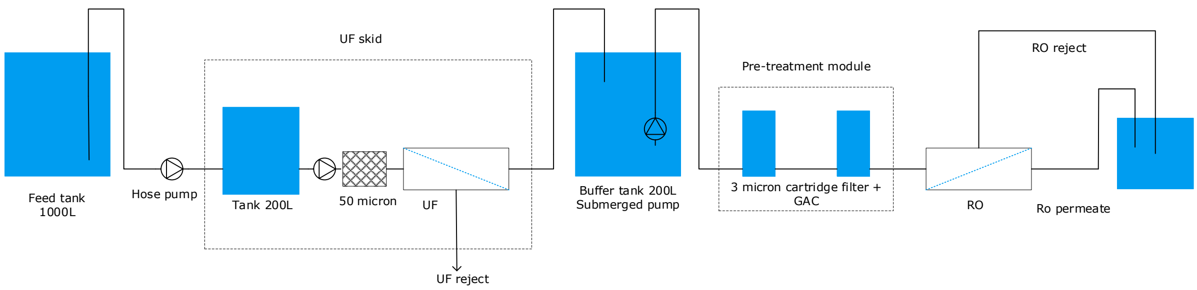

Figure 5: Test installation process flow at Skagen Salmon.

The feed water for the batch test was supplied in a 1,000 L IBC tank. The unit allowed to pump this to a 200 L feed tank, from where the wastewater was pumped into a series of filtration units.

The process started with a BOLL Mikro-Mia 2.0 UF unit, which incorporated 50-micron pre-filtration, and two ceramic membranes made from silicon carbide (SiC) and zirconium dioxide (ZrO_2), each with a surface area of 0.09 m². UF operates as a pressure-driven membrane separation process, where a transmembrane pressure gradient forces water through a semi-permeable membrane. Ceramic membranes, such as those made from SiC and ZrO_2, 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, to safeguard its performance. It included a 3-micron absolute cartridge filter for fine particulate removal and a granular activated carbon (GAC) filter to eliminate dissolved organic compounds and chlorine, which could damage the polyamide RO membranes.

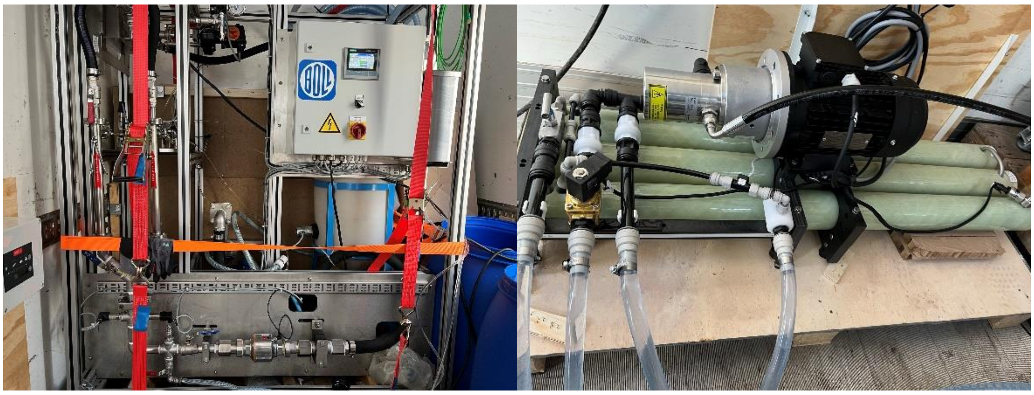

Figure 6: The setup of the ceramic filtration system (on the left) and the reverse osmosis system (on the right).

At the heart of the system was the AQSEP WM2000B-340 RO unit, equipped with three DOW SW30-4040 membranes, providing a total surface area of 22.2 m^2. 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 6. This integrated design ensured the technologies operated in harmony, delivering reliable and effective water treatment through a multi-barrier approach.

5.4 Execution of the pilot test

From October 1st to 3rd 2024, pilot tests were conducted on wastewater from Skagen Salmon, with Boll Filter overseeing the operation. Representatives from Ramboll and Business Lolland-Falster were present throughout the testing. Despite challenges such as equipment failure and electrical outages, the tests successfully demonstrated the system's operation and generated key data for further analyses. The operating set points for the UF and RO is seen in Figure 7.

01-okt							
	Flux (lmh)	TMP (bar)	Flux/TMP (lmh/bar)	TCSF/TMP (lmh/bar)	V-channel (m/s)	Temp (°C)	Notes
15:33	90	0.64	141	102	3.1	30.3	Flux 2h after installing new membrane (M2)
02-okt							
12:20	48	0.93	52	39	3.6	29.0	Addition of 25L feed to UF skid (75L initial feed volume)
15:11	60	0.99	61	38	3.1	34.7	Addition of 25L feed to UF skid
17:43	66	0.96	69	39	3.1	38.0	Addition of 25L feed to UF skid
03-okt							
01:03	74	0.87	85	47	3.0	39.4	Pilot stopped during the night
08:28	60	0.81	74	50	2.9	33.0	Pilot started to complete 150L feed cycle and collect samples

(*) TCSF = Temperature corrected specific flux at 20°C = $\frac{flux}{TMP}\ x\ e^{\wedge}(-0.031\ x\ (T-20))$

RO operating set points:

03-okt	flux (lmh)	membrane pressure (bar)	TCSF (lmh)	recovery (%)	salinity (ppm)	Temp (°C)
09:50	14	50	17	57	61	10 (*)
10:00	16	59	19	65	61	10 (*)
10:02	17	66	21	73	61	10 (*)
10:44	18	67	22	74	N/A	10 (*)

(*) Temperature was estimated from UF data

Figure 7: UF- and RO set points during the pilot test.

The following summarizes the activities and outcomes of each day:

Day 1 (October 1st):
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. Approximately 800 liters of RAS wastewater were collected and used to fill the UF skid feed tank. About 100 liters of UF permeate were collected and used to start and evaluate the RO system, ensuring that its flux, pressure, and salinity performance were within expected ranges.

Day 2 (October 2nd):
The second day marked the start of continuous UF operation. An additional 800 liters of RAS wastewater were collected, with 75 liters used to refill the UF skid feed tank. UF permeate was collected in a 200-liter tank, with 25 liters of feed added approximately every three hours during operation, amounting to 150 liters of total feed for the day. The UF skid was operated steadily throughout the day, producing permeate for testing. However, plans to begin the RO test were delayed due to repeated electrical outages, postponing the RO operation to the following day.

Day 3 (October 3rd):
The final day focused on completing the UF and RO tests and collecting water samples for laboratory analysis. The UF skid was restarted, producing 142.5 liters of permeate and leaving 7.5 liters of reject in the dead volume of the skid. Following this, the RO skid was initiated, with RO permeate and reject samples collected at recovery rates of 57%, 65%, and 73%. However, during the final recovery test

at 73%, a failure in the check valve caused the RO test to end prematurely. After testing concluded, the system was disassembled.

In Figure 8 the UF feed water, permeate and reject is seen.

Figure 8: UF feed water (left), UF permeate (center), UF reject (right).

5.5 Execution of the MD laboratory test

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 particularly advantageous in cases where low-grade thermal energy, such as waste heat, is available.

The 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. Given such low conductivity levels are valuable for the end-user of the technical water resulting in higher capital and operational costs as well as increased challenges in managing brine. Furthermore, MD is highly tolerant of high salinity and fouling-prone feedwaters, such as brines or complex wastewaters, where RO would face significant performance limitations.

<u>Experimental Setup and Heat Supply</u>

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 plate-and-frame heat exchanger, where feedwater was heated to 55°C using an external temperature-controlled water bath. The heating system simulated the use of low-grade waste heat, making it relevant for industrial applications where surplus heat is available.

The experimental setup is illustrated in Figure 9 below:

Figure 9: Experimental MD setup.

5.6 Results

The following section examines the composition and quality of UF-RO permeate, UF-RO reject, and membrane distillation (MD) distillate obtained during the pilot tests. It provides a detailed analysis of the removal efficiency of salts, organic matter, nutrients, and metals at different recovery rates, highlighting the impact of process conditions and potential challenges. Additionally, the influence of operational factors, such as check valve malfunctions, is discussed to ensure accurate interpretation of the results. The complete test report is seen in Appendix 2 .

5.6.1 UF-RO permeate

During the pilot test, permeate water samples were collected at various recovery rates, with the results presented in Table 4.

Table 4: The results of the experiment, where permeate was extracted at different recovery rates.

	Unit	UF Feed	CUF Permeate/ RO Feed	UF-RO Permeate 65%	UF-RO Permeate 73%
pH	pH	7.4	8.3	6.6	7
Temp. at pH meas.	°C	20	20	20	22
Suspended solids	mg/l	29	9.6	3.8	-
Conductivity	mS/m	-	1,700	25	-
Alkalinity, gran plot	mmol/l	-	-	-	0.029
Alkalinity, as CaCO3	mg/l	310	290	5.5	< 5
Total alkalinity	mmol/l	6.25	5.88	-	-
Ammonia + ammonium-N	mg/l	5.2	3.7	< 1	-
Chloride, filtered	mg/l	14,000	15,000	55	24
Fluoride, filtered	mg/l	0.48	0.45	< 0.05	< 0.05
Nitrite + nitrate-N, filtered	mg/l	21	26	0.48	0.41
Silicate-Si, filtered	mg/l	1.4	1.4	0.18	< 0.05
Sulfate, filtered	mg/l	2,000	2,000	6.5	< 0.5
Total hardness	°dH	270	280	< 0.1	< 0.1
Calcium (Ca)	mg/l	320	350	< 5	< 5
Magnesium (Mg)	mg/l	1,000	1,000	< 1	< 1
Total nitrogen	mg/l	27	31	1.1	0.78
Total phosphorus	mg/l	4.3	0.96	0.024	< 0.01
COD	mg/l	100	41	< 15	< 15
DOC	mg/l	20	12	2.3	< 1
NVOC	mg/l	25	17	2.7	1.5
VOC	mg/l	< 0.5	< 0.5	< 0.5	< 0.5
TOC	mg/l	25	17	2.7	1.5
Aluminum (Al)	mg/l	-	-	< 0.03	< 0.03
Barium (Ba)	mg/l	0.012	0.0094	< 0.001	< 0.001
Lead (Pb)	mg/l	< 0.0005	< 0.0005	< 0.0005	< 0.0005
Calcium (Ca)	mg/l	390	390	< 0.5	< 0.5
Chromium (Cr)	mg/l	< 0.0005	< 0.0005	< 0.0005	< 0.0005
Iron (Fe)	mg/l	9.4	0.066	< 0.05	< 0.05
Potassium (K)	mg/l	330	350	1.5	1.3
Copper (Cu)	mg/l	0.0013	0.0045	< 0.0005	0.0011
Magnesium (Mg)	mg/l	1,100	1,100	0.13	0.21
Manganese (Mn)	mg/l	0.079	0.07	< 0.005	< 0.005

Sodium (Na)	mg/l	9,100	9,200	18	16
Nickel (Ni)	mg/l	< 0.001	0.0013	< 0.001	< 0.001
Strontium (Sr)	mg/l	6.4	7.2	< 0.001	0.001

The presented data provide insights into the composition of the UF and RO permeate at different recovery rates. The RO process effectively reduces the concentration of dissolved solids and contaminants in the feed water, resulting in significantly improved water quality in the permeate stream.

Salts and Ions

The RO permeate produced at a recovery rate of 65% shows a marked decrease in salts and ions when compared to the UF feed water. The conductivity, which is a key indicator of dissolved ions, drops from 1,700 mS/m in the UF feed to 25 mS/m in the RO permeate. Chloride concentrations reduce significantly, from 14,000 mg/l in the UF feed to just 55 mg/l in the RO permeate, well below the drinking water quality limits. Sulfate levels also decrease substantially after RO filtration, meeting the established technical water standards. At the 73% RO recovery rate, similar reductions in conductivity and chloride levels are observed. Reductions of ammonia + ammonium-N are not available because of insufficient permeate sample volume availability. Consequently, full validation of ion reduction at this higher recovery rate is pending further testing.

Organic Matter and Nutrients

The RO process is highly effective in reducing organic matter and nutrients. Total Organic Carbon (TOC) decreases from 17 mg/l in the UF feed to 1.5 mg/l in the permeate, well within the limits for drinking water. Similarly, Dissolved Organic Carbon (DOC) levels drop from 41 mg/l to below the detection limit. For nutrients, ammonia + ammonium-N is reduced to less than 1 mg/l, while both total nitrogen and phosphorus concentrations show significant declines. These reductions confirm the membrane's efficiency in removing organic compounds and nutrients, ensuring production of permeate water that meets drinking water standards.

Metals and Trace Elements

The removal of metals and trace elements is another key aspect of the treatment process. Iron, which is present at 9.4 mg/l in the UF feed, is reduced to below the detection limit in both 65% and 73% recovery permeate samples. Similarly, lead concentrations drop from 6.4 µg/l to less than 0.5 µg/l, well below the drinking water limit. Copper, chromium, and manganese are also effectively removed, with concentrations decreasing to levels well below acceptable thresholds. These results demonstrate that the membrane filtration process is effective in eliminating metals and trace elements, contributing to the production of high-quality permeate water.

Impact of Check Valve Malfunction

The permeate results at the 73% recovery rate may be influenced by the malfunction of the check valve during testing, which could have caused mixing of permeate and reject water. As a result, some of the observed concentrations may be skewed, leading to potential inaccuracies in the analysis. Consequently, the data from the 73% recovery rate should be treated with caution. The permeate results at the 65% recovery rate, however, remain reliable and demonstrate that the water produced is of drinking water quality, consistent with established standards.

5.6.2 Reject water

During the pilot test, reject water samples were also collected at the respective recovery rates. with the results presented in Table 5.

Table 5: The results of the experiment, where the reject was extracted at different recovery rates.

	Unit	UF Feed	CUF Reject	RO Reject 65%	RO Reject 73%
Conductivity	mS/m	-	-	-	5,300

Ammonia + ammonium-N	mg/l	5,2	6,4	6,8	4,7
Chloride, filtered	mg/l	14,000	15,000	29,000	19,000
Fluoride, filtered	mg/l	0,48	0,48	0,61	0,51
Nitrite + nitrate-N, filtered	mg/l	21	25	0,88	38
Silicate-Si, filtered	mg/l	1,4	1,3	4,3	6,4
Sulfate, filtered	mg/l	2,000	2,100	4,000	2,700
Total hardness	°dH	270	280	550	360
Calcium (Ca)	mg/l	320	360	620	460
Magnesium (Mg)	mg/l	1,000	1,000	2,000	1,300
Total nitrogen	mg/l	27	56	61	42
Total phosphorus	mg/l	4,3	33	2,3	0,67
BI5 (with ATU)	mg/l	-	> 15	3,5	3
COD, chemical oxygen demand	mg/l	100	550	31	43
DOC, dissolved organic carbon	mg/l	20	69	19	18
NVOC, non-volatile organic carbon	mg/l	25	150	20	16
VOC, volatile organic carbon	mg/l	< 0,5	< 0,5	< 0,5	< 0,5
TOC, total organic carbon	mg/l	25	150	20	16
Barium (Ba)	mg/l	0,012	0,077	0,036	0,033
Lead (Pb)	mg/l	< 0,0005	0,0064	0,0014	0,0009
Calcium (Ca)	mg/l	390	450	760	500
Chromium (Cr)	mg/l	< 0,0005	0,0091	< 0,0005	< 0,0005
Iron (Fe)	mg/l	9,4	86	< 0,05	< 0,05
Potassium (K)	mg/l	330	380	720	380
Copper (Cu)	mg/l	0,0013	0,093	0.011	0,013
Magnesium (Mg)	mg/l	1,100	980	2,300	1,200
Manganese (Mn)	mg/l	0,079	0,18	0,14	0,1
Sodium (Na)	mg/l	9,100	8,200	19,000	10,000
Nickel (Ni)	mg/l	< 0,001	0,0056	0,0026	0,0023
Strontium (Sr)	mg/l	6,4	8,6	12	7,6

The data in Table 4 shows the analytical results of the Skagen wastewater sample taken before the initiation of the pilot tests. The sample composition is in line with the information on Skagen salmon discharge water quality in Table 2, however, a few parameters differ significantly. The suspended solids in the sample is 3 times lower (29 vs. 100 mg/l), and the COD is only half (100 vs 210 mg/L). Additionally, metal concentrations differ largely with barium, iron, cupper and strontium being found in much larger concentrations than expected in the Skagen Salmon effluent.

The presented data provide insights into the quality of reject water from various stages of the treatment process: CUF Reject, RO Reject 65%, and RO Reject 73%. It is important to note that the RO Reject 73% sample was influenced by a malfunction in the check valve, rendering its data unreliable and less representative of normal operating conditions.

The RO process is designed to concentrate dissolved solids and contaminants in the reject stream while producing purified permeate as the final product. The data clearly shows that the reject contains high concentrations of salts, nutrients, and organic matter, which increase from CUF Reject to RO Reject 65%.

<u>Salts and ions</u>
In the reject streams, various salts and ions become significantly concentrated. For instance, chloride concentrations in the reject water increase notably, with levels rising from 14,000 mg/l in the UF Feed to 29,000 mg/l in the RO Reject 65% and 19,000 mg/l in the RO Reject 73%. Similarly, sulfate concentrations range from 2,000 mg/l in the UF Feed to 4,000 mg/l in the RO Reject 65% and 2,700 mg/l in the RO Reject 73%. Other ions such as sodium also exhibit higher concentrations in the reject, with levels increasing from 9,100 mg/l in the UF Feed to 19,000 mg/l in the RO Reject 65%. These increases are indicative of the rejection of dissolved ions during the filtration processes, which results in the concentration of dissolved salts.

Organic matter and nutrients

The concentration of organic matter and nutrients, including nitrogen, phosphorus, and organic carbon compounds also rises in the reject streams. For example, total nitrogen concentrations increase from 27 mg/l in the UF Feed to 61 mg/l in the RO Reject 65%, while total phosphorus jumps from 4.3 mg/l to 33 mg/l in the CUF Reject. Similarly, DOC levels rise from 20 mg/l in the UF Feed to 69 mg/l in the CUF Reject. This concentration effect is particularly noticeable in organic parameters such as TOC and NVOC, where the levels in the reject streams are much higher than in the feed water. This concentration of organic materials is a direct consequence of the filtration processes, which keeps the organics on the reject side of the membrane unit.

Metals and trace elements

The concentration of metals and trace elements also increase in the reject streams, with varying levels of concentration across different types of rejects. For instance, calcium concentration rises from 390 mg/l in the UF Feed to 760 mg/l in the RO Reject 65%, and magnesium increases from 1,100 mg/l in the UF Feed to 2,300 mg/l in the RO Reject 65%. Other trace elements like iron and copper are present in low concentrations in the feed water but become more concentrated in the reject streams. Iron, for example, increases from 9.4 mg/l in the UF Feed to 86 mg/l in the CUF Reject. Similarly, metals such as lead and nickel remain low in the feed but are more concentrated in the reject streams, with lead rising to 0.0064 mg/l in the CUF Reject and nickel to 0.0056 mg/l in the CUF Reject. This accumulation of metals in the reject water underscores the rejection and concentration processes that occur during RO filtration.

Impact of check valve malfunction

The rupture of the check valve during the RO Reject 73% process has significant implications for the analysis. This failure likely caused mixing of permeate and reject, which could explain the unexpectedly lower concentrations of certain ions and nutrients. Consequently, the data from the 73% sample should be interpreted with caution and should not serve as a definitive basis for evaluating performance differences between 65% and 73% recovery rates.

The results demonstrate that the RO process is highly effective at concentrating salts and reducing organic matter and metal concentrations in the reject stream. KUF Reject and RO Reject 65% provide a clear representation of process trends, while the RO Reject 73% sample is associated with significant uncertainties. To ensure more reliable analysis in the future, valve malfunctions must be avoided, and both reject and permeate samples should be included for a comprehensive assessment of system performance.

5.6.3 Membrane distillation

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.

Membrane distillation results

The feedwater and distillate qualities from the MD process are summarized in Table 6. Following the experiment, both the distillate and reject were sent to Eurofins for further analysis.

Table 6: Results from membrane distillation experiments conducted by DTU.

	Unit	Distillate	Reject
pH	pH	6	-
Temperature at pH measurement	°C	22	-
Suspended solids	mg/l	0.9	-
Conductivity at 20°C	mS/m	0.26	6,900
Alkalinity, Gran plot	mmol/l	0.013	-

Ammonia + Ammonium-N	mg/l	2.1	-
Chloride, filtered	mg/l	< 1	37,000
Fluoride, filtered	mg/l	< 0.05	-
Nitrite + Nitrate-N, filtered	mg/l	< 0.1	-
Silicate-Si, filtered	mg/l	< 0.05	-
Sulfate, filtered	mg/l	< 0.5	-
Hardness, total	°dH	< 0.1	-
Calcium (Ca)	mg/l	< 5	-
Magnesium (Mg)	mg/l	< 1	-
Total Nitrogen	mg/l	0.17	-
Total Phosphorus	mg/l	< 0.01	-
COD	mg/l	< 15	-
DOC	mg/l	0.2	-
NVOC	mg/l	< 1	-
VOC	mg/l	< 0.5	-
TOC	mg/l	#	-
Aluminum (Al)	mg/l	< 0.03	-
Barium (Ba)	mg/l	< 0.001	-
Lead (Pb)	mg/l	< 0.0005	-
Calcium (Ca)	mg/l	< 0.5	-
Chromium (Cr)	mg/l	0.0007	-
Iron (Fe)	mg/l	< 0.05	-
Potassium (K)	mg/l	< 0.5	-
Copper (Cu)	mg/l	0.0061	-
Magnesium (Mg)	mg/l	< 0.05	-
Manganese (Mn)	mg/l	< 0.005	-
Sodium (Na)	mg/l	< 0.5	-
Nickel (Ni)	mg/l	0.011	-

 # No parameters detected

The results from the MD experiment at DTU highlight the effectiveness of the process in producing high-quality water. The pH of the distillate is 6, slightly acidic, with a temperature of 22°C at the time of measurement. Suspended solids are low at 0.9 mg/l, indicating clean water. The conductivity of the distillate is 0.26 mS/m, while the reject stream shows much higher conductivity at 6,900 mS/m, reflecting the concentration of dissolved ions.

Alkalinity is low at 0.013 mmol/l, and chloride levels are 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 are all below detection limits. The distillate is very soft, with minimal calcium and magnesium, and iron, aluminum, barium, and lead are all below detection limits.

Organic content is low, with DOC at 0.2 mg/l and minimal volatile and non-volatile organic carbon. Trace metals like chromium (0.7 µg/l), copper (6.1 µg/l), and nickel (11 µg/l) are present in low concentrations.

In summary, the MD process successfully produces high-quality water with low contaminants, while the reject stream contains higher levels of salts and dissolved solids, typical of membrane distillation processes.

6. Applications for permeate and reject

In the following sections, the analysis results for permeate water will be compared against Danish drinking water quality requirements, while the reject water will be evaluated against the specific requirements for four potential reuse scenarios: agriculture, biogas production, discharge to the sea or direct discharge to a wastewater treatment plant.

6.1 Permeate

The analysis of the CUF permeate and RO permeates (65% and 73%) in relation to drinking water maximum concentration limits reveals that these permeates do not meet all the requirements for drinking water quality due to several exceedances of key parameters.

The CUF permeate shows that metals like lead, chromium, and copper, as well as fluoride, are within safe limits of drinking water quality. However, the high conductivity (1,700 mS/m), far exceeding the drinking water limit of 25 mS/m, indicating a high salinity level. Chloride levels (15,000 mg/l) are also significantly higher than the permissible 250 mg/l for drinking water, posing a serious concern for technical water application of the permeate, since these chloride concentrations are corrosive to water distribution equipment materials. The ammonia concentration (3.7 mg/l) is well above the drinking water limit of 0.05 mg/l.

The RO permeates at 65% and 73% recovery rates 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 of the RO permeate at 65% (25 mS/m) is within the drinking water limit, but requires further monitoring and optimization. Chloride levels in RO 65% (55 mg/l) are well below the drinking water limit of 250 mg/l, indicating no concerns regarding chloride. The ammonia concentration in RO 65% is measured at <1 mg/l, but this detection limit is orders of magnitude higher than the Danish drinking water limit for ammonia (0,05 mg/l). A theoretical estimation of ammonia in the RO permeate at 65% suggests compliance with this limit: an expected 0,037 mg/l ammonia in the permeate, based on a theoretical ammonia rejection of 99% for DOW SW30 RO membrane (informed by Boll Filter and DuPont).
It is 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 technical reuse.

The MD permeate generally meets drinking water quality standards, with a few exceptions. Its pH of 6.0 is slightly below the acceptable range of 7.0-8.5, but it might be within tolerance for some technical applications. The conductivity (0.26 mS/m) and chloride concentration (<1 mg/l) are well within acceptable limits, making it suitable for technical use without concerns about scaling or mineral buildup. Fluoride, nitrites, and sulfates are also within safe limits. However, the ammonia concentration (2.1 mg/l) exceeds the drinking water limit of 0.05 mg/l. Despite this, the MD permeate is suitable for various industrial applications, with low levels of metals and organic contaminants.

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 found 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.

6.2 Reject water

During the treatment of wastewater from the RAS facility, both RO and MD have been tested. Both membrane filtration processes produce treated wastewater by merely concentrating the undesired contaminants in the wastewater. This results in a concentrate containing the retained contaminants, 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. In this report, an initial high-level techno-economic assessment of concentrate management is included.

Reject water management as such is not a new topic for the water industry, as it is generated in any full-scale membrane-based drinking and process water plant. The additional challenge for RAS plants, or other WRF using wastewater, lies in the fact that the reject water is more complex and contaminated than these. The full-scale reject water discharge typically originate from groundwater, surface water or seawater as a feed to the membrane filtration plants. In Section 5.6.2 and 5.6.3, the theoretically expected composition of the reject water has already been described in detail, and finds a high concentration of both inorganics (salts, minerals, metals, heavy metals, etc.) and organic compounds including environmentally harmful substances.

Thanks to an 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 valorize or handle reject water rich in organics, though not containing the high amount of salts that the RAS reject water contains. The following options can be considered in the given order of priority:

1. Can the reject stream be valorized? 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)

In many cases, option 1 is difficult due to the complexity of the contamination matrix and risk of carry-over of the contaminants into the valorization process. However, in Section 6.2.1 and 6.2.2, the possibilities for reuse from the RAS facility are assessed. More often, option 2 and 3, discharge with or without treatment is required. This is discussed in Section 6.2.3 and 6.2.4 for discharge to marine environment or connection to the WWTP. Option 4 has not been considered and is mainly relevant for regions without water body recipients and/or strict conditions for environmentally safe discharge.

An ongoing large-scale Dutch study, for example, the Vechtstromen Water Board (GBLT Vechtstromen, u.d.), is being carried out to investigate whether the conventional biological activated sludge systems in municipal wastewater treatment plants can treat the reject water (option 3). These full-scale experiences will bring new knowledge as to which level of treatment it takes to be able to discharge these types of waters to the public WWTP, if at all.

The following sections explore the potential for option 1 valorizing this reject water as fertilizer in agriculture or as a feedstock in biogas production. Additionally, the feasibility of discharging the reject water directly into the Baltic Sea or a wastewater treatment plant has been examined (option 2 and 3).

6.2.1 Agriculture

The first scenario for reusing reject water from the RAS facility is as fertilizer in agriculture. As outlined in Section 5.6.2, the reject water contains a variety of nutrients critical for agricultural use. The primary nutrients found in the reject water include:

- Ammonia + ammonium-N: A nitrogen source essential for plant growth.
- Nitrite + nitrate-N: A highly bioavailable nitrogen source for plants.
- Total nitrogen: Represents the overall nitrogen content, key to the fertilizer's effectiveness.
- Total phosphorus: Phosphorus supports root development and flowering.
- Potassium (K): Enhances plant strength and is vital for photosynthesis.

To utilize the reject water in agriculture, it must comply with the Danish Executive Order on the Use of Waste for Agricultural Purposes (BEK nr. 1001, 2018), which regulates sludge and wastewater from recirculated aquaculture systems for fish farming.

The regulation specifies threshold values for heavy metals and environmentally harmful substances, as shown in Table 7, along with test results from the pilot study converted into comparable units.

Table **7**: Threshold values for heavy metals and environmentally harmful substances (BEK nr. 1001, 2018).

Heavy metals	**Unit**	**CUF reject**	**RO reject 65%**	**RO reject 73%**	**BEK nr. 1001, 2018**
Cadmium	mg/kg dry matter	-	-	-	0,8
Mercury	mg/kg dry matter	-	-	-	0,8
Lead1	mg/kg dry matter	0.23	0.02	0.02	120
Nickel	mg/kg dry matter	0.20	0.04	0.06	30
Chromium	mg/kg dry matter	0.33	-	-	100
Zink	mg/kg dry matter	-	-		4,000
Copper	mg/kg dry matter	3.38	0.16	0.31	1,000
Environmental substances	**Unit**	**CUF reject**	**RO reject 65%**	**RO reject 73%**	**BEK nr. 1001, 2018**
LAS2	mg/kg dry matter	-	-	-	1,300
Σ PAH3	mg/kg dry matter	-	-	-	3
NPE4	mg/kg dry matter	-	-	-	10
DEHP5	mg/kg dry matter	-	-	-	50
Σ PCB76	mg/kg dry matter	-	-	-	0,2[7]

[1]The lead value is 60 mg per kg dry matter or 5,000 mg per kg total phosphorus for private garden use. Additionally, for private garden use, the arsenic value is 25 mg per kg dry matter.
[2]LAS: Linear Alkylbenzenesulfonates.
[3]PAH: Polycyclic Aromatic Hydrocarbons. Σ PAH = Σ Acenaphthene, Phenanthrene, Fluorene, Fluoranthene, Pyrene, Benzfluoranthenes (b+j+k), Benz(a)pyrene, Benz(ghi)perylene, Indeno(1,2,3-cd)pyrene.
[4]NPE: Nonylphenol (+ethoxylates). NPE includes the substance nonylphenol and nonylphenolethoxylates with 1-2 ethoxy groups.
[5]DEHP: Di(2-ethylhexyl)phthalate.
[6]PCB7: PCB28, PCB52, PCB101, PCB118, PCB138, PCB153, and PCB180. This applies only to wastewater sludge covered by Annex 1, point E.
[7]Sampling and analysis for PCB7 should only be conducted if there is suspicion of the presence of PCB7.
[*]Values below detection limit.

The regulation also includes hygiene-related usage restrictions for waste. Sludge and wastewater from recirculated aquaculture systems are categorized as "sludge from fish farming," with usage restrictions based on treatment type (see Table 8).

Table 8: Hygiene-based usage restrictions for waste.

Waste Type	**Untreated**	**Stabilized**	**Controlled composting**	**Controlled hygiene treatment**
Sludge from fish farming	Not allowed on recreational areas or private gardens	No restrictions	No restrictions	No restrictions

As shown in Table 7, the analyzed parameters meet the regulatory thresholds. However, compliance with these values does not guarantee suitability for agricultural use. The regulation requires test results to consistently meet the thresholds for dry matter-related limits:

- For chromium, zinc, and copper, at least 75% of the last five samples must fall below the threshold, and no sample may exceed the limit by more than 50%. If a sample exceeds the limit by 0-50%, retesting is required immediately.

In addition to regulated substances, salts and ions play a significant role in agricultural suitability. As shown in Table 6, the reject water contains high concentrations of salts and ions, some of which may harm soil and plants:

- Chloride: Damages plants and causes soil salinization.
- Sodium: Can lead to sodic soils, harming soil structure.
- Sulfate: May acidify soil at high concentrations.

It is worth noting that chloride levels vary significantly depending on the water source. Based on data from Miljøportalen (Danmarks Miljøportal, 2025), the average chloride concentration in the Baltic Sea (Østersøen) is estimated to be between 4000–6000 mg/l, which is significantly lower than the chloride levels observed in Skagen, where concentrations are considerably higher.

To summarize the nutrient-rich reject water shows potential as agricultural fertilizer. However, compliance with regulatory limits for heavy metals, environmental substances, and hygiene restrictions is mandatory. Additionally, high salt concentrations could negatively impact soil health and plant growth, requiring careful monitoring and management.

In addition to the CUF-RO reject water, reject water from the CUF-MD process has also been examined. However, it is important to note that only conductivity (6,900 mS/m) and chloride concentration (37,000 mg/L) have been measured for CUF-MD reject water. The parameters required to comply with the Danish Executive Order on the Use of Waste for Agricultural Purposes (BEK nr. 1001, 2018), including heavy metals and environmental substances, have not been analyzed for this reject stream, due to the limited volume of water available. As a result, it is unknown whether CUF-MD reject water meets the regulatory requirements for agricultural use.

The measured chloride concentration (37,000 mg/l) is significantly higher than typical levels in natural waters and could pose challenges for soil salinity if used as fertilizer. The high conductivity also indicates a considerable presence of dissolved salts, which may impact soil structure and plant health.

To determine the feasibility of using CUF-MD reject water in agriculture, a comprehensive analysis of all relevant parameters, including heavy metals and organic pollutants, is necessary. Without this data, it cannot be confirmed whether CUF-MD reject water complies with Danish environmental regulations or if additional treatment is required before agricultural application.

6.2.2 Biogas

The different reject streams from the treatment process were evaluated for their potential use as a feedstock in biogas production. The CUF Reject contains high concentrations of chloride (15,000 mg/l) and sodium (8,200 mg/l), both of which are known to be inhibitory to anaerobic digestion, potentially disrupting microbial activity and reducing methane yield. The RO Reject 65% and RO Reject 73% have even higher chloride levels (29,000 mg/l and 19,000 mg/l, respectively) and sodium levels (19,000 mg/l and 10,000 mg/l), further increasing the risk of salinity-related inhibition.

Additionally, the COD values vary across the reject streams, with CUF Reject at 550 mg/l, RO Reject 65% at 31 mg/l, and RO Reject 73% at 43 mg/l. These low COD concentrations indicate a limited supply of biodegradable organic matter necessary for efficient biogas production. The total nitrogen content is also relatively high in all reject streams, particularly in the CUF Reject (56 mg/l), and RO Reject 65% (61 mg/l), which could lead to ammonia inhibition in anaerobic digestion.

The CUF-MD Reject also exhibits characteristics that make it unsuitable for biogas production. It has an extremely high chloride concentration of 37,000 mg/l and a conductivity of 6,900 mS/m, which further exacerbates the salinity-related challenges. These values indicate a highly saline environment that would severely inhibit anaerobic microbial activity and compromise the stability of the digestion process.

Given these characteristics, none of the reject streams can be considered an energy-rich substrate or a suitable medium for dilution in anaerobic digestion systems. The high salinity levels pose a significant challenge, as they can lead to osmotic stress on microbial communities, thereby hindering process stability. Alternative treatment or dilution strategies would be required to mitigate these inhibitory effects if reuse in biogas production is to be considered.

6.2.3 Marine Discharge

Another potential scenario for handling reject water from the RAS facility is direct discharge into the sea. The Baltic Sea is expected to be very close to the site and require only limited discharge piping infrastructure. However, this approach requires careful consideration of the water quality parameters to ensure compliance with strict environmental regulations, such as the Danish Executive Order on the Establishment of Environmental Objectives for Rivers, Lakes, Transitional Waters, Coastal Waters, and Groundwater (BEK nr. 796, 2023), which governs discharges into marine surface waters. The Danish Environmental Protection Agency has sent an updated version of this executive order in public consultation until June 2025 as part of the revisit of the Danish River basin management plans 2021-2027.

The composition of the reject water varies depending on the treatment process. Key parameters relevant to marine discharge include:

- Chloride concentrations: The reject water contains chloride levels ranging from 15,000 mg/l (CUF Reject) to 29,000 mg/l (RO Reject 65%), with the MD reject having a chloride concentration of 37,000 mg/l. These values are significantly higher than the calculated average chloride concentration in the Baltic Sea, which ranges between 4,000-6,000 mg/l. Such elevated chloride concentrations could potentially affect local salinity and marine ecosystems.
- Nutrients: The reject water contains ammonia + ammonium-N levels ranging from 4.7 mg/l to 6.8 mg/l, while total nitrogen levels are between 42 mg/l and 61 mg/l. In comparison, the average concentration of ammonia + ammonium-N in the Baltic Sea is approximately 0.013 mg/l, and total nitrogen has an average value of 0.281 mg/l. These values indicate that the reject water has significantly higher nutrient concentrations, which could contribute to eutrophication, leading to algal blooms and oxygen depletion in marine environments.
- Heavy metals: Some measured heavy metals, including lead (0.0009–0.0064 mg/L), copper (0.011–0.093 mg/L), and nickel (0.0023–0.0056 mg/L), must be evaluated against the regulatory thresholds for marine discharges. For instance, the concentration of barium (0.033–0.077 mg/L) exceeds the limit for other surface waters (0.0058 mg/L), indicating potential toxicity concerns.
- Organic contaminants: The BOD5 values (3–3.5 mg/l) and COD values (31–550 mg/l) suggest that organic matter is present in varying concentrations. While the RO-treated reject water exhibits lower organic loads, untreated CUF reject may require additional treatment to prevent oxygen depletion in receiving waters.

Table 9 summarize the key parameters for each type of reject water and their compliance the Danish Executive Order on the Establishment of Environmental Objectives for Rivers, Lakes, Transitional Waters, Coastal Waters, and Groundwater (BEK nr. 796, 2023) also including new threshold values in consultation:

Table **9**: Key water quality parameters of reject water from various treatment processes compared to the regulatory limits for the Baltic Sea (BEK nr. 796, 2023). Values in bold exceed the threshold value. The potential future threshold is the threshold values from the version currently in public consultation.

	Unit	**KUF Reject**	**RO Reject 65%**	**RO Reject 73%**	**MD reject**	**BEK nr. 796, 2023 /potential future threshold**
Conductivity	mS/m	-	-	5,300	6,900	-
Ammonia + ammonium-N	mg/l	6.4	6.8	4.7		-
Chloride, filtered	mg/l	15,000	29,000	19,000	37,000	-
Fluoride, filtered	mg/l	0.48	0.61	0.51	-	-
Nitrite + nitrate-N, filtered	mg/l	25	0.88	38	-	-
Silicate-Si, filtered	mg/l	1.3	4.3	6.4	-	-
Sulfate, filtered	mg/l	2,100	4,000	2,700	-	-
Total hardness	°dH	280	550	360	-	-
Calcium (Ca)	mg/l	360	620	460	-	-
Magnesium (Mg)	mg/l	1,000	2,000	1,300	-	-
Total nitrogen	mg/l	56	61	42	-	-
Total phosphorus	mg/l	33	2.3	0.67	-	-
BI5 (with ATU)	mg/l	> 15	3.5	3	-	-
COD	mg/l	550	31	43	-	-
DOC	mg/l	69	19	18	-	-
NVOC	mg/l	150	20	16	-	-
VOC	mg/l	< 0.5	< 0.5	< 0.5	-	-
TOC	mg/l	150	20	16	-	-
Barium (Ba)	mg/l	**0.077**	**0.036**	**0.033**	-	0.0058
Lead (Pb)	mg/l	**0.0064**	**0.0014**	0.0009	-	0.0013
Calcium (Ca)	mg/l	450	760	500	-	-
Chromium (Cr)	mg/l	**0.0091**	< 0.0005	< 0.0005	-	0.0034/0.0025
Iron (Fe)	mg/l	86	< 0.05	< 0.05	-	-
Potassium (K)	mg/l	380	720	380	-	-
Copper (Cu)	mg/l	**0.093**	**0.011**	**0.013**	-	0.0049
Magnesium (Mg)	mg/l	980	2,300	1,200	-	-
Manganese (Mn)	mg/l	**0.18**	0.14	0.1	-	0.15
Sodium (Na)	mg/l	8,200	19,000	10,000	-	-
Nickel (Ni)	mg/l	0.0056	0.0026	0.0023	-	0.0086/0.0068
Strontium (Sr)	mg/l	**8.6**	**12**	**7.6**	-	2.1

Table 9 leads to conclude that removal of lead, cupper, strontium, barium, chromium, manganese and likely organics will be necessary prior to discharge of the collected reject waters to the Baltic Sea.

Treatment implications

Potential treatment technologies include activated carbon (AC) and granular ferric hydroxide (GFH), both of which offer effective removal of contaminants.

AC is widely used for the adsorption of organic compounds, including DOC and NVOC. AC functions by providing a large surface area with micropores that trap organic molecules through physical adsorption. This process is particularly effective for removing residual organic contaminants that may contribute to oxygen depletion in the receiving marine environment. Furthermore, AC can assist in the removal of trace heavy metals, such as lead and copper, by adsorption, though its primary function remains organic contaminant reduction.

GFH is an iron-based adsorbent primarily used for the removal of heavy metals and metalloids, including lead, copper, and strontium. GFH operates through adsorption and surface complexation mechanisms, effectively reducing metal concentrations in reject water to meet regulatory limits. The high affinity of GFH for metal ions makes it a suitable choice for mitigating potential toxicity concerns associated with heavy metal discharge into marine environments.

The integration of AC and GFH in a treatment system can provide a complementary approach, addressing both organic and inorganic contaminants. AC would primarily target the reduction of organic load, thereby minimizing the risk of oxygen depletion, while GFH would focus on heavy metal removal, ensuring compliance with environmental regulations.

A comprehensive environmental impact assessment is necessary to evaluate the potential effects on marine life, including salinity changes, nutrient loads, and heavy metal accumulation. Additionally, dilution modeling should be conducted to determine the dispersion characteristics of the reject water in the receiving marine environment.

To ensure compliance with environmental regulations, mitigation strategies such as pre-treatment, controlled discharge rates, and monitoring programs should be implemented. If reject water characteristics exceed permissible limits, alternative disposal methods or additional treatment may be required before discharge into the marine environment.

Impact of potential new thresholds
The proposed new thresholds, although still in consultation, are unlikely to change the overall conclusion. The need for advanced treatment systems, such as AC and GFH, remains crucial for ensuring that the reject water meets the regulatory requirements for safe discharge into the Baltic Sea. The integration of these systems would continue to target both organic and inorganic contaminants, helping to mitigate the potential environmental impacts.

In summary, while the new thresholds might adjust the regulatory limits, the reject water characteristics still exceed the limits in several critical parameters. Therefore, the necessity for comprehensive treatment and mitigation strategies, including pre-treatment systems and controlled discharge rates, remains unchanged. Extensive monitoring and environmental impact assessments would still be essential to ensure compliance and minimize the risk of harm to the marine environment.

6.2.4 Wastewater treatment plant

Another relevant scenario to consider is the possibility of discharging reject water directly into a wastewater treatment plant WWTP. In this case, the guidelines specified in the Danish Guidelines on the Discharge of Industrial Wastewater into Public Sewerage Systems (VEJ nr. 9810, 2006) would apply.

Table 10 presents an overview of the measured concentrations in different types of reject water—CUF reject, RO reject (65% and ~73% recovery), and MD reject - compared to the current and expected new thresholds guidelines for discharge to WWTP.

Table 10: Overview of analytical parameters and threshold values (VEJ nr. 9810, 2006).

	Unit	**CUF Reject**	**RO Reject 65%**	**RO Reject ~ 73%**	**MD Reject**	**VEJ nr. 9810, 2006**
Ammonia + ammonium-N	mg/l	6.4	6.8	4.7	-	-
Chloride, filtered	**mg/l**	**15,000**	**29,000**	**19,000**	**37,000**	**1,000**
Fluoride, filtered	mg/l	0.48	0.61	0.51	-	-
Nitrite + nitrate-N, filtered	mg/l	25	0.88	38	-	-
Silicate-Si, filtered	mg/l	1.3	4.3	6.4	-	-
Sulfate, filtered	**mg/l**	**2,100**	**4,000**	**2,700**	**-**	**500**
Total hardness	°dH	280	550	360	-	-
Calcium (Ca)	mg/l	360	620	460	-	-
Magnesium (Mg)	mg/l	1,000	2,000	1,300	-	-

Total nitrogen	mg/l	56	61	42	-	-
Total phosphorus	mg/l	33	2.3	0.67	-	-
BOD5 (with ATU)	mg/l	> 15	3.5	3	-	-
COD	mg/l	550	31	43	-	-
DOC	mg/l	69	19	18	-	-
NVOC	mg/l	150	20	16	-	-
VOC	mg/l	< 0.5	< 0.5	< 0.5	-	-
TOC	mg/l	150	20	16	-	-
Barium (Ba)	mg/l	0.077	0.036	0.033	-	-
Lead (Pb)	mg/l	0.0064	0.0014	0.0009	-	0.1*
Calcium (Ca)	mg/l	450	760	500	-	-
Chromium (Cr)	mg/l	0.0091	< 0.0005	< 0.0005	-	0.3
Iron (Fe)	mg/l	86	< 0.05	< 0.05	-	-
Potassium (K)	mg/l	380	720	380	-	-
Copper (Cu)	mg/l	0.093	0.011	0.013	-	-
Magnesium (Mg)	mg/l	980	2300	1200	-	-
Manganese (Mn)	mg/l	0.18	0.14	0.1	-	-
Sodium (Na)	mg/l	8200	19000	10000	-	-
Nickel (Ni)	mg/l	0.0056	0.0026	0.0023	-	0.25*
Strontium (Sr)	mg/l	8600	12000	7600	-	-

* *The water quality criterion/requirement used as the basis for setting the limit value is under revision by the EU*

The data highlights significant discrepancies between the measured concentrations in reject water and the permissible limits in the guidelines. For example, chloride levels in RO reject water are 15 to 29 times higher than the allowable limit, and sulfate concentrations in both RO and MD reject exceed the permissible level by a factor of 4 to 8. These elevated concentrations make it clear that substantial pretreatment of the reject water would be required to comply with the connection guidelines.

The heavy metals such as chromium and cobber in all tested reject water samples fall within acceptable limits of the new and expected threshold limits but lead and nickel cannot comply with the expected threshold limits. Other parameters, including sodium, magnesium, and total hardness, show levels that could interfere with the WWTP's processes. Excessive sodium in RO and MD reject, for instance, may inhibit biological treatment processes, while high hardness levels, particularly in CUF and RO reject, can cause scaling issues.

Not all tested parameters have corresponding threshold values in the guidelines, leaving room for case-by-case assessments by the WWTP operator. This underscores the importance of thorough dialogue with the plant to evaluate each type of reject water's compatibility with their system. Given the high levels of salts and other critical substances, advanced filtration, dilution, or chemical pretreatment would likely be necessary to meet the required standards before discharge can be considered.

<u>Impact of potential new thresholds</u>
An updated version of the guidelines has been submitted for consultation by the Danish Environmental Protection Agency. This version includes revised and new threshold values for several heavy metals and other substances. The new guidelines are expected to be published in 2025 (Miljøstyrelsen, 2025). These thresholds define acceptable concentrations of various parameters in wastewater to ensure that treatment plants can handle the incoming loads without compromising operational processes or the surrounding environment. The threshold values for acceptable concentrations are lower than the currently valid thresholds used in Table 10.

The Danish Environmental Protection Agency's indicative threshold values are based on compliance with environmental quality standards for surface waters. When setting conditions in a discharge permit, including threshold values, it must be ensured that the environmental quality standards for the receiving water body are met. These standards represent the maximum acceptable concentration of a substance in the effluent, after accounting for the initial dilution in the receiving freshwater or marine environment. Environmental quality standards may apply to water, biota, and sediment, and the most critical of these is used as the basis when drafting permit conditions.

Based on the new indicative threshold values, copper is currently the only parameter expected to exceed the future limits - specifically in the CUF reject stream. The measured concentration of copper in this stream is 0.093 mg/l, which exceeds the future freshwater threshold of 0.045 mg/l.

6.2.5 Summary of permeate and reject water applications

The analysis of permeate and reject water from the treatment processes highlights their potential applications and challenges. Permeate water, particularly from MD treatment, generally meets drinking water standards, though some parameters, such as ammonia concentration and pH, require adjustments for full compliance. While RO permeates (65% and 73%) show improvement over CUF permeate in terms of conductivity and chloride levels, they still fail to meet all drinking water requirements without further treatment. However, permeate water remains highly suitable for industrial and technical applications, such as cooling systems and cleaning.

Reject water from the treatment processes contains high levels of salts, 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. However, high salinity and chloride concentrations pose potential risks to soil health. Similarly, reject water is 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, additional treatment may be required to meet environmental standards.

7. Costing and economic analysis of a full-scale WRF

In addition to conducting a batch pilot test to evaluate the performance and design parameters of a RAS WRF, Boll Filter was tasked with providing a cost assessment for a full-scale WRF capable of treating 200 m^3/h of RAS wastewater. Their complete report can be found in Appendix 2.
On the basis of the costing of the full-scale WRF an economic analysis is made. The economic analysis is made over a 20-year horizon evaluating the total expenditures (TOTEX), considering both CAPEX and OPEX.

7.1 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 backpulse, backwash, and chemical cleaning-in-place (CIP), all initiated automatically. The cleaning frequency is set at every 600 hours. Pre-treatment includes a 100-micron self-cleaning filter preceding the SiC UF ceramic membranes, with anti-scalants dosed before the spiral RO membranes.

The membranes, control cabinets, electrical cabinets and chemical dosing must be placed inside a building. Where the system layout will feature 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. Therefore, it is assumed that there is no downtown on the WRF, meaning that there can be produced 123.5 m^3/h of technical water all year round, resulting in a yearly production of 1,081,860 m^3/year.

The process flow diagram of the system is seen in Figure 10.

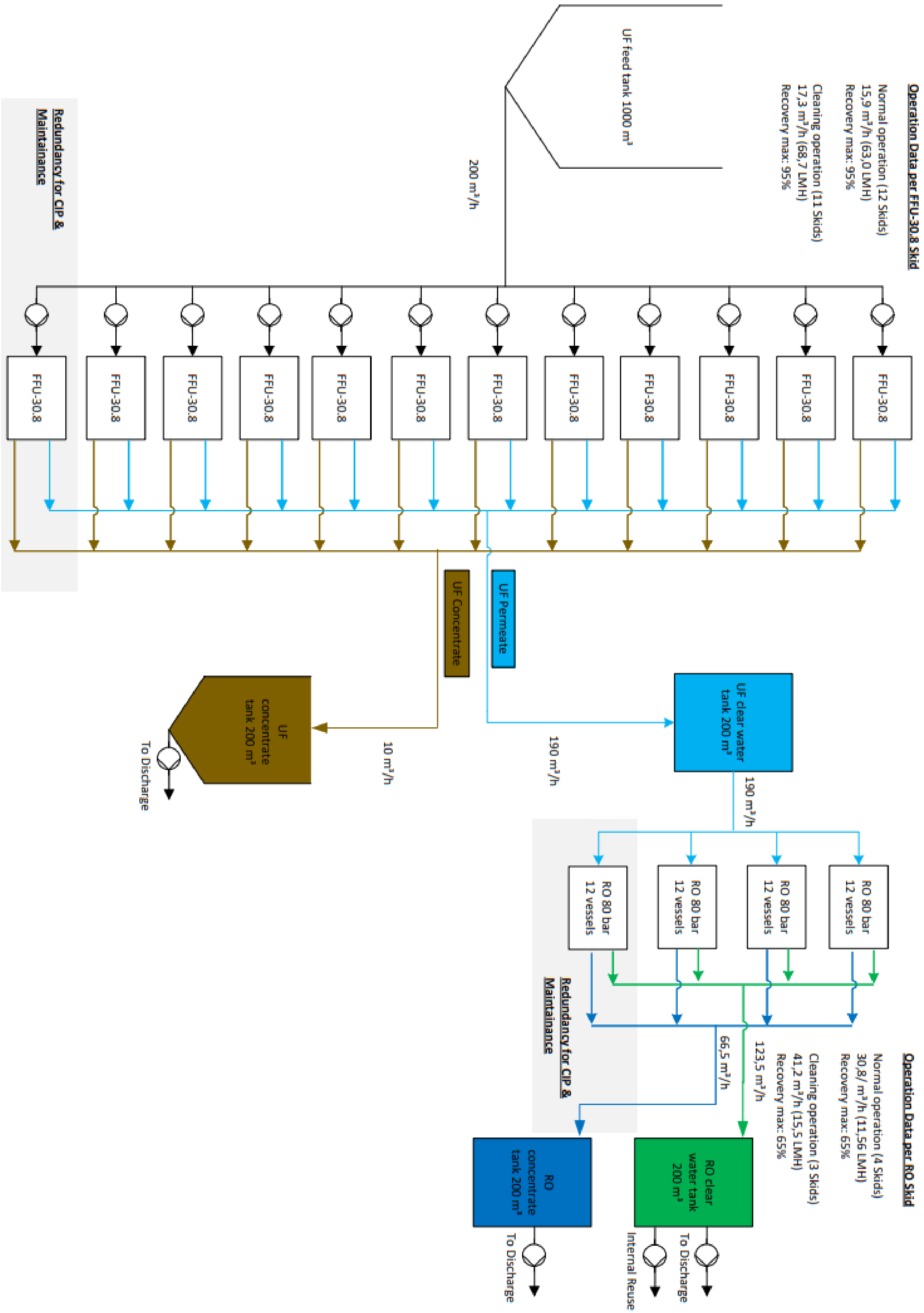

Figure 10: Process flow diagram of the full-scale water treatment system. The UF feed tank and piping, pumping, and other infrastructure from the permeate and concentrate tanks are not included in the costing.

7.1.1 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 seen in Appendix 3.
The total estimated CAPEX for the project is EUR 15.63 million, with a margin of error of +/- 30%.

The cost of the building is based on a complete light building of 1,050 m^2 with a price of 1,675 EUR/m^2 including electrical work, sewerage, foundations etc. For the outdoor fortified area, with the outdoor tanks, the area is estimated to be 400 m^2, and the cost is 670 EUR/m^2, including wells, paving etc.
Consultancy and Miscellaneous and unforeseen expenses have been estimated by Rambøll based on experience to 10% and 14%, respectively.

Boll Filter's basic lay-out is seen in Figure 11. Additional details, including equipment datasheets, are available in Appendix 2.

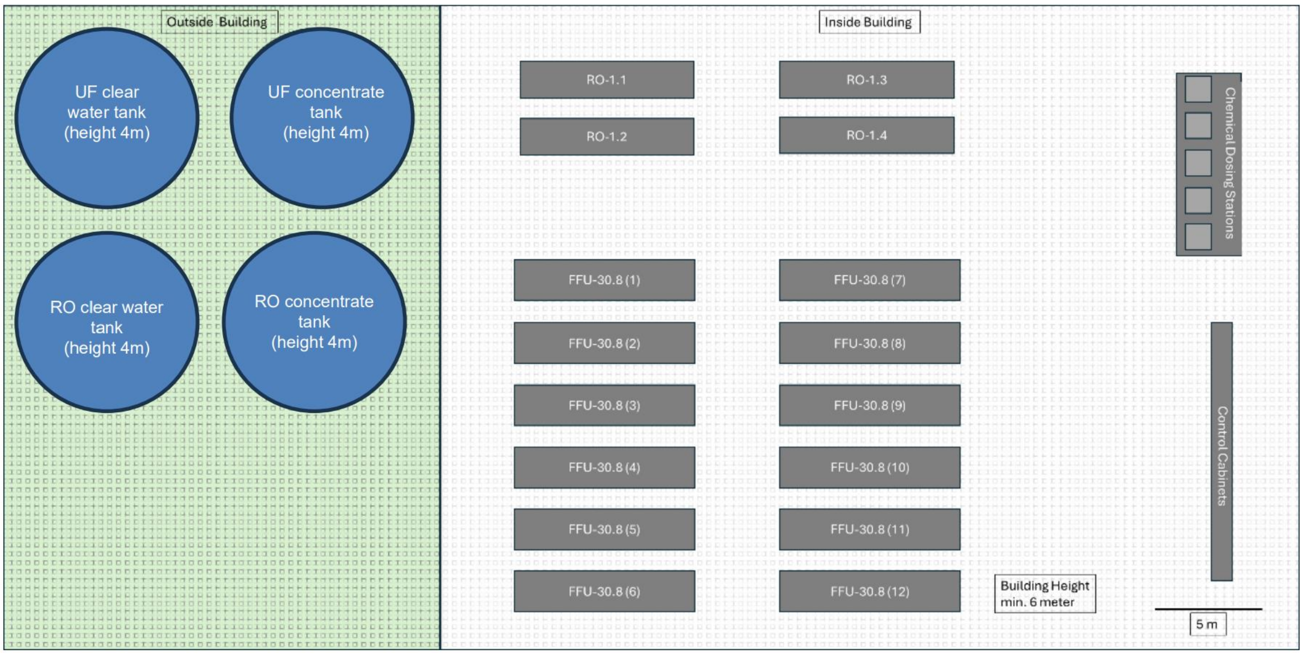

Figure 11: Basic lay-out drawing of a full-scale water treatment facility.

The key components contributing to the CAPEX are summarized in
Table 11:

Table 11: CAPEX – Overview of components and costs

CAPEX			
Category	**Description**	**Quantity / Size**	**Cost [EUR]**
Tanks	UF permeate tank	200 m^3	
	UF concentrate tank	200 m^3	
	RO permeate tank	200 m^3	
	RO concentrate tank	200 m^3	

	Total Tanks		€ 550,000
UF system	Pre-filter (pre-UF)	1 unit	
	BOLL FineFilterUnit 30.8 UF-skids	12 pcs.	
	Total UF system		€ 7,500,000
RO system	RO pre-treatment		
	BOLL RO-skids	4 pcs.	
	Total RO-system		€ 2,500,000
Building and fortified area	Light building and fortified area	Building 1,050 m^2, outdoor fortified area 400 m^2	€ 2,027,000
Consultancy		10% of total CAPEX	€ 1,509,240
Miscellaneous and unforeseen expenses		14% of total CAPEX	€ 1,760,780
Total CAPEX			**€ 15,847,020**

7.1.2 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. Based on the test conducted at Skagen Salmon, the velocity through the membranes is budgeted to 3 m/s through each membrane channel to create sufficient turbulence to keep the membranes clean. The electricity price is assumed to 0.134 EUR/kWh.

A detailed breakdown of the annual OPEX components is provided in Table 12. 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 12: OPEX – Overview of Operating Costs – annual expenses.

OPEX - annual			
Category	**Description**	**Quantity / Size**	**Annual Cost [EUR]**
Electricity	UF: ~5,500 MWh/year (crossflow) RO: ~5,500 MWh/year Assumed price: EUR 0.134/kWh	11,000 MWh/year	€ 1,474,531
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 (dosing)	5 ml/m^3	€ 74,898
	Caustic soda (50%)	80 L/year	€ 200
	Sulfuric acid (96%)	30 L/year	€ 200
Operation and maintenance		7 % of annual OPEX	€ 111,848
Total annual OPEX			**€ 1,709,677**

Bollfilter have informed that the lifespan of the membranes is 10 and 4 years for the UF- and RO-membranes respectively, as seen in Table 13. That means that every 10^{th} year, there is an additional cost of 11.760 EUR to replace the 12 UF-membranes and an additional cost of 3.920 EUR every 4^{th} year to replace the RO-membranes.

Table 13: 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 periode is 42,428,288 EUR.

The OPEX does not include any costs for discharging of reject water from the UF- or RO membranes.

7.1.3 Economic optimizations

Boll Filter have adopted conservative engineering assumptions in sizing and material selection, which adds robustness to the design but also increases the investment cost. 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, Boll Filter 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. 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.

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.

7.1.4 Cost of reject water

For the RAS facility, Section 6.2 leads to conclude that treatment and discharge of the treated reject water to marine recipient 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 (Miljøstyrelsen, 2024).

The ballpark capacity of the 1 GW Power-to-X plant, for which these cost estimates were done, is in the same range as the RAS facility in this study, which allows for extrapolation (see Table 14). 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 a first indication of the ballpark cost range, see Appendix 4 for the calculations.

Table 14: Assumptions for extrapolation of reject treatment plant cost estimate from (Miljøstyrelsen, 2024)

Parameter	Unit	Value
Technical water plant feed volume	m3/year	1,728,000
Reject water plant feed volume	m3/year	660,960
PFAS removal from reject water	-	No

The cost estimates are extrapolated from reject water treatment cost estimates (Miljøstyrelsen, 2024) 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 below.

The first step of coagulation involves chemical dosing of a coagulant (e.g. PIX, $FeCl_3$) to cause lumping of dissolved compounds that become undissolved, colloid and/or particulate matter. The lumps or flocs can now be removed by e.g. settling or cloth filtration of the chemical sludge. Coagulation is used as an initial treatment step to remove larger organic molecules and phosphorus.

The following oxidation step aims to degrade undesirable substances, either completely or partially. An example of this is ozonation, which has proven effective in removing micropollutants, but which can also be used to make a partial oxidation of difficult-to-degrade organic matter, thereby making the organic matter available for biodegradation in a next treatment step. Ozonation on rejects (brine) from treated wastewater has shown a removal of DOC of 20-30% as stand-alone, and >90% removal in combination with a biological and physical treatment step (Zhou, 2011). Likewise, to biological treatment, advanced oxidation can be inserted before an adsorption process (e.g. activated carbon) to remove organic matter so that it does not consume the adsorption capacity of the full adsorption material. Finally, advanced oxidation can also be used as a post-polishing agent for the removal of substances that are difficult to degrade, such as pharmaceuticals etc.

Following this "unlocking" of any hard-to-degrade carbon present, biological treatment (MBR, MBBR) enabling longer sludge ages per volume compared to the traditional activated sludge process can be applied. Biological treatment is still considered to be the most cost-effective technology for the removal of phosphorus, ammonium, nitrate and bioavailable COD. The increased amount of salts and other inhibitory substances in the reject water are expected to inhibit the biological turnover of ammonium and nitrate must, however, be taken into account.

As a final step, adsorption of residual organic matter and metals is applied. This can be either activated carbon or granular iron filters or a combination thereof.

Table 15: 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/m3 reject water)	1,10	3,29

Table 15 shows to conclude that the costs for cleaning the reject water vary between 1.1 – 3.3 EUR/m^3 of reject water. It should be noted that the costs are extrapolated from another feasibility study and subject to minimum 50% uncertainty. Note that additional costs related to discharge are not included.

7.2 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 a 20-year project horizon 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. The NPV calculations is seen in Appendix 3.

7.2.1 TOTEX

In Table 16 the total CAPEX and OPEX that was presented in chapter 7.1 is shown for the 20-year period.

Table 16: CAPEX, OPEX and TOTEX in 2025-values projected with a 2% net price increase.

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

7.2.2 Net Present Value (NPV)

In Table 17 the NPV for the CAPEX and OPEX is presented.
It is assumed that the CAPEX is in year 0 (2025), and OPEX is from year 1 to 20 (2026-2045).

Table 17: NPV of CAPEX, OPEX and TOTEX and cost of technical water.

NPV TOTEX		
Category	**Interval**	**Cost**
CAPEX, NPV	Year 0	€ 15,847,020
OPEX, NPV	NPV 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 suggested in section 7.1.3 the lower salinity in the seawater at Lolland-Falster can 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 seen in Table 18.

Table 18: NPV of CAPEX, OPEX and TOTEX and cost of technical water, due to lower salinity in Lolland-Falster.

NPV TOTEX		
Category	**Interval**	**Cost**
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.

7.2.3 Impact of reject water cost

The cost of discharging of 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 estimations in Section 7.1.4, revealed high costs associated with treatment of the reject water upon discharge. They are estimated to vary between 1.1 – 3.3 EUR/m3 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.

8. Conclusion

As the main activity within this study, Boll Filter successfully completed local pilot trials with RAS wastewater in Skagen 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 analysis showed:

- <u>Salts and Ions:</u> The conductivity dropped from 1,700 mS/m in the UF feed to 25 mS/m in the RO permeate, indicating effective removal of dissolved ions. Chloride concentration also reduced substantially, from 14,000 mg/l to 55 mg/l, below drinking water limits.
- <u>Organic Matter and Nutrients:</u> TOC and DOC were significantly lowered, while ammonia + ammonium-N was reduced to less than 1 mg/l (theoretically expected 0.037 mg/l). These results meet standard limits for Danish drinking water, confirming the effectiveness of RO in removing organic compounds and nutrients.

<u>Metals and Trace Elements:</u> Key metals like iron, lead, copper, chromium, and manganese were effectively removed, falling below detection limits. This indicates high efficiency in eliminating metals, contributing to the production of high-quality permeate.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:

- <u>Higher Recovery Rates</u>: MD achieved recovery rates exceeding 80-90%, compared to 50-75% typically seen with RO, making it highly effective for challenging feedwaters.
- <u>Superior Distillate Quality:</u> 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.
- <u>Tolerance to High Salinity:</u> MD demonstrated resilience in handling high salinity and fouling-prone feedwaters, making it particularly useful for complex wastewaters where RO faces limitations.

The bench-scale tests conducted at DTU revealed that MD permeate had low suspended solids (0.9 mg/l) and significant reductions in chloride and other ions than RO permeate. Trace metals like chromium, copper, and nickel were present in minimal concentrations, reflecting high water purity.

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 deemed possible for it to be available in 2-3 years in full-scale operation.

One of the critical challenges is the effective management of reject water, which contains a complex mixture of contaminants and high salt concentrations. The potential for valorizing reject water as fertilizer in agriculture or as a feedstock in biogas production is promising, however the reject water is not suitable for any of the two purposes due to high chloride concentrations and heavy metals, and in terms of biogas production, its low levels of COD make it undesirable in the biogas process. Advanced treatment methods, including biological systems, adsorption and advanced oxidation, are necessary to degrade contaminants and ensure environmentally safe discharge.

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 m^3. 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 m^3. These figures underscore the financial implications of establishing and operating the full-scale WRF.
Boll Filter 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% by transitioning from crossflow SiC tubular membranes to flat sheet dead-end 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 m^3 shows the related uncertainties regarding reject water management can have a significant negative impact on the feasibilityrequiring more efforts to optimize treatment processes and explore valorization opportunities.

9. Discussion

The feasibility of producing technical water from treated wastewater of a RAS plant presents several promising opportunities and associated risks. The opportunity to reuse water in the water-scarce region of Lolland in Denmark is a potential benefit; however, the treatment and discharge costs for reject water, along with potential regulatory issues concerning PFAS and organic micropollutants in both technical water and reject water, pose significant risks that could lead to increased costs. The applicability of the conclusions in this feasibility study in other Baltic Sea regions must be carefully evaluated due to variations in industrial infrastructure and local regulatory frameworks.

For a such technical WRF to be feasible, industrial driving forces within the vicinity of the RAS plant are crucial. The successful implementation will require at least one symbiotic industrial or regulatory need to meet demands for technical water use, waste heat offtake and the ability to manage reject water despite its high salt content. For MD to be a feasible technology, it requires surplus heat, emphasizing the need for collaboration with other industries to effectively utilize waste heat. Investment collaboration with stakeholders is typically forming symbiotic partnerships to share resources and mitigate individual risks and challenges. This process should be initiated early in the process, as there is typically a large amount of initial work before companies will make a financial investment decision. A part of this initial work is to analyze which technical water qualities the individual company needs, since some processes can be satisfied with a lower quality of the technical water, and in this way optimize the costs of the WRF.

Furthermore, whether this solution is feasible for receivers of technical water depends on their specific needs and capacities to handle the associated costs and regulatory constraints.

As the MD process demonstrated recovery rates exceeding 80% and achieved higher distillate purity compared to RO, it shows potential for industrial applications. The pilot tests yielding a steady flux of 7 LMH with MD even at high recovery rates, while achieving similar contaminant removal to RO. MD offers distinct advantages in recovery rates and water purity, particularly in handling challenging feedwaters high in salinity and prone to fouling. That said, the full-scale application of MD in industrial settings is expected to become viable in only the next 2-3 years. For the many planned Power-to-X plants, which are consuming large amounts of technical water in their production and for cooling, MD could be a possible technical solution, as Power-to-X plants have great amounts of surplus heat.

Despite these advancements, the treatment of reject water remains a major challenge. High chloride concentrations and the presence of heavy metals impair its potential use in agriculture and biogas production, necessitating advanced treatment methods for safe environmental discharge.

Economic analyses emphasize substantial investment requirements but also highlight potential savings through optimization strategies—such as transitioning to flat sheet dead-end membranes and utilizing closed-circuit RO configurations. Another cost optimizing step is, as mentioned before, to analyze what technical water quality is necessary, to avoid over-implementation. While the feasibility study indicates high costs, these optimization strategies show opportunities to reduce CAPEX and OPEX significantly, making technical water production more economically viable in the long-term.

In conclusion, the feasibility of producing technical water from RAS wastewater depends on effective industrial collaboration and strategic investments. While promising results from pilot tests illustrate strong potential with existing technology, careful planning and continuous innovation are essential to navigate the financial and regulatory landscape and finally implement sustainable, cost-effective RAS solutions.

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Appendix 1
Process Specification - TETRAS

PROCESS SPECIFICATION

Design and operation of a pilot test and costing of a future full-scale plant for reclamation of wastewater from a land-based RAS plant.

Confidential

Project Name	**TETRAS 1 – Water reclamation from landbased RAS-plant**
Project No.	**1100056488**
Document type	**Process Specification**
Version	**1**
Date	**02-05-2024**
Prepared by	**jsbo, sybt, awer**
Checked by	**mhtn**
Approved by	**mhtn**

RAMBOLL

Table of contents

1. BACKGROUND

Business Lolland-Falster (BLF) is project partner on the Interreg Baltic Sea Region (BSR) project 'TETRAS' (Technology Transfer for Thriving Recirculating Aquaculture Systems in the Baltic Sea Region) with partner participation from Denmark, Germany, Estonia, Poland, and Lead Partner from Lithuania, see Figure 1.

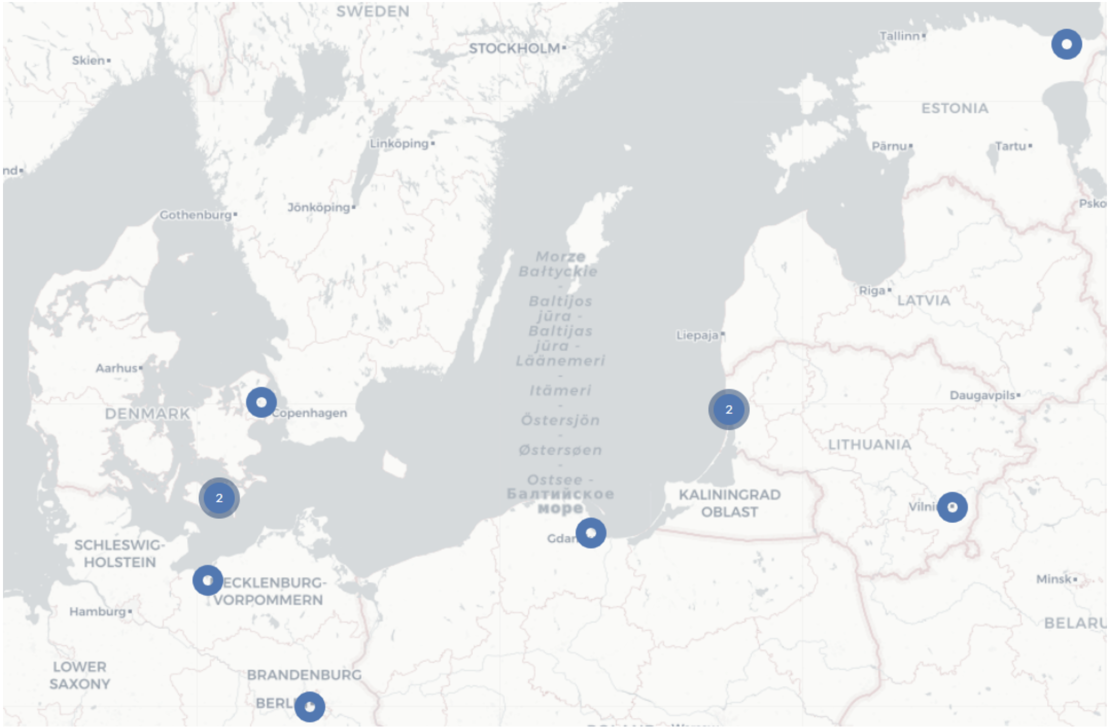


Figure 1 - Countries and projects participating in the TETRAS consortium.

The project started in January 2023 and ends in December 2025, and has an overall budget of €2.96 million EUR. The TETRAS project uses innovative pilots to lead the way for sustainable aquaculture in the BSR. The project consists of four pilots of which this project is the first one.
The pilot is made in cooperation with BLF and investigates the possibility of using the wastewater from a land based Recirculating Aquaculture System (RAS) saltwater plant as technical water for other industries such as concrete casting and electrolysis in connection with the production of green fuels (P2X). This will be achieved by purifying the wastewater with membrane filtration methods.

Ramboll's responsibility in this project is to prepare a design of a water reuse plant that treats the RAS plant effluent to drinking water quality, and to demonstrate this process by conducting a pilot test. The pilot will be the basis for a full-scale Wastewater Reclamation Facility (WRF). The data will be available for all partners in the TETRAS project, making it highly relevant for all future RAS plants in the BSR.

2. INTRODUCTION

The interest for land-based saltwater RAS systems is growing, as it enables a controlled environment, both with respect to the process and the waste and wastewater produced.

In a saltwater RAS plant, pretreated seawater is used as process water to cultivate the fish. The process water is to a large extent recirculated inside the plant, while a part of the process water is removed from the system and taken out as wastewater. A salmon RAS plant with a production capacity of 5.000

tons of salmon per year generates about 2,6 million m^3 wastewater per year. The exact amount varies with internal recirculation rate and process. If a permit can be granted, the wastewater can be treated to reach a quality for discharge.

In Lolland-Falster, where groundwater resources are scarce, it is difficult for industries to obtain new permits for groundwater intake. Therefore, it is relevant to investigate the possibility of treating the wastewater for reuse in other industrial processes. Due to the limited amount of groundwater in Lolland-Falster, this pilot test will be focusing on reuse of the wastewater rather than discharge to recipient, see Figure 2.

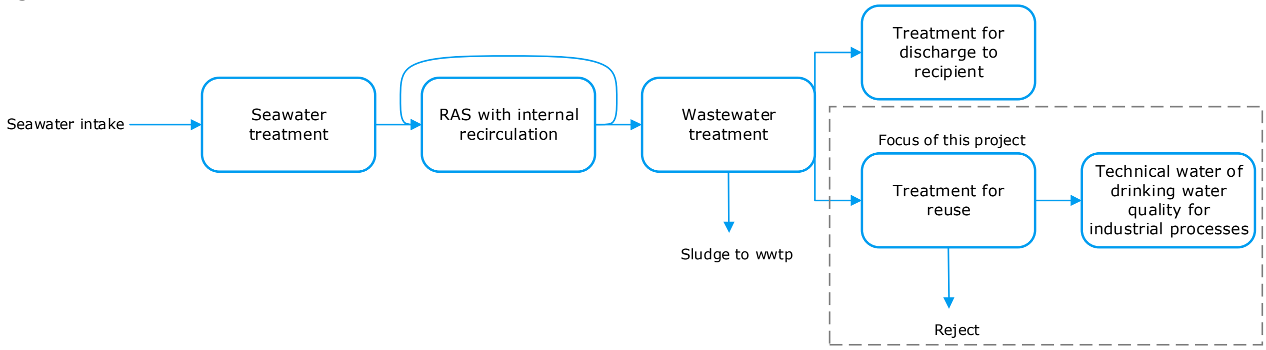


Figure 2 - Water flow diagram for land-based seawater RAS plant

The large quantity of the wastewater stream makes it relevant to reclaim it as technical water for feed to other industries, e.q. PtX plants (feed to Ultrapure water for electrolysis) or water for cement production. To investigate feasibility of the RAS wastewater reclamation, a techno-economic study will be conducted.

Ramboll reaches out to technology suppliers to

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

The process specification's design basis for Deliverable 1 and 2 differs slightly since the wastewater for testing will originate from a currently operational RAS plant with a different location and seawater composition than expected in Lolland-Falster. It is assumed that a plant built in Lolland-Falster will use a similar RAS process incl. internal water treatment and the effluent water will therefore be of similar quality as at Skagen Salmon.

The selected process technology to be used in both the pilot test as well as the full-scale WRF cost model is membrane filtration, more specifically desalination by Reverse osmosis (RO). When using membrane technology, the feed water is divided into two streams, the permeate and the reject stream. To maximise water reuse and minimize water sent to municipality/discharge, the plant design should focus on minimizing the reject stream volume as much as possible. Hence, Ramboll is interested in seeing high-recovery RO processes.

3. DELIVERABLE 1: BATCH PILOT TEST

In this project, wastewater from the operational Skagen Salmon RAS plant will be used as basis for the study for the future Lolland-Falster RAS facility. At Skagen Salmon, internal RAS water treatment is currently followed by an additional external wastewater treatment based on denitrification and sedimentation before the water is discharged to recipient. Skagen Salmon treatment process is as seen in Figure 3.

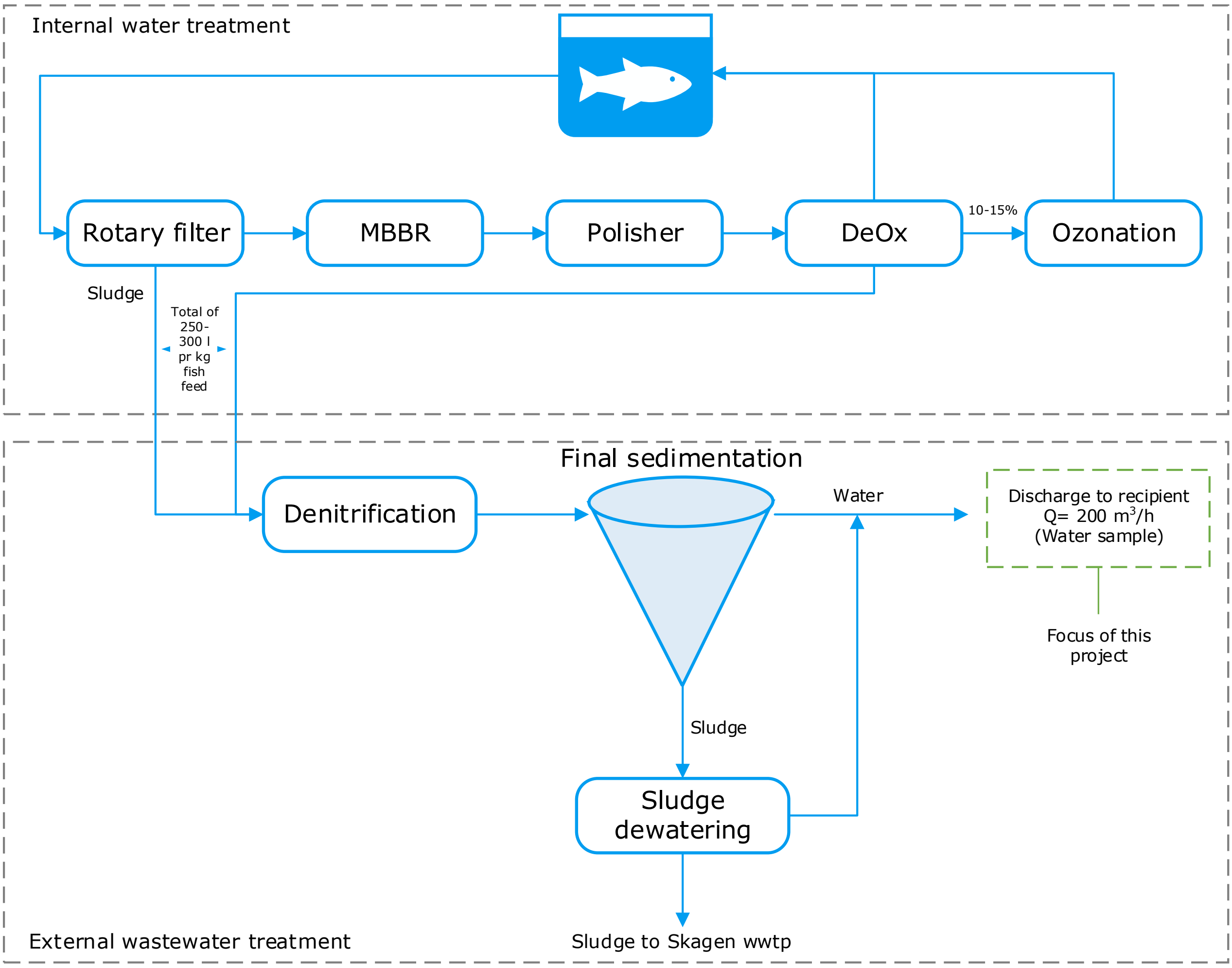


Figure 3 - Internal treatment in RAS and external treatment at Skagen Salmon before discharge.

3.1 FEED WATER CONDITIONS & QUALITY

A single sample of wastewater from Skagen Salmon has been collected at the outlet of the RAS plant and named: "Water sample", see the green square in Figure 3Figure 3 - Internal treatment in RAS and external treatment at Skagen Salmon before discharge.Figure 3. The composition of the collected water sample from Skagen Salmon should be used as design basis for pilot test. The water sample is analysed by Eurofins and presented in Table 1, column 3. In the same table the Danish requirements for drinking water (maximum concentrations) for the analyzed parameters are stated in column 4.

Comparing the water sample from Skagen Salmon with the quality requirements for drinking water, the focus species to be removed are:

- Suspended solids
- Nutrients (such as ammonia and phosphor)

- Silicium
- Various dissolved monovalent and bivalent ions (chloride, sulphate, calcium, potassium, magnesium, and sodium)

Table 1 - Composition of Skagen Salmon wastewater compared to drinking water quality. The sample is from 24-01-24. The focus species to be removed are marked in bold.

Component	Unit	Water sample: From final water treatment at Skagen Salmon	Main objective: Drinking water max. concentrations[1]
pH	pH	7,6	7,0-8,5
Temperature at pH-measurement	°C	21	
Suspended solids	**mg/l**	**100**	
Alkalinity, total	mmol/l	6,8	
Ammonia-N	**µg/l**	**3.600**	**50**
Bromide (Br), filtered	mg/l	35	
Chloride, filtered	**mg/l**	**12.000**	**250**
Fluoride, filtered	mg/l	0,45	1,5
Total phosphor	**µg/l**	**2.800**	
Hydrogencarbonate	mg/l	415	
Nitrate-N, filtered	mg/l	0,48	50*
Nitrit-N	mg/l	0,084	0,1
Silicium (Si)	**µg/l**	**3.400**	
Sulphate, filtered	**mg/l**	**1.600**	**250**
Hardness, total	°dH	210	
Total Nitrogen	µg/l	7.400	
BI5 (with ATU)	mg/l	4,9	
BI5 filtered (with ATU)	mg/l	5	
COD, chemical oxygen demand	mg/l	210	
DOC, dissolved organic carbon	mg/l	14	
NVOC, non-volatile organic carbon	mg/l	17	4
VOC, volatile organic carbon	mg/l	< 0,5	
TOC, total organic carbon	mg/l	17	
Aluminium (Al)	µg/l	33	200
Barium (Ba)	µg/l	9,5	
Lead (Pb)	µg/l	< 0,2	5
Calcium (Ca)	**µg/l**	**310.000**	
Chromium (Cr)	µg/l	1,4	25
Iron (Fe)	mg/l	1,8	0,2
Potassium (K)	**µg/l**	**220.000**	
Copper (Cu)	µg/l	3,5	2000
Magnesium (Mg)	**µg/l**	**680.000**	
Manganese (Mn)	mg/l	0,11	0,05
Sodium (Na)	**µg/l**	**2.900.000**	**175.000**
Nickel (Ni)	µg/l	2,4	20
Strontium (Sr)	µg/l	1.900	
Titanium (Ti)	mg/l	< 0,5	

[1] Drikkevandsbekendtgørelsen (Drinking water declaration), Ministry of the Environment, Denmark.

3.2 PROCESS SOLUTION AND EXPECTED PERFORMANCE

The WRF process technology train is proposed in

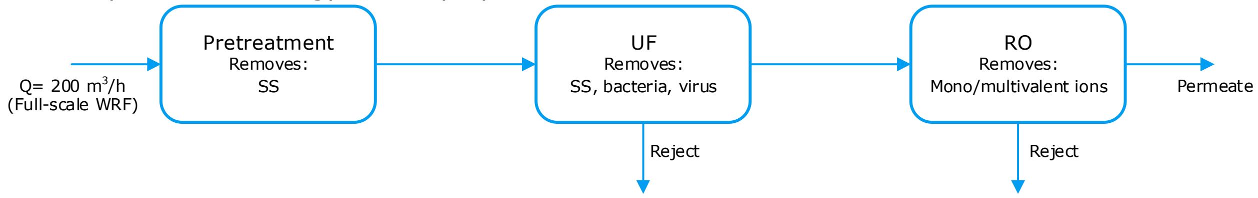


Figure 4. Membrane filtration with ultrafiltration (UF) and Reverse Osmosis (RO) will be used to treat the wastewater from the outlet of the RAS plant water treatment system. In the pilot test the proposed water treatment is to be pretreated with a suitable technique to protect UF and RO membranes downstream. The volume of the reject stream should be limited, and therefore the RO recovery should be as high as possible. Integration of a specialized high-recovery RO system will be preferred for the WRF.

The reject stream will be further treated to limit the volume as much as possible thus less discharge to recipient and possibility to recover relevant resources. This further treatment of the reject stream will be performed later in 2024 based on results from the pilot test.

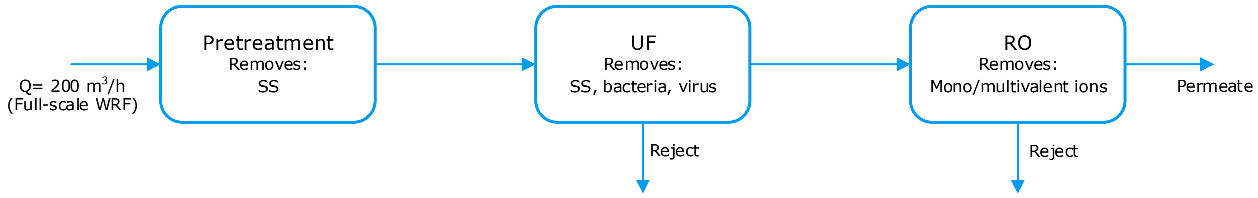


Figure 4 - Water flow diagram of WRF proposal.

The focus of the pilot test is to:

- Achieve and test as high as possible recovery of RO filtration on saline wastewater.
- Determine realistic design fluxes that require minimal CIP frequencies.
- Determine concentrations in permeate for water reuse.
- Determine concentrations in reject streams.

Design requirements of the pilot is described in Table 2.

Table 2 - Design requirements of pilot.

Scope	Pilot plant
Batch volume	2-10 m^3 of wastewater will be available for testing (after agreement with Skagen Salmon).
Feed quality	Similar water quality as "water sample" in Table 1, column 3. Water will be obtained from Skagen Salmon.
Required treatment steps	• Pretreatment to sufficiently protect UF- and RO-system. • UF. • RO, as high recovery as possible.
Required reclaimed water quality	Maximum Danish drinking water concentrations. • See Table 1, column 4.
Timeframe	Minimal test duration.

3.3 DELIVERABLES

The pilot test deliverable shall include:

- Design and construction of pilot set-up.
- Delivery to chosen location.
- Operation of pilot incl. estimated man hours.
- Final pilot test report with:
  - Full description and flow diagram/P&ID of test system, and key design values (e.g., active membrane areas).
  - Full description of testing methods, operational parameters (crossflow velocities, recovery rates, etc.), sampling locations and cleanings performed.
  - Set of raw data with analytical water chemistry & temperature results for feed, reject and permeate water, as well as online flow data of feed-, permeate and concentrate for the full pilot duration.
  - Pictures of process units and water samples, and important observations during testing.
  - Analysis, conclusions and full-scale recommendations based on the above and on additional parameters deemed relevant to prepare a full-scale design.

3.4 INFORMATION REQUIRED IN PROPOSAL

The pilot test proposal shall as a minimum include:

- Description of pilot test setup, including:
  1. Description of system:
     a. Fully automated system or manual operation.
     b. Footprint of pilot system.
     c. Utility needs.
  2. Type of pretreatment, type of membranes for UF and RO or other technology.
  3. Expected treated water quality after UF and RO (concentrations, and removal rate, %).
  4. Estimated operating fluxes and recovery rates.
  5. Estimated wastewater volume required for testing.
  6. Equipment datasheet and/or basic process flow diagram.
- Suggestion for location of pilot test (Pilot water source is located in Skagen).
  a) If applicable price for transportation of water.
- Pilot test plan:
  a) Duration and earliest possible starting time of pilot testing.

b) Staffing of the pilot tests and related activities.
c) Confirmation of sampling possibility of both feed, concentrate and permeate.
d) Sampling and analysis list planned to be performed.
e) Confirmation of possibility to deliver minimum 30 L RO concentrate for testing activities with further treatment of reject stream later in the project.

4. DELIVERABLE 2: COSTING OF FULL-SCALE WRF

The costing of the full-scale WRF shall be based on the key results and design basis obtained through the pilot test with Skagen Salmon RAS wastewater. However, since the focus of the TETRAS project is the Baltic Sea Region, with coastal seawaters with lower salinities, an evaluation of the impact of seawater compositions near Lolland-Falster coasts on the design and costing is also requested. Costing shall include CAPEX and OPEX for all necessary process equipment in the WRF.

4.1 FEED WATER CONDITIONS & QUALITY

For the costing, the currently available feedwater composition information is the Skagen Salmon wastewater sample analysis shown in Table 1. Additional wastewater composition data obtained through pilot testing shall be included in the WRF design basis.

For the impact analysis of the BSR seawater composition, both seasonal and absolute variations in composition between Table 1 and the future RAS wastewater in Lolland-Falster are to be expected. Salinity is expected to differ significantly and have an impact on the WRF design and was therefore investigated. The seawater in Skagen has a higher content of salt than in the sea surrounding Lolland-Falster, see Figure 5. The salinity at Skagen is 33 ‰ which is significantly higher compared to sea surrounding Lolland-Falster estimated to 17 ‰ this is mostly due to variation higher concentration of calcium, magnesium, sodium, potassium and sulphate, see Table 3.

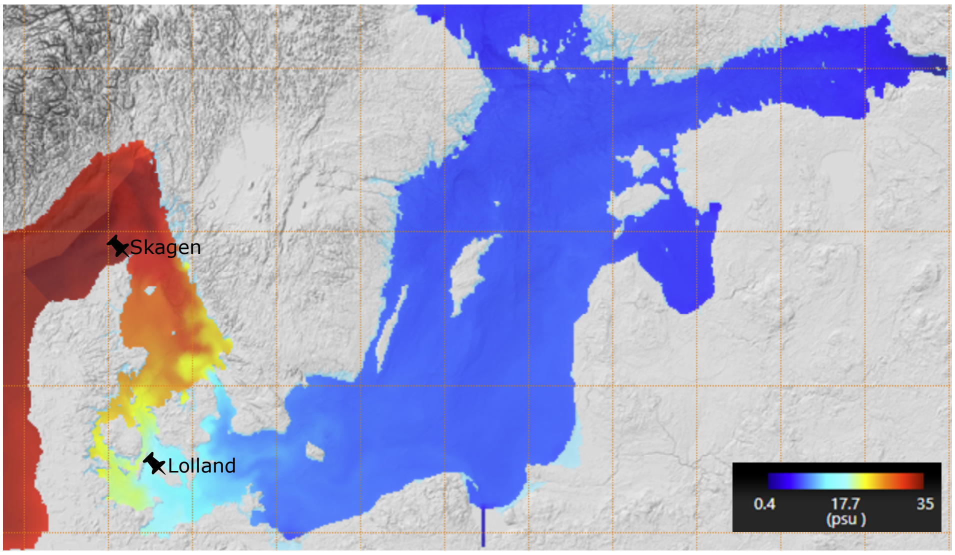


Figure 5 – Salinity of water around Denmark and the BSR (Ebaltic, 2023).

Table 3 - Estimated content of seawater used in Skagen Salmon and content of seawater from Fehmarn Belt, Lolland-Falster.

	Unit	Skagen	Lolland-Falster	
			Min	Max
Salinity	‰	33	17	
Temperature	°C	3-18	2,5	20
TSS	mg/l	25	2	29
Calcium	mg/l	387	94,4	161,1
Magnesium	mg/l	1.207	241,5	444,4
Sodium	mg/l	10.164	-	7.100
Potassium	mg/l	377	87,2	158,5
Chloride	mg/l	18.244	18.000	18.000
Sulphate	mg/l	2.555	620	620

4.2 PROCESS SOLUTION AND EXPECTED PERFORMANCE

The treatment processes in the full-scale WRP are expected to be the same as the ones tested at pilot-scale. The expected performance of the full-scale WRP is summarized in Table 4.

Based on the pilot test, pricing a full-scale design of the WRF, including CAPEX and OPEX shall be conducted. CAPEX and OPEX is performed for the full-scale WRF based on the water used in the pilot (water from Skagen Salmon), with an estimation on how water with lower salinity similar to seawater surrounding Lolland-Falster will affect the CAPEX and OPEX.

Table 4 - Design requirements of full scale.

Scope	Full scale
Feed flow	200 m^3/h
Feed quality	The estimate of CAPEX and OPEX should be made based on the feed water qualities: 1. Similar water quality as "water sample" in Table 1, column 3, same as pilot test. 1.1 How the price of the full-scale WRF plant would be impacted by water with lower salinity more similar to the water surrounding Lolland-Falster and the BSR, as "Lolland-Falster min-max" in Table 3
Required treatment steps	• Pretreatment to sufficiently protect UF- and RO-system. • UF. • RO, as high recovery as possible.
Required reclaimed water quality	Maximum Danish drinking water concentrations • See Table 1, column 4

Robustness and redundancy	• A design with min. two trains to enable min. 50% of average flow production in case of chemical cleaning or maintenance of one unit. • Modular design for future expansion

4.3 DELIVERABLES

The full-scale plant deliverables shall include:

- Description of full-scale WRF, including:
  1. Description of system:
     a. Fully automated system or manual operation.
     b. Type of pretreatment, type of membranes for UF and RO or other technology.
     c. Intermediate storage tanks or backwash tanks to suit the supplied process.
     d. Basic lay-out drawings and area footprint.
     e. Process flow diagram.
     f. Key equipment datasheets.
  2. Expected treated water quality after UF and RO (concentrations, and removal rate, %).
  3. Estimated operating fluxes and recovery rates.
- Costing including:
    - Investment cost (CAPEX) (+/- 30%).
    - Complete system and per treatment step.
- Operation cost (OPEX) - Required utilities and consumables (+/- 30%):
    - Complete system and per treatment step.
    - Annual Power consumption.
    - Annual Chemical consumption (incl. Specify type of chemicals, frequency of cleaning).
    - Instrument air.
    - Other consumables.
- Guaranteed and expected lifetime of key components.
- Replacement cost of key components (+/- 30%).
    - 3 relevant references of similar application, capacity and scope.
- Impact analysis of water quality on system description, CAPEX and OPEX based on variation of water quality with lower salinity in the water surrounding Lolland-Falster.

4.4 INFORMATION REQUIRED IN PROPOSAL

The full-scale plant deliverables shall include estimated hours.

5. BUDGET

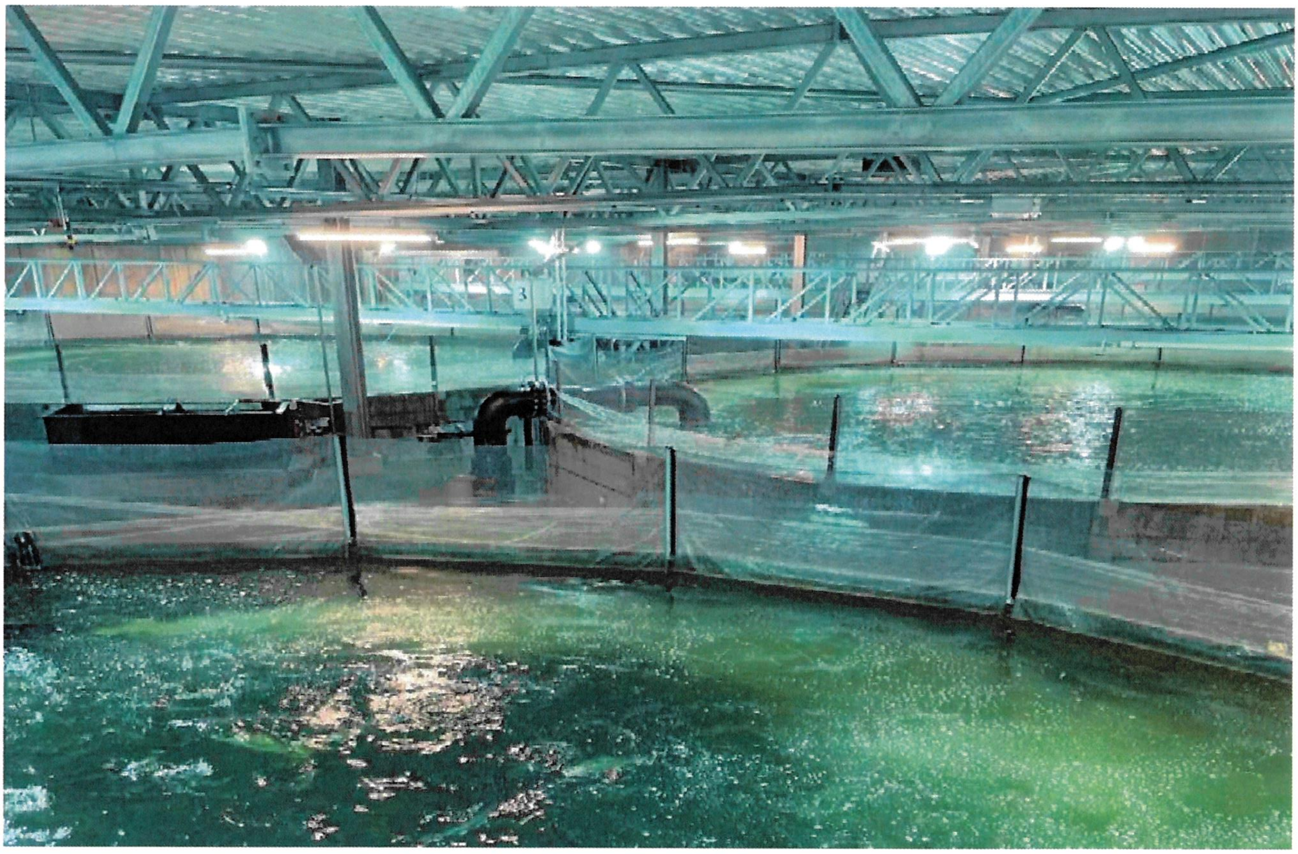
The available budget for these deliverables including batch pilot tests and full-scale plant design is 350.000 DKK, excl. VAT.

All naturally occurring costs in connection with completing this project must be included in the proposal.

Appendix 2
Boll Filter test report incl. appendix

BOLLFILTER
Protection Systems

Design and operation of a pilot test and costing of a future full-scale plant for reclamation of wastewater from a land-based RAS plant



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Subject to technical modifications without prior notice.

Table of Contents:

1. Summary

On-site pilot test with SiC ceramic Ultra Filtration (UF) membranes and Reverse Osmosis (RO) membranes were conducted at Skagen Salmon over the days 01 OCT to 03 OCT 2024. The purpose of the pilot test was to investigate if end of pipe wastewater from a Recirculating Aquaculture System (RAS) can be treated to meet Danish drinking water quality requirements. The pilot test confirmed the possibility to achieve such treated water quality – as shown in below table:

		RAS WW	RO (65% rec.) permeate	DW max conc.	Comments
Parameter	Unit	Value	Value	Value	
pH	pH	7.4	6.6	7.0-8.5	
Ammonia+ammonium-N	mg/l	5.2	< 1	0.050	*
Chloride, filtered	mg/l	14,000	55	250	
Fluoride, filtered	mg/l	0.48	< 0.05	1.5	OK in raw WW
Nitrite+nitrate-N, filtered	mg/l	21	0.48	50	OK in raw WW
Sulphate, filtered	mg/l	2,000	6.5	250	
NVOC	mg/l	25	2.7	4	
Lead (Pb)	µg/l	< 0.5	< 0.5	5	OK in raw WW
Chrome (Cr)	µg/l	< 0.5	< 0.5	25	OK in raw WW
Iron (Fe)	mg/l	9.4	< 0.05	0.2	OK after UF
Copper (Cu)	µg/l	1.3	< 0.5	2,000	OK in raw WW
Manganese (Mn)	mg/l	0.079	< 0.005	0.05	
Sodium (Na)	mg/l	9,100	18	175	
Nickel (Ni)	µg/l	< 1	< 1	20	OK in raw WW
Aluminum (Al)	µg/l		< 30	200	

* Analyse method not able to determine concentrations lower than 1 mg/L.

One UF operating set point (maintained throughout the test period) and three RO operating set points were evaluated. The project owner wanted to investigate a high RO recovery scenario (reduced volume of RO reject), thus three RO recoveries were evaluated at 57%, 65% and 73% respectively.

The pilot test results and data gathered during the three-day pilot duration were used to estimate a full-scale water treatment solution to treat 200 m3/h RAS wastewater to drinking water quality.

Besides fulfilling the main project objectives, the pilot results furthermore included:

1) Validation of the WAVE RO modelling software for the treated RAS wastewater – an engineering tool to design and predict RO system performance
2) Empirical data related to UF removal efficiencies of phosphor, COD and heavy metals
3) Suggestions for optimizing full scale treatment solution to address NVOC
4) Suggestions for future investigations

2. Introduction & aim of the pilot test

The aim of the pilot test was to verify that end-of pipe RAS wastewater can be treated by UF and RO to reach drinking water quality requirements for industrial water reuse – hereunder:

- Achieve and test as high as possible recovery of RO filtration on saline wastewater.
- Determine realistic membrane design fluxes that require minimal CIP frequencies.
- Determine concentrations in permeate for water reuse.
- Determine concentrations in reject streams.

Pilot test performance and laboratory water analysis results will be used to do costing of a full scale (200 m3/h) water treatment plant for RAS wastewater to be reused. OPEX and CAPEX estimates for full scale installation will be applied to evaluate techno-commercial viability of the proposed water treatment system.

The considered RAS wastewater treatment plant is shown in Figure 1:

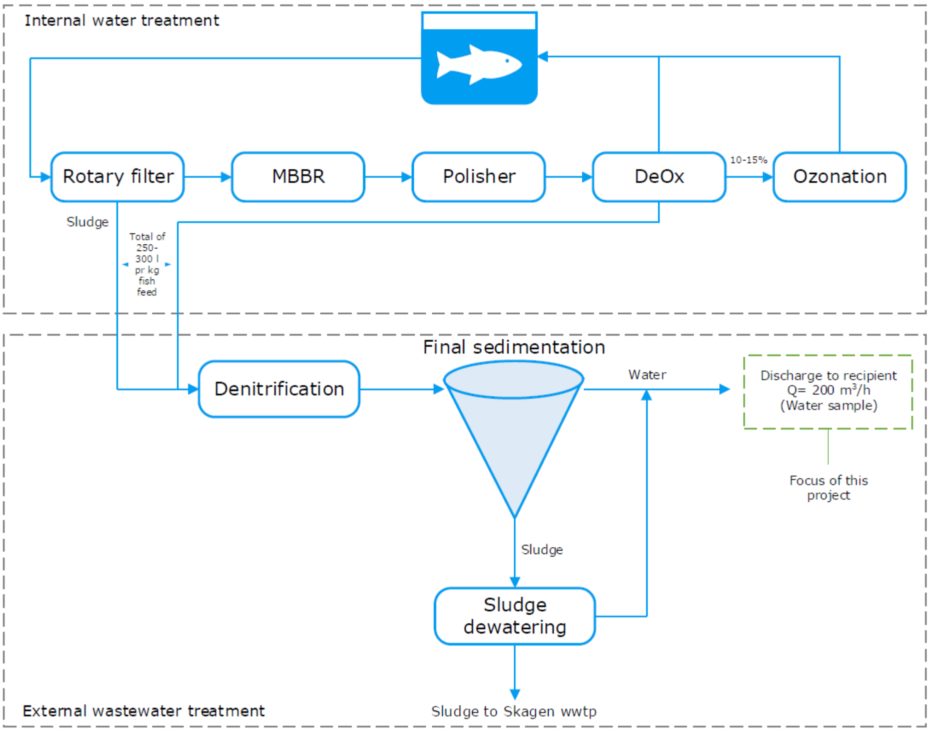


Figure 1: Internal and external water treatment at RAS (Skagen Salmon)

The focus of this project is to further treat the wastewater currently discharged – shown in below Figure 2:

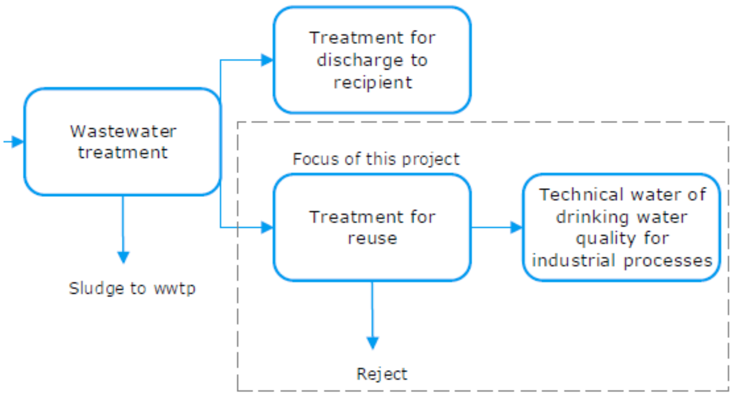


Figure 2: Focus of this project - treatment of RAS WW for reuse

3. Test set up & execution

The test setup consisted of the following modules:

1) BOLL Mikro-Mia 2.0 UF test unit – installed with 50 micron pre-filtration and 2 pcs. SiC/ZrO_2 ceramic membranes each with a surface area of 0.09 m^2.

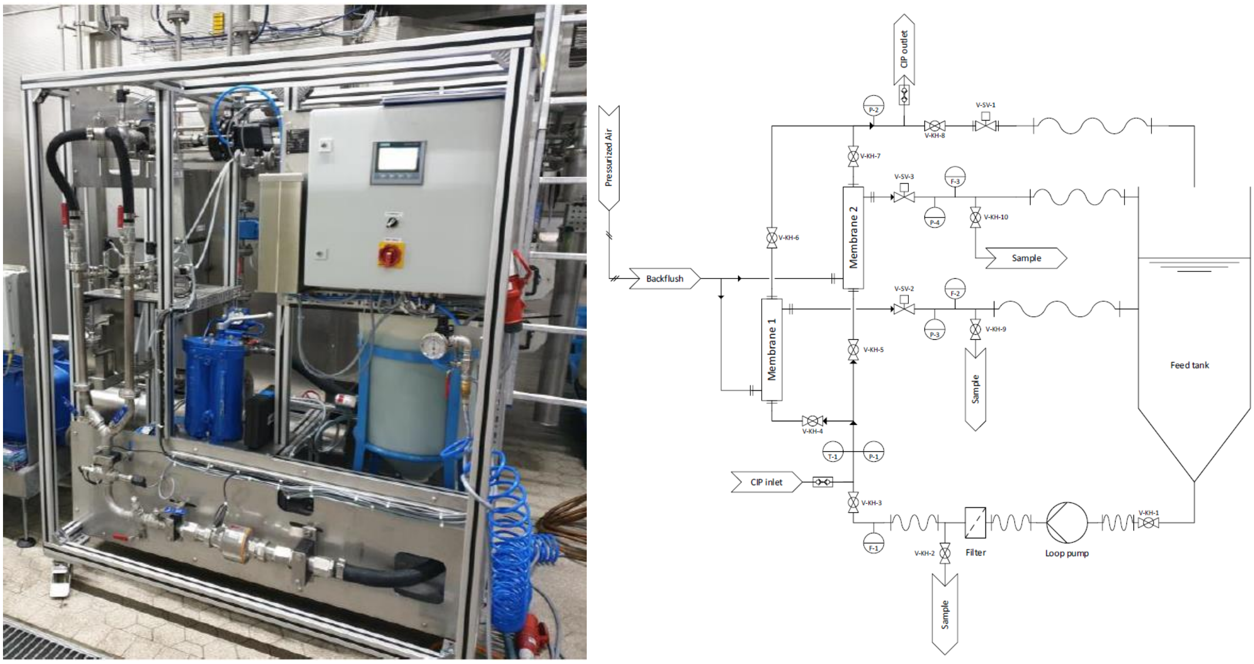


Figure 3: Picture and simplified flow chart of the mobile membrane test plant (Mikro-Mia 2.0)

2) RO pre-treatment module with (a) 3 micron absolute cartridge filter, (b) granular activated carbon filter on the feed water side and (c) a 10 micron cartridge filter on the flush water side.

3) AQSEP WM2000B-340 RO unit installed with 3 pcs. DOW SW30-4040 membranes each 7.4m^2 surface area.

Feed tanks and pumps between the modules were installed as shown on Figure 4:

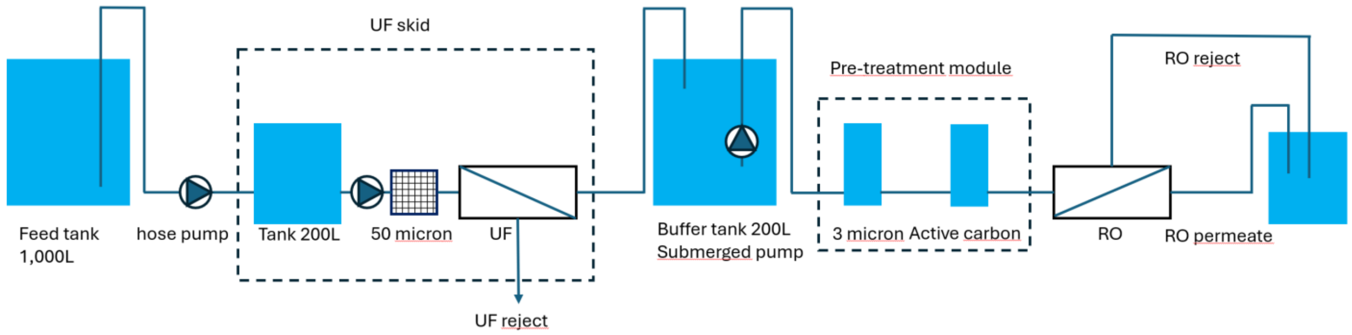


Figure 4: Test installation process flow at Skagen Salmon

Test summary:

Day 1 (OCT 1st):

1) Arrived at test location – installation of test equipment – first run with tap water.
2) Collected ~800L of RAS WW in IBC tank and filled UF skid feed tank. Started UF and established constant operation (constant flux and trans membrane pressure (TMP)).
3) Collected ~100L of UF permeate and started RO and checked operating performance was within expected range (flux, pressure and salinity of RO permeate).

Day 2 (OCT 2nd):

1) Collected ~800L RAS WW in IBC tank and filled the UF skid with 75L of feed water.
2) Started UF skid and continued constant operation while collecting UF permeate in 200L tank.
3) Added 25L of feed for every ~3 hours of UF operation – a total of 150L feed was added to the UF skid.
4) Stopped UF during the night.

Day 3 (OCT 3rd):

1) Started UF skid and collected feed, permeate and reject samples for laboratory analyses.

   142.5L of UF permeate was produced – 7.5L of UF reject remaining in the UF skid dead volume and feed tank.
2) Started RO skid and returned RO permeate and RO reject to RO feed tank.
3) Collected RO permeate and reject samples at 57%, 65 and 73 % recovery respectively.
4) Ended test and disassembled the test installation.

UF operating set points:

01-okt							
	Flux (lmh)	TMP (bar)	Flux/TMP (lmh/bar)	TCSF/TMP (lmh/bar)	V-channel (m/s)	Temp (°C)	Notes
15:33	90	0.64	141	102	3.1	30.3	Flux 2h after installing new membrane (M2)
02-okt							
12:20	48	0.93	52	39	3.6	29.0	Addition of 25L feed to UF skid (75L initial feed volume)
15:11	60	0.99	61	38	3.1	34.7	Addition of 25L feed to UF skid
17:43	66	0.96	69	39	3.1	38.0	Addition of 25L feed to UF skid
03-okt							
01:03	74	0.87	85	47	3.0	39.4	Pilot stopped during the night
08:28	60	0.81	74	50	2.9	33.0	Pilot started to complete 150L feed cycle and collect samples

(*) TCSF = Temperature corrected specific flux at 20°C = $\frac{flux}{TMP}\ x\ e\hat{}(-0.031\ x\ (T-20))$

RO operating set points:

03-okt	flux (lmh)	membrane pressure (bar)	TCSF (lmh)	recovery (%)	salinity (ppm)	Temp (°C)
09:50	14	50	17	57	61	10 (*)
10:00	16	59	19	65	61	10 (*)
10:02	17	66	21	73	61	10 (*)
10:44	18	67	22	74	N/A	10 (*)

(*) Temperature was estimated from UF data

The RO permeate and RO reject streams were both returned to the RO feed tank.

4. Laboratory water analysis results

The picture below shows the visual appearance of the UF feed water, permeate and reject water respectively:

Picture 1: UF feed water (left), UF permeate (center) and UF reject (right)

The picture below shows the visual appearance of the RO feed water and RO permeate at 60% recovery:

Picture 2: RO feed water (left) and RO permeate at 60% recovery

The UF water analyses can be found in the table below:

		UF Feed	UF reject	UF permeate	UF reduction
Parameter	Unit	Value	Value	Value	%
pH	pH	7.4	N/A	8.3	
Temperature at pH-measurement	°C	20	N/A	20	
Suspended solids	mg/l	29	N/A	9.6	67%
Alkalinity, as CaCO3	mg/l	310	N/A	290	
Alkalinity, total	mmol/l	6.25	N/A	5.88	
Ammonia + ammonium-N	mg/l	5.2	6.4	3.7	29%
Chloride, filtered	mg/l	14,000	15,000	15,000	
Fluoride, filtered	mg/l	0.48	0.48	0.45	6%
Nitrite + nitrate-N, filtered	mg/l	21	25	26	
Silicate-Si, filtered	mg/l	1.4	1.3	1.4	
Sulfate, filtered	mg/l	2,000	2,100	2,000	
Hardness, total	°dH	270	280	280	
Magnesium (Mg)	mg/l	1,000	1,000	1,000	
Total Nitrogen	mg/l	27	56	31	
Total Phosphor	mg/l	4.3	33	0.96	78%
COD	mg/l	100	550	41	59%
DOC	mg/l	20	69	12	40%
NVOC	mg/l	25	150	17	32%
VOC	mg/l	< 0.5	< 0.5	< 0.5	
TOC	mg/l	25	150	17	32%
Barium (Ba)	µg/l	12	77	9.4	22%
Lead (Pb)	µg/l	< 0.5	6.4	< 0.5	>90% *
Calcium (Ca)	mg/l	390	450	390	
Chrome (Cr)	µg/l	< 0.5	9.1	< 0.5	>90% *
Iron (Fe)	mg/l	9.4	86	0.066	99%
Potassium (K)	mg/l	330	380	350	
Copper (Cu)	µg/l	1.3	93	4,5	X
Magnesium (Mg)	mg/l	1,100	980	1,100	
Manganese (Mn)	mg/l	0.079	0.18	0.07	11%
Sodium (Na)	mg/l	9,100	8,200	9,200	
Nickel (Ni)	µg/l	< 1	5.6	1.3	>80% *
Strontium (Sr)	µg/l	6,400	8,600	7,200	

It can be seen that the ultra filtration membranes have achieved a significant reduction of the following parameters:

- Suspended solids: a 67% reduction has been achieved to 9.6 mg/L – which is within expectations.
- Total phosphor: a 78% reduction to 0.96 mg/L, which is of relevance considering the interest to reduce phosphor discharge to recipients.
- COD and TOC: a reduction of 59% and 32% respectively to permeate values below 50 mg/L and 20 mg/L.
- Iron: a 99% reduction to < 0.1 mg/L, which could be of interest for some RAS plants wanting to reduce ocher in the circulation water.

- (*) It can be seen that lead, chrome and nickel are retained by the UF membranes and concentrated from below detection limits to well above detection limit. Assuming feed concentrations at detection limits for the three components – the heavy metals have been reduced by >90% for lead and chrome and >80% for nickel.
- (X) The copper results are unexpected and can't be explained. We assume either leaching from wetted components or measurement error.

The RO water analyses can be found in the table below:

		RO 65% reject	RO 65% permeate	RO 73% reject	RO 73% permeate
Parameter	Unit	Value	Value	Value	Value
pH	pH		6.6		7
Temperature at pH-measurement	°C		20		22
Suspended solids	mg/l		3.8		
Alkalinity, as CaCO3	mg/l				< 5
Alkalinity, total	mmol/l				0.029
Ammonia+ammonium-N	mg/l	6.8	< 1	4.7	
Chloride, filtered	mg/l	29,000	55	19,000	24
Fluoride, filtered	mg/l	0.61	< 0.05	0.51	< 0.05
Nitrite+nitrate-N, filtered	mg/l	0.88	0.48	38	0.41
Silicate-Si, filtered	mg/l	4.3	0.18	6.4	< 0.05
Sulfate, filtered	mg/l	4,000	6.5	2,700	< 0.5
Hardness, total	°dH	550	< 0.1	360	< 0.1
Magnesium (Mg)	mg/l	2,000	< 1	1,300	< 1
Total Nitrogen	mg/l	61	1.1	42	0.78
Total Phosphor	mg/l	2.3	0.024	0.67	< 0.01
COD	mg/l	31	< 15	43	< 15
DOC	mg/l	19	2.3	18	< 1
NVOC	mg/l	20	2.7	16	1.5
VOC	mg/l	< 0.5	< 0.5	< 0.5	< 0.5
TOC	mg/l	20	2.7	16	1.5
Barium (Ba)	µg/l	36	< 1	33	< 1
Lead (Pb)	µg/l	1.4	< 0.5	0.9	< 0.5
Calcium (Ca)	mg/l	760	< 0.5	500	< 0.5
Chrome (Cr)	µg/l	< 0.5	< 0.5	< 0.5	< 0.5
Iron (Fe)	mg/l	< 0.05	< 0.05	< 0.05	< 0.05
Potassium (K)	mg/l	720	1.5	380	1.3
Copper (Cu)	µg/l	11	< 0.5	13	1.1
Magnesium (Mg)	mg/l	2,300	0,13	1,200	0.21
Manganese (Mn)	mg/l	0.14	< 0.005	0.1	< 0.005
Sodium (Na)	mg/l	19,000	18	10,000	16
Nickel (Ni)	µg/l	2.6	< 1	2.3	< 1
Strontium (Sr)	µg/l	12,000	< 1	7,600	
Aluminum (Al)	µg/l		< 30		< 30

The installed DOW SW30-4040 RO membranes (product specification sheet in Appendix 1) promise a 99.7% salt rejection at 55 bar feed pressure. It can be seen that the RO membranes have significantly reduced all parameter concentrations as expected.

The parameter concentrations in both RO 65% recovery and RO 73% recovery reject samples are lower than expected considered the recovery values. This, together with relatively low RO feed pressures, indicates that the UF permeate has been diluted with fresh water prior to the RO test unit. This will be discussed further in the Pilot test results section.

5. Pilot test results

UF pilot results

Figure 5 shows the temperature corrected specific UF flux over the pilot period.

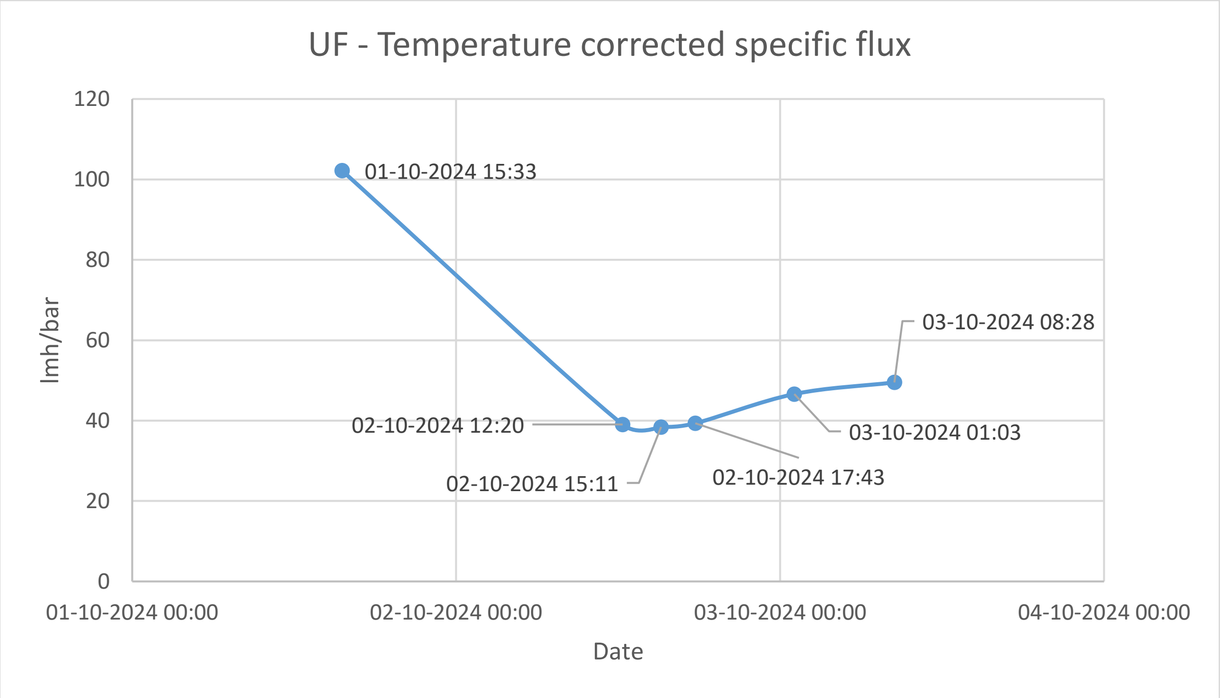


Figure 5: Temperature corrected specific flux at 20°C for UF pilot

UF permeability

The UF skid initially performed 102 LMH/bar with new/clean membranes, which stabilized at approx. 40LMH/bar. The permeability at the end of the test period increased to ~50 LMH/bar, which is counter intuitive since the recovery ratio (permeate to feed ratio) is peaking. We believe the increased flux can be explained by suspended particles being dissolved in the cross-flow recirculation loop over time/increasing temperature.

The UF pilot unit was not equipped to perform backpulse or backwash and there was no other (chemical) cleaning of the membranes throughout the test period. In a full-scale system with backpulse and backpulse, we anticipate that a stable design flux of 75 LMH @ 1 bar TMP can be applied for dimensioning a full-scale UF system.

UF recovery

A final UF recovery of 95% was targeted by knowing the total feed volume (150L) and estimating the total reject volume in the UF pilot unit (~7.5L). Based on the stable operation, we expect an even higher recovery during filtration could be possible. The higher recovery could be “invested” in back pulse/wash sequences and thus achieving a total recovery of ~95% including backpulse/wash.

UF TMP

Trans membrane pressure (TMP) was stable at < 1 bar throughout the test period. Future work may include higher flux/TMP evaluation to reduce CAPEX of a full-scale plant – keeping in mind OPEX will increase for this scenario.

UF filtration efficiency and full scale design input

The UF test results summary can be found in the table below:

		UF Feed	UF reject	UF permeate	UF reduction
Parameter	Unit	Value	Value	Value	%
Suspended solids	mg/l	29	N/A	9.6	67%
Ammonia + ammonium-N	mg/l	5.2	6.4	3.7	29%
Total Phosphor	mg/l	4.3	33	0.96	78%
COD	mg/l	100	550	41	59%
DOC	mg/l	20	69	12	40%
NVOC	mg/l	25	150	17	32%
TOC	mg/l	25	150	17	32%
Barium (Ba)	µg/l	12	77	9.4	22%
Lead (Pb)	µg/l	< 0.5	6.4	< 0.5	>90%
Chrome (Cr)	µg/l	< 0.5	9.1	< 0.5	>90%
Iron (Fe)	mg/l	9.4	86	0.066	99%
Manganese (Mn)	mg/l	0.079	0.18	0.07	11%
Nickel (Ni)	µg/l	< 1	5.6	1.3	>80%
UF full scale design input	Permeability	TMP	Recovery		
	75 LMH	1 bar	95%		

RO pilot results

Figure 6 shows the RO temperature corrected specific flux, membrane pressure and recovery at the four sampling points during OCT 3rd:

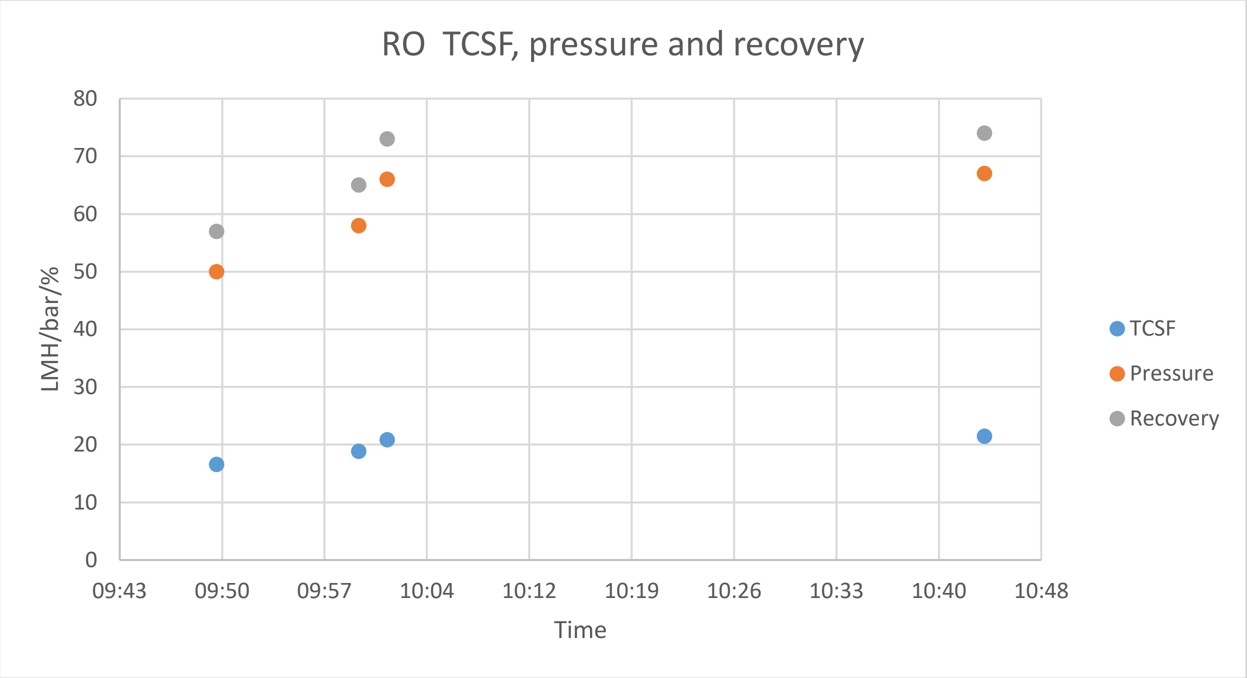


Figure 6: Temperature corrected specific flux at 20°C, RO membrane pressure and recovery for RO pilot

Recovery versus feed pressure

The first RO operating set point (14 LMH, 50 bar feed pressure, 57% recovery) matches well with the DOW RO design modelling software WAVE (Water Application Value Engine). WAVE is a recognized engineering tool to predict RO performance and design of full scale commercial RO plants. Please see the "WAVE RO 57%" summary report in Appendix 2 when applying the first RO operating set point and obtained feed water laboratory analysis from the UF pilot test. The design output from WAVE is (14 LMH, 51.8 bar feed pressure, 57% recovery). The higher feed pressure (3.6%) estimated by WAVE could be caused by sources of errors from RO permeate and reject flow and pressure readings on the RO test unit. The chloride concentration measurement in UF feed (14,000 mg/L) and UF permeate (15,000 mg/L) indicates a sample/measurement error, since the UF membranes don't influence chloride concentration.

Based on the first RO operating set point we conclude the WAVE modelling software matches well with the pilot results and thus validated for modelling RO performance and system design for this project. The minor deviation between pilot test and software simulation is considered negligible since the objective is to budget estimate a full-scale solution.

The second RO operating set point (19 LMH, 58 bar feed pressure, 65% recovery) does not match well with the corresponding water analysis results and WAVE simulated results (please see the "WAVE RO 65%" summary report in Appendix 3).

At 65% recovery the expected chloride reject concentration is ~40,000 mg/L whereas the analysis shows 29,000 mg/L. This indicates the RO feed water was diluted to ~73% of the original salt concentration (due to automatic RO membrane flushing with fresh water to protect the RO membranes from scaling). The membrane pressure is expected to be ~ 62 bar at this salt concentration, whereas 58 bar was recorded.

The third RO operating set point (21 LMH, 66 bar feed pressure, 73% recovery) does not match well with the corresponding water analysis results and WAVE simulated results (please see the “WAVE RO 73%” summary report in Appendix 4).

At 73% recovery the expected chloride reject concentration is ~51,000 mg/L whereas the analysis shows 19,000 mg/L. This indicates the RO feed water was diluted to ~37% of the original salt concentration. The membrane pressure is expected to be ~80 bar, whereas 66 bar was recorded.

Recovery versus salt rejection (permeate quality)

In case of RO feed dilution, the RO permeate will also have lower salt concentrations. Doing a cross-check WAVE simulation comparing the measured RO 65% analyses results with the WAVE simulated results on diluted feed water (“WAVE RO 65% diluted” summary report in Appendix 5) - it can be seen that the measured chloride concentrations match well with the simulated results:

	RO 65% pilot test	WAVE 65%	
RO feed chloride concentration		10,220	mg/L
RO reject chloride concentration	29,000	29,101	mg/L
RO permeate chloride concentration	55	59	mg/L

The cross-check confirms that WAVE is a viable tool to predict the RO reject and permeate qualities for the pilot test and full scale RO installation.

RO permeate quality versus drinking water quality requirements

One of the main project objectives is to verify the RO permeate can meet drinking water max. concentrations for specific parameters. Below table shows that all the listed parameters are in compliance with the requirements – some are below the maximum values in the feed water prior to UF and one parameter is below after UF:

		UF Feed	65% perm.	73% perm.	DW max conc.	Comments
Parameter	Unit	Value	Value	Value	Value	
pH	pH	7.4	6.6	7	7.0-8.5	
Ammonia+ammonium-N	mg/l	5.2	< 1		0.050	
Chloride, filtered	mg/l	14,000	55	24	250	
Fluoride, filtered	mg/l	0.48	< 0.05	< 0.05	1.5	OK in raw WW
Nitrite+nitrate-N, filtered	mg/l	21	0.48	0.41	50	OK in raw WW
Sulfate, filtered	mg/l	2,000	6.5	< 0.5	250	
NVOC	mg/l	25	2.7	1.5	4	*
Lead (Pb)	µg/l	< 0.5	< 0.5	< 0.5	5	OK in raw WW
Chrome (Cr)	µg/l	< 0.5	< 0.5	< 0.5	25	OK in raw WW
Iron (Fe)	mg/l	9.4	< 0.05	< 0.05	0.2	OK after UF
Copper (Cu)	µg/l	1.3	< 0.5	1.1	2,000	OK in raw WW
Manganese (Mn)	mg/l	0.079	< 0.005	< 0.005	0.05	

Sodium (Na)	mg/l	9,100	18	16	175	
Nickel (Ni)	µg/l	< 1	< 1	< 1	20	OK in raw WW
Aluminum (Al)	µg/l		< 30	< 30	200	

(*) Assuming a linear relation between measured RO permeate NVOC concentrations and RO reject chloride concentrations (representing general salt concentration), we can extrapolate the expected NVOC concentration in a non-diluted 65% RO permeate:

RO reject chloride concentration	19,000 (measured)	29,000 (measured)	40,000 (calculated)	mg/L
RO permeate NVOC concentration	1.5 (measured)	2.7 (measured)	4.0 (extrapolated)	mg/L

The extrapolated value of 4.0 mg/L NVOC is the maximum allowed concentration in drinking water. Post treatment (granular activated coal or advanced oxidation) of NVOC is recommended in case of full-scale implementation.

All other permeate concentrations are well below the allowed maximum concentrations, thus a deviation between measured and calculated values is considered negligible.

Full scale RO design input

Using the process validated WAVE modelling software, below table shows expected RO operating conditions and performance at selected recoveries:

RO recovery	60%	65%	75%	
Membrane pressure	55	63	87	bar
Permeability	15	16	18	LMH
Permeate conductivity	291	300	348	µS/cm
Specific energy	3.20	3.34	4.09	kWh/m3

6. Pilot test conclusion and summary

UF pilot test

The UF pilot demonstrated a constant performance in terms of permeability and trans membrane pressure levels. The expected recovery ratio of treated water vs. feed water was achieved. The UF membranes demonstrated a significant concentration reduction of several components in the RAS wastewater. The key UF performance indicators are shown below:

		UF Feed	UF reject	UF permeate	UF reduction
Parameter	Unit	Value	Value	Value	%
Suspended solids	mg/l	29	N/A	9.6	67%
Ammonia + ammonium-N	mg/l	5.2	6.4	3.7	29%
Total Phosphor	mg/l	4.3	33	0.96	78%
COD	mg/l	100	550	41	59%
DOC	mg/l	20	69	12	40%
NVOC	mg/l	25	150	17	32%
TOC	mg/l	25	150	17	32%
Barium (Ba)	µg/l	12	77	9.4	22%
Lead (Pb)	µg/l	< 0.5	6.4	< 0.5	>90%
Chrome (Cr)	µg/l	< 0.5	9.1	< 0.5	>90%
Iron (Fe)	mg/l	9.4	86	0.066	99%
Manganese (Mn)	mg/l	0.079	0.18	0.07	11%
Nickel (Ni)	µg/l	< 1	5.6	1.3	>80%
UF full scale design input	Flux	TMP	Recovery		
	75 LMH	1 bar	95%		

We note the 78% reduction of phosphor is relevant for the RAS operators considering the interest to reduce phosphor emissions to the recipient.

Based on the achieved UF pilot results, we recommend the following investigations for further application development:

1) Implementing backwash/backpulse sequences to increase average UF membrane permeability
2) Investigate higher permeabilities at increased TMP
3) Investigate higher recovery with the aim to reduce reject volume
4) Reduce membrane cross-flow velocity with the aim to reduce energy consumption
5) Extended pilot duration (2-3 months) to evaluate long term effects and need for chemical cleaning

RO pilot test

Key RO performance indicators (pressure, recovery, permeability and rejection) were measured and analysed at three operating set points – at 56%, 65% and 73% recovery. The performance indicators at the first operation set point was used to validate a commercial software modelling tool (WAVE) developed by the manufacturer of the RO membranes used in this pilot. WAVE is applied for designing industrial RO membrane system and predicting the operating performance of these.

Contrary to the first operating set point, the performance indicators at operating set points two and three didn't match neither our expectations nor the WAVE modelling predictions. The expected correlation between RO recovery and RO reject salt concentrations was not confirmed, indicating either a dilution of feed water with fresh water or wrong analytical results.

Based on the high credibility of WAVE and the model verification by empirical results from first RO operating set point, we conclude that the WAVE simulated results are valid for this pilot and for full scale design and budget estimates.

The RO pilot demonstrated the capability to reduce concentrations of targeted pollutants in the RO permeate to levels below drinking water requirements:

		RAS WW	RO (65% rec.) permeate	DW max conc.	Comments
Parameter	Unit	Value	Value	Value	
pH	pH	7.4	6.6	7.0-8.5	Increase pH
Ammonia+ammonium-N	mg/l	5.2	< 1	0.050	*
Chloride, filtered	mg/l	14,000	55	250	
Fluoride, filtered	mg/l	0.48	< 0.05	1.5	OK in raw WW
Nitrite+nitrate-N, filtered	mg/l	21	0.48	50	OK in raw WW
Sulphate, filtered	mg/l	2,000	6.5	250	
NVOC	mg/l	25	2.7	4	
Lead (Pb)	µg/l	< 0.5	< 0.5	5	OK in raw WW
Chrome (Cr)	µg/l	< 0.5	< 0.5	25	OK in raw WW
Iron (Fe)	mg/l	9.4	< 0.05	0.2	OK after UF
Copper (Cu)	µg/l	1.3	< 0.5	2,000	OK in raw WW
Manganese (Mn)	mg/l	0.079	< 0.005	0.05	
Sodium (Na)	mg/l	9,100	18	175	
Nickel (Ni)	µg/l	< 1	< 1	20	OK in raw WW
Aluminum (Al)	µg/l		< 30	200	

* Analyse method not able to determine concentrations lower than 1 mg/L.

Considering a dilution of RO feed water and cross-checking the permeate concentration results with a feed concentration sensitivity investigation, only the NVOC concentration reaches the maximum value. We recommend a granular activated carbon (GAC) module to be included in a full-scale installation.

RO membrane permeability, pressure and recovery measured (RO operating set point 1) and modelled in WAVE have confirmed our expectations. Based on WAVE modelling the following full scale RO operating performance is estimated:

RO recovery	60%	65%	75%	
Membrane pressure	55	63	87	bar
Permeability	15	16	18	LMH
Conductivity	291	300	348	µS/cm
Specific energy consumption	3.20	3.34	4.09	kWh/m3

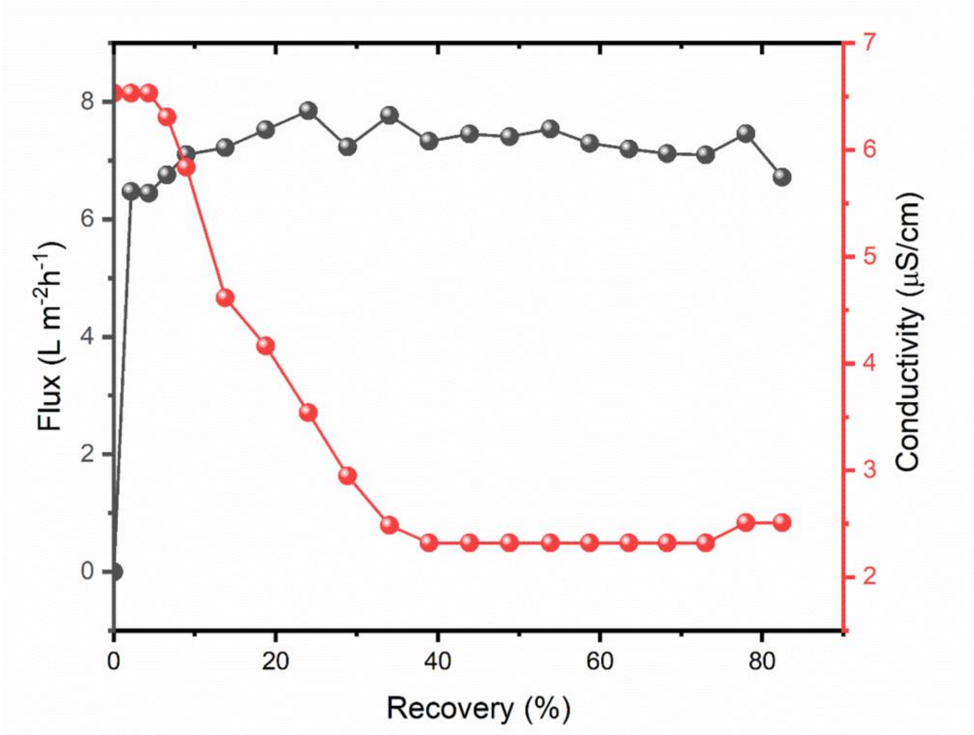
Based on the achieved RO pilot results, we recommend the following investigations for further application development:

1) Extended RO pilot duration (2-3 months) to evaluate long term effects and need for chemical cleaning
2) Investigate further NVOC reduction by GAC
3) Evaluate closed circuit RO system design to reduce energy consumption and RO reject volume
4) Conduct new ammonia analysis by appropriate method and potentially evaluate ammonia removal options

Membrane Distillation (MD) lab test

MD was evaluated as alternative to RO for desalination of the UF permeate. The MD process is gaining more interest due to its capability to recover waste heat and apply the thermal energy for driving the separation process. MD is furthermore able to achieve higher recoveries and improved distillate quality compared to RO. These properties are of great interest for wastewater reuse applications where the treated water will be used for boiler feed or electrolyser applications (PtX).

A sample of UF permeate was collected and brought to a lab at the Technical University of Denmark (DTU) to be processed with a MD lab unit. The direct contact (DC) MD operating results can be seen in the figure below:



It can be seen that the flux is consistent at 7 LMH for increasing recoveries up to 80%. The average distillate conductivity was 3.5 µS/cm (compared to 300 µS/cm for RO). It will require two stage RO to achieve a conductivity less than 5 µS/cm – adding to RO CAPEX/OPEX and brine handling cost.

The feed and distillate qualities can be found in the table below:

Parameter	Fish Farm Waste Water	MD Treated FFW 55 °C
pH	6.89	6.51
Conductivity	42.15 mS/cm	3.5 µS/cm
NO_x (mg/L)	19.9	<0.2
NO_2 (mg/L)	0.48	<0.1
NH_3 (mg/L)	2.24	<0.4
PO_4^{-3} (mg/L)	2.66	<0.1
TN_b (mg/L)	49.3	<1
TOC (mg/L)	15.5	0.58
Na (mg/L)	16037	0.61
Mg (mg/L)	1860	<0.1
K (mg/L)	611	0.10
Ca (mg/L)	667	<0.5

7. Costing of a full scale water treatment installation for 200 m3/h RAS WW

1. Description of full-scale system:
   a. The full-scale system will be completely automated – automation will monitor and adjust operating pressure and capacity. The UF and RO membranes will cleaned by a combination of techniques – backpulse, backwash and chemical cleaning in place – all sequences initiated by the system.
   b. The installation will include a 100 micron automatic self-cleaning filter before the SiC UF ceramic membranes. Anti-scalants will be dosed prior to the spiral RO membranes.
   c. Four main tanks will be installed:
      UF permeate tank of 200m3
      UF concentrate tank of 200m3
      RO permeate tank of 200m3
      RO concentrate tank of 200m3
   d. The basic lay-out drawing can be found in Appendix 6 Basic lay-out drawings and area footprint
   e. The process flow diagram can be found in Appendix 7 PFD_TETRAS_Rev00.
   f. Key equipment datasheets can be found in Appendix 8 Equipment datasheets

2. Expected treated water quality after UF will be identical to this UF pilot test results. The expected treated water quality after RO is provided in Appendix 3 (RO 65% (Wave) and shown below.

Concentrations (mg/L as ion)				
		Concentrate	Permeate	
	Feed	Stage1	Stage1	Total
NH_4^+	3.70	10.50	0.04	0.04
K^+	350.0	995.7	2.36	2.36
Na^+	8,550	24,336	50.70	50.70
Mg^{+2}	1,100	3,140	1.41	1.41
Ca^{+2}	350.0	999.2	0.43	0.43
Sr^{+2}	7.20	20.56	0.01	0.01
Ba^{+2}	0.01	0.03	0.00	0.00
CO_3^{-2}	20.38	191.4	0.00	0.00
HCO_3^-	2,965	8,191	6.70	6.49
NO_3^-	26.00	73.46	0.44	0.44
F^-	0.51	1.46	0.00	0.00
Cl^-	14,000	39,851	81.13	81.13
Br^{-1}	0.00	0.00	0.00	0.00
SO_4^{-2}	2,141	6,115	1.05	1.05
PO_4^{-3}	0.90	2.57	0.00	0.00
SiO_2	0.83	2.35	0.01	0.01
Boron	0.00	0.00	0.00	0.00
CO_2	195.5	269.9	207.3	207.4
TDS[a]	29,516	83,931	144.0	144.1
Cond. µS/cm	41,970	104,382	300	300
pH	7.0	7.5	5.1	5.1

3. Estimated operating flux and recovery rates:

	UF	RO	
Design flux (operation)	63.0	11.6	LMH
Design flux (during cleaning)	68.7	15.5	LMH
Recovery	95	65	%
TMP/membrane pressure	1	63	bar
Feed flow	200	190	m3/h
Permeate flow	190	123.5	m3/h
Reject flow	10	66.5	m3/h

4. Estimated Investment cost (CAPEX +/- 30%) for complete full-scale system:
   EUR 10.35 million

5. Estimated operating cost (OPEX +/- 30%):
   Total electrical consumption per year = ~11,000 MWh/yr.
   UF electrical consumption of ~ 5.5 MWh/yr (primarily to cross-flow pumps)
   Chemical consumption:
   BollClean 1550 (acidic cleaner) every 600 operating hours: 6,000L/yr @ EUR 4/L
   BollClean 3300 (alkaline cleaner) every 600 operating hours: 6,000L/yr @ EUR 4/L
   Antiscalant dosing 5ml/m3 RO feed flow @EUR 9,000/m3
   Caustic soda (50%): 80L/yr
   Sulfuric acid (96%): 30L/yr
   Total cost of EUR 125,000 per year.
   Pressurized Air Requirements: ~5 m³/h Dry and de-oiled ISO 8573-1 Class 1

6. Guaranteed and expected lifetime of key components:
   The RO and UF membranes are considered as wear & tear items and as such have a lifetime. Therefore, giving a warranty on these membranes is not straight forward. We offer a 2-year warranty for the RO and UF membranes with a full 1 (one) year warranty and, due to their wear & tear character, the remaining 12 months warranty on a Pro Rata basis. The warranty reduction corresponds to 1/warranty time on a monthly basis. The guarantee is connected to the operation of the unit according to the respective manuals and the process water composition listed in the tender documentation. The warranty starts after first contact of the membranes with the water and at the latest 3 months after delivery.
   The expected lifetime of the RO Membranes is 3-5 years. The expected lifetime of the UF Membranes is 10 years.

7. Replacement cost of key components:
   BOLL SiC Membranes: 980 €/pcs
   RO Membranes: 980 €/pcs

8. 3 relevant references of similar application, capacity and scope can be found in Appendix 9 Reference list

9. The lower salinity at Lolland-Falster compared to Skagen will not have any impact on the UF membrane performance and system design.

   Considering the fact that the feed chloride concentration determined in the pilot study was 14,000 mg/L it can be concluded that the UF feed water had a lower salinity than expected Skagen sea water (~18,000 mg/L). We learned during the pilot that the RAS plant feed water intake (beach well) is located in a boundary zone between sea water and fresh water (ground water).
   The lower chloride and sulphate concentrations in the feed water indicate that the achieved pilot results are closer to expected operating conditions at a potential Lolland-Falster plant compared to

100% Skagen sea water.

In case of even lower salinity at Lolland-Falster – using the values in Process Specifications Table 3 and adjusting ions – a simulation case based on 21,800 mg/L TDS (Skagen was 29,000 mg/L) shows that the RO operating pressure can be reduced by ~12 bar – representing a reduced electrical energy consumption of ~600 MWh/yr.

The RO permeate quality will improve with lower feed salinity. Using the case above – the RO permeate conductivity will drop to ~250 µS/cm.

Comments to full-scale WRF CAPEX and OPEX estimates

UF:

The full-scale UF design flux is based on a short duration pilot operated at a single operating set point (TMP and cross-flow velocity). The full scale CAPEX and OPEX are very sensitive to flux, cross-flow velocity and pressure. It is foreseen that at more extensive pilot investigation (2-3 months) with attention to optimize mentioned key operating parameters and furthermore evaluate membrane cleaning schemes, will contribute to significant CAPEX and OPEX reductions (~could be up to 25%).

The material selection and engineering practice applied for the presented estimations are conservative, i.e. more solid design input generated from an extensive pilot test will reduce safety factors and thus CAPEX and OPEX.

Last, the tested tubular SiC membranes in cross-flow mode represent one system configuration. For CAPEX and OPEX reduction exercise, we recommend evaluating SiC tubular membranes operating in dead-end/semi dead-end and SiC flat sheet membranes operating in dead-end (vacuum) – both alternatives are offered by Bollfilter.

RO:

It is possible to install RO energy recovery devices (pressure exchanges RO brine pressure and feed water pressure). This could potentially reduce RO electrical consumption by 20% (according to the supplier).

Closed-circuit RO (CCRO) systems work by recirculating pressurized feedwater until a desired recovery level is reached. Brine is replaced with fresh feed without stopping the flow of pressurized feed or permeate. CCRO systems achieve recovery by recirculation, not with multiple membrane elements and stages in series.

CCRO systems will reduce brine waste up to 75% and energy consumption up to 35%, compared to traditional reverse osmosis designs (according to the supplier).

MD:

MD is a novel technology of relevance when waste heat is available in conjunction with request for ultra pure water (low conductivity). Utilizing waste heat instead of electrical energy is a more sustainable solution compared to RO.

In case the treated wastewater shall meet ultra pure water quality, MD achieves such quality in a single pass, whereas a two-stage pass is needed for RO – adding significant CAPEX and OPEX. Up to 75% OPEX reduction compared to RO is possible, while offering a higher recovery (reduced brine volume) and superior distillate water quality.

MD has not been applied for industrial (large volume) applications however expected to be available in 2-3 years.

Product Data Sheet
Reverse Osmosis Membranes

FilmTec™ Membranes

FilmTec™ Seawater RO Elements for Commercial Systems

Description

Improved FilmTec™ Seawater Reverse Osmosis Elements offer the highest productivity while maintaining excellent salt rejection.

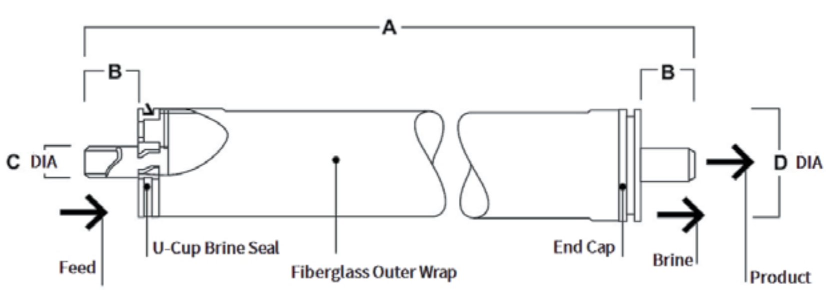
- FilmTec™ SW30 Membrane Elements have the highest flow rates available to meet the water demands of both sea-based and land-based desalinators.
- FilmTec™ SW30 Elements may also be operated at lower pressure to reduce pump size, cost and operating expenses.
- Improved FilmTec™ seawater membrane combined with automated, precision element fabrication result in the most consistent product performance available

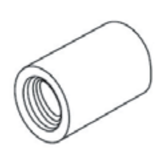
Typical Properties

Product	Part Number	Applied Pressure psig (bar)	Permeate Flow Rate gpd (m^3/d)	Stabilized Salt Rejection (%)	MinimumSalt Rejections (%)
SW30-2514	80733	800 (55)	150 (0.6)	99.4	99.4
SW30-2521	80734	800 (55)	300 (1.1)	99.4	99.4
SW30-2540	12082989	800 (55)	700 (2.6)	99.7	99.5
SW30-4021	80740	800 (55)	800 (3.0)	99.4	99.2
SW30-4040	12082966	800 (55)	1,950 (7.4)	99.7	99.5

1. Permeate flow and salt rejection based on the following test conditions: 32,000 ppm NaCl, pressure specified above, 77°F (25°C) and the following recovery rates: SW30-2514 – 2%, SW30-2521 & SW30-4021 – 5%, SW30-2540 & SW30-4040 – 8%.
2. Permeate flows for individual elements may vary +/-20%.
3. For the purpose of improvement, specifications may be updated periodically.

Element Dimensions





FilmTec™ coupler part number 89055 is ordered separately for each element. Each coupler includes two 2-210 EPR O-rings (part number 89255).

	Product	Maximum Feed Flow Rate gpm (m^3/h)	Dimensions – Inches (mm) A	B	C	1 inch = 25.4 mm D
Small commercial	SW30-2514	6 (1.4)	14.0 (356)	1.19 (30.2)	0.75 (19)	2.4 (61)
	SW30-2521	6 (1.4)	21.0 (533)	1.19 (30.2)	0.75 (19)	2.4 (61)
	SW30-4021	16 (3.6)	21.0 (533)	1.05 (26.7)	0.75 (19)	3.9 (99)
	Product	**Maximum Feed Flow Rate gpm (m^3/h)**	**Dimensions – Inches (mm) A**	**B**	**C**	**1 inch = 25.4 mm D**
Large commercial	SW30-2540	6 (1.4)	40.0 (1,016)	1.19 (30.2)	0.75 (19)	2.4 (61)
	SW30-4040	16 (3.6)	40.0 (1,016)	1.05 (26.7)	0.75 (19)	3.9 (99)

1. Refer to FilmTec™ Design Guidelines for multiple-element systems of midsize elements (Form No. 45-D01588-en).
2. SW30-2514, SW30-2521 and SW30-2540 Elements fit nominal 2.5-inch I.D. pressure vessels.
   SW30-4021 and SW30-4040 Elements fit nominal 4-inch I.D. pressure vessel.

Operating and Cleaning Limits

Membrane Type	Polyamide Thin-Film Composite
Maximum Operating Temperature	113°F (45°C)
Maximum Operating Pressure	1,200 psi (83 bar)
Maximum Pressure Drop	15 psig (1.0 bar)
pH Range Continuous Operation[a] Short-Term Cleaning[b]	 2 - 11 1 - 13
Maximum Feed Silt Density Index	SDI 5
Free Chlorine Tolerance[c]	<0.1 ppm

a. Maximum temperature for continuous operation above pH 10 is 95°F (35°C).
b. Refer to FilmTec™ Cleaning Guidelines (Form No. 45-D01696-en).
c. Under certain conditions, the presence of free chlorine and other oxidizing agents will cause premature membrane failure. Since oxidation damage is not covered under warranty DuPont Water Solutions recommends removing residual free chlorine by pretreatment prior to membrane exposure. Please refer to Dechlorinating Feedwater (Form No. 45-D01569-en) for more information.

Important Information

Proper start-up of reverse osmosis water treatment systems is essential to prepare the membranes for operating service and to prevent membrane damage due to overfeeding or hydraulic shock. Following the proper start-up sequence also helps ensure that system operating parameters conform to design specifications so that system water quality and productivity goals can be achieved.

Before initiating system start-up procedures, membrane pretreatment, loading of the membrane elements, instrument calibration and other system checks should be completed.

Please refer to the application information literature entitled Start-Up Sequence (Form No. 45-D01609-en) for more information.

Operation Guidelines

Avoid any abrupt pressure or cross-flow variations on the spiral elements during startup, shutdown, cleaning or other sequences to prevent possible membrane damage. During start-up, a gradual change from a standstill to operating state is recommended as follows:

- Feed pressure should be increased gradually over a 30-60 second time frame.
- Cross-flow velocity at set operating point should be achieved gradually over 15-20 seconds:

General Information

- Keep elements moist at all times after initial wetting.
- If operating limits and guidelines given in this bulletin are not strictly followed, the limited warranty will be null and void.
- To prevent biological growth during prolonged system shutdowns, it is recommended that membrane elements be immersed in a preservative solution.
- The customer is fully responsible for the effects of incompatible chemicals and lubricants on elements.
- Maximum pressure drop across an entire pressure vessel (housing) is 50 psi (3.4 bar).
- Avoid static permeate-side backpressure at all times.

Product Stewardship

DuPont has a fundamental concern for all who make, distribute, and use its products, and for the environment in which we live. This concern is the basis for our product stewardship philosophy by which we assess the safety, health, and environmental information on our products and then take appropriate steps to protect employee and public health and our environment. The success of our product stewardship program rests with each and every individual involved with DuPont products—from the initial concept and research, to manufacture, use, sale, disposal, and recycle of each product.

Customer Notice

DuPont strongly encourages its customers to review both their manufacturing processes and their applications of DuPont products from the standpoint of human health and environmental quality to ensure that DuPont products are not used in ways for which they are not intended or tested. DuPont personnel are available to answer your questions and to provide reasonable technical support. DuPont product literature, including safety data sheets, should be consulted prior to use of DuPont products. Current safety data sheets are available from DuPont.

Please be aware of the following:

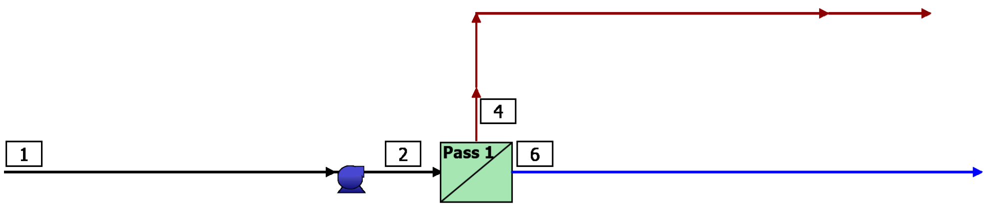
- The use of this product in and of itself does not necessarily guarantee the removal of cysts and pathogens from water. Effective cyst and pathogen reduction is dependent on the complete system design and on the operation and maintenance of the system.
- Permeate obtained from the first hour of operation should be discarded.

Have a question? Contact us at:
dupont.com/water/contact-u

Form No. 45-D01519-en, Rev. 9
May 2024

RO Summary Report

RO System Flow Diagram



#	Description	Flow (m³/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	0.58	29,516	0.0
2	Net Feed to Pass 1	0.58	29,584	51.8
4	Total Concentrate from Pass 1	0.25	68,416	51.4
6	Net Product from RO System	0.33	138.2	0.0

RO System Overview

Total # of Units	1	Online =	1	Standby =	0	RO Recovery	57.0 %
System Flow Rate	(m³/h)	Net Feed =	0.58	Net Product =	0.33		

Pass		Pass 1
Stream Name		Stream 1
Water Type		Sea Water (Conventional pretreatment,SDI<5)
Number of Elements		3
Total Active Area	(m²)	23.7
Feed Flow per Pass	(m³/h)	0.58
Feed TDS[a]	(mg/L)	29,584
Feed Pressure	(bar)	51.8
Flow Factor Per Stage		1.00
Permeate Flow per Pass	(m³/h)	0.33
Pass Average flux	(LMH)	14.0
Permeate TDS[a]	(mg/L)	138.2
Pass Recovery		56.9 %
Average NDP	(bar)	18.6
Specific Energy	(kWh/m³)	3.18
Temperature	(°C)	14.0
pH		7.0
Chemical Dose		-
RO System Recovery		57.0 %
Net RO System Recovery		57.0%

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Flow Table (Stage Level) - Pass 1

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow (m^3/h)	Recirc Flow (m^3/h)	Feed Press (bar)	Boost Press (bar)	Conc Flow (m^3/h)	Conc Press (bar)	Press Drop (bar)	Perm Flow (m^3/h)	Avg Flux (LMH)	Perm Press (bar)	Perm TDS (mg/L)
1	SW30-4040	1	3	0.58	0.00	51.5	0.0	0.25	51.4	0.1	0.33	14.0	0.0	138.1

RO Solute Concentrations - Pass 1

Concentrations (mg/L as ion)				
		Concentrate	Permeate	
	Feed	Stage1	Stage1	Total
NH_4^+	3.70	8.56	0.04	0.04
K^+	350.0	811.4	2.28	2.28
Na^+	8,550	19,832	48.63	48.63
Mg^{+2}	1,100	2,558	1.33	1.33
Ca^{+2}	350.0	813.9	0.41	0.41
Sr^{+2}	7.20	16.74	0.01	0.01
Ba^{+2}	0.01	0.02	0.00	0.00
CO_3^{-2}	20.38	131.4	0.00	0.00
HCO_3^-	2,965	6,723	6.39	6.24
NO_3^-	26.00	59.94	0.43	0.43
F^-	0.51	1.19	0.00	0.00
Cl^-	14,000	32,476	77.82	77.82
Br^{-1}	0.00	0.00	0.00	0.00
SO_4^{-2}	2,141	4,981	0.99	0.99
PO_4^{-3}	0.90	2.09	0.00	0.00
SiO_2	0.83	1.92	0.01	0.01
Boron	0.00	0.00	0.00	0.00
CO_2	195.5	244.7	204.2	204.4
TDS[a]	29,516	68,416	138.1	138.2
Cond. µS/cm	41,970	87,500	288	288
pH	7.0	7.3	5.0	5.0

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Design Warnings

Design Warning		Limit	Value	Pass	Stage	Element	Product
Concentrate Flow Rate < Minimum Limit	(m³/h)	0.91	0.39	1	1	1	SW30-4040
Concentrate Flow Rate < Minimum Limit	(m³/h)	0.91	0.29	1	1	2	SW30-4040
Concentrate Flow Rate < Minimum Limit	(m³/h)	0.91	0.25	1	1	3	SW30-4040
Element Recovery > Maximum Limit	(%)	13.0	31.9	1	1	1	SW30-4040
Element Recovery > Maximum Limit	(%)	13.0	25.6	1	1	2	SW30-4040
Element Recovery > Maximum Limit	(%)	13.0	15.3	1	1	3	SW30-4040

Special Comments

None

RO Flow Table (Element Level) - Pass 1

Stage	Element	Element Name	Recovery (%)	Feed Flow (m³/h)	Feed Press (bar)	Feed TDS (mg/L)	Conc Flow (m³/h)	Perm Flow (m³/h)	Perm Flux (LMH)	Perm TDS (mg/L)
1	1	SW30-4040	31.9	0.58	51.5	29,583	0.39	0.18	23.4	67.86
1	2	SW30-4040	25.6	0.39	51.5	43,317	0.29	0.10	12.8	154.1
1	3	SW30-4040	15.3	0.29	51.5	58,076	0.25	0.04	5.7	392.3

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Solubility Warnings

Warning	Pass No
Stiff & Davis Stability Index > 0	1
Anti-scalants may be required. Consult your anti-scalant manufacturer for dosing and maximum allowable system recovery.	1

RO Chemical Adjustments

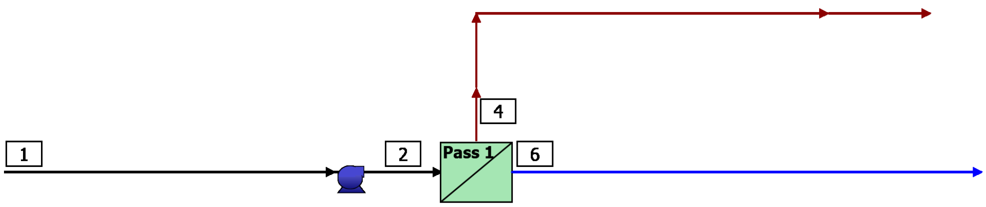
	Pass 1 Feed	RO 1st Pass Conc
pH	7.0	7.3
Langelier Saturation Index	1.1	2.08
Stiff & Davis Stability Index	0.20	1.05
TDS[a] (mg/l)	29,516	68,416
Ionic Strength (molal)	0.57	1.35
HCO_3^- (mg/L)	2,965	6,723
CO_2 (mg/l)	195.5	244.6
CO_3^{-2} (mg/L)	20.38	131.4
$CaSO_4$ (% saturation)	17.3	48.4
$BaSO_4$ (% saturation)	31.6	81.9
$SrSO_4$ (% saturation)	12.7	39.7
CaF_2 (% saturation)	2.2	22.1
SiO_2 (% saturation)	0.80	3.4
$Mg(OH)_2$ (% saturation)	0.00	0.01

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Summary Report

RO System Flow Diagram



#	Description	Flow (m³/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	0.58	29,516	0.0
2	Net Feed to Pass 1	0.58	29,598	62.7
4	Total Concentrate from Pass 1	0.20	83,931	62.3
6	Net Product from RO System	0.38	144.1	0.0

RO System Overview

Total # of Units	1	Online =	1	Standby =	0	RO Recovery	65.0 %
System Flow Rate	(m³/h)	Net Feed =	0.58	Net Product =	0.38		

Pass		Pass 1
Stream Name		Stream 1
Water Type		Sea Water (Conventional pretreatment,SDI<5)
Number of Elements		3
Total Active Area	(m^2)	23.7
Feed Flow per Pass	(m^3/h)	0.58
Feed TDS[a]	(mg/L)	29,598
Feed Pressure	(bar)	62.7
Flow Factor Per Stage		1.00
Permeate Flow per Pass	(m^3/h)	0.38
Pass Average flux	(LMH)	15.9
Permeate TDS[a]	(mg/L)	144.1
Pass Recovery		65.5 %
Average NDP	(bar)	23.5
Specific Energy	(kWh/m^3)	3.34
Temperature	(°C)	14.0
pH		7.0
Chemical Dose		-
RO System Recovery		65.0 %
Net RO System Recovery		65.0%

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Flow Table (Stage Level) - Pass 1

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow (m^3/h)	Recirc Flow (m^3/h)	Feed Press (bar)	Boost Press (bar)	Conc Flow (m^3/h)	Conc Press (bar)	Press Drop (bar)	Perm Flow (m^3/h)	Avg Flux (LMH)	Perm Press (bar)	Perm TDS (mg/L)
1	SW30-4040	1	3	0.58	0.00	62.4	0.0	0.20	62.3	0.1	0.38	15.9	0.0	144.0

RO Solute Concentrations - Pass 1

Concentrations (mg/L as ion)				
		Concentrate	Permeate	
	Feed	Stage1	Stage1	Total
NH_4^+	3.70	10.50	0.04	0.04
K^+	350.0	995.7	2.36	2.36
Na^+	8,550	24,336	50.70	50.70
Mg^{+2}	1,100	3,140	1.41	1.41
Ca^{+2}	350.0	999.2	0.43	0.43
Sr^{+2}	7.20	20.56	0.01	0.01
Ba^{+2}	0.01	0.03	0.00	0.00
CO_3^{-2}	20.38	191.4	0.00	0.00
HCO_3^-	2,965	8,191	6.70	6.49
NO_3^-	26.00	73.46	0.44	0.44
F^-	0.51	1.46	0.00	0.00
Cl^-	14,000	39,851	81.13	81.13
Br^{-1}	0.00	0.00	0.00	0.00
SO_4^{-2}	2,141	6,115	1.05	1.05
PO_4^{-3}	0.90	2.57	0.00	0.00
SiO_2	0.83	2.35	0.01	0.01
Boron	0.00	0.00	0.00	0.00
CO_2	195.5	269.9	207.3	207.4
TDS[a]	29,516	83,931	144.0	144.1
Cond. µS/cm	41,970	104,382	300	300
pH	7.0	7.5	5.1	5.1

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Design Warnings

Design Warning		Limit	Value	Pass	Stage	Element	Product
Concentrate Flow Rate < Minimum Limit	(m^3/h)	0.91	0.35	1	1	1	SW30-4040
Concentrate Flow Rate < Minimum Limit	(m^3/h)	0.91	0.24	1	1	2	SW30-4040
Concentrate Flow Rate < Minimum Limit	(m^3/h)	0.91	0.20	1	1	3	SW30-4040
Element Recovery > Maximum Limit	(%)	13.0	39.3	1	1	1	SW30-4040
Element Recovery > Maximum Limit	(%)	13.0	31.4	1	1	2	SW30-4040
Element Recovery > Maximum Limit	(%)	13.0	16.2	1	1	3	SW30-4040

Special Comments

None

RO Flow Table (Element Level) - Pass 1

Stage	Element	Element Name	Recovery (%)	Feed Flow (m^3/h)	Feed Press (bar)	Feed TDS (mg/L)	Conc Flow (m^3/h)	Perm Flow (m^3/h)	Perm Flux (LMH)	Perm TDS (mg/L)
1	1	SW30-4040	39.3	0.58	62.4	29,597	0.35	0.23	28.8	62.71
1	2	SW30-4040	31.4	0.35	62.3	48,586	0.24	0.11	14.0	169.6
1	3	SW30-4040	16.2	0.24	62.3	70,532	0.20	0.04	5.0	546.8

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Solubility Warnings

Warning	Pass No
Stiff & Davis Stability Index > 0	1
$BaSO_4$ (% saturation) > 100	1
Anti-scalants may be required. Consult your anti-scalant manufacturer for dosing and maximum allowable system recovery.	1

RO Chemical Adjustments

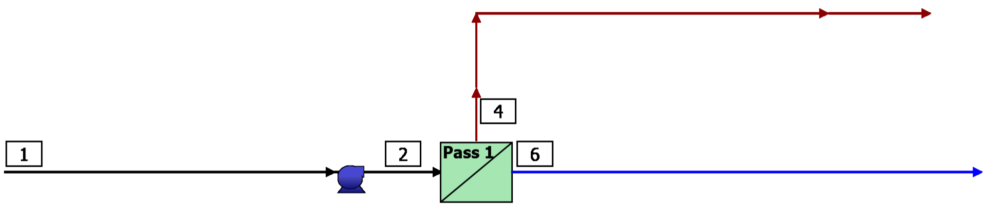
	Pass 1 Feed	RO 1st Pass Conc
pH	7.0	7.5
Langelier Saturation Index	1.1	2.40
Stiff & Davis Stability Index	0.20	1.39
TDS[a] (mg/l)	29,516	83,931
Ionic Strength (molal)	0.57	1.66
HCO_3^- (mg/L)	2,965	8,191
CO_2 (mg/l)	195.5	270.0
CO_3^{-2} (mg/L)	20.38	191.4
$CaSO_4$ (% saturation)	17.3	63.7
$BaSO_4$ (% saturation)	31.6	104.8
$SrSO_4$ (% saturation)	12.7	56.8
CaF_2 (% saturation)	2.2	38.6
SiO_2 (% saturation)	0.80	4.5
$Mg(OH)_2$ (% saturation)	0.00	0.03

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Summary Report

RO System Flow Diagram



#	Description	Flow (m^3/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	0.58	29,516	0.0
2	Net Feed to Pass 1	0.58	29,620	80.5
4	Total Concentrate from Pass 1	0.16	108,511	80.2
6	Net Product from RO System	0.42	160.9	0.0

RO System Overview

Total # of Units	1	Online =	1	Standby =	0	RO Recovery	73.0 %
System Flow Rate	(m^3/h)	Net Feed =	0.58	Net Product =	0.42		

Pass		Pass 1
Stream Name		Stream 1
Water Type		Sea Water (Conventional pretreatment,SDI<5)
Number of Elements		3
Total Active Area	(m^2)	23.7
Feed Flow per Pass	(m^3/h)	0.58
Feed TDS[a]	(mg/L)	29,620
Feed Pressure	(bar)	80.5
Flow Factor Per Stage		1.00
Permeate Flow per Pass	(m^3/h)	0.42
Pass Average flux	(LMH)	17.9
Permeate TDS[a]	(mg/L)	160.9
Pass Recovery		72.4 %
Average NDP	(bar)	30.6
Specific Energy	(kWh/m^3)	3.88
Temperature	(°C)	14.0
pH		7.0
Chemical Dose		-
RO System Recovery		73.0 %
Net RO System Recovery		73.0%

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Flow Table (Stage Level) - Pass 1

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow (m³/h)	Recirc Flow (m³/h)	Feed Press (bar)	Boost Press (bar)	Conc Flow (m³/h)	Conc Press (bar)	Press Drop (bar)	Perm Flow (m³/h)	Avg Flux (LMH)	Perm Press (bar)	Perm TDS (mg/L)
1	SW30-4040	1	3	0.58	0.00	80.2	0.0	0.16	80.2	0.1	0.42	17.9	0.0	160.9

RO Solute Concentrations - Pass 1

Concentrations (mg/L as ion)				
		Concentrate	Permeate	
	Feed	Stage1	Stage1	Total
NH_4^+	3.70	13.56	0.04	0.04
K^+	350.0	1,287	2.62	2.62
Na^+	8,550	31,470	56.66	56.66
Mg^{+2}	1,100	4,064	1.59	1.59
Ca^{+2}	350.0	1,293	0.49	0.49
Sr^{+2}	7.20	26.60	0.01	0.01
Ba^{+2}	0.01	0.03	0.00	0.00
CO_3^{-2}	20.38	292.9	0.00	0.00
HCO_3^-	2,965	10,508	7.43	7.12
NO_3^-	26.00	94.83	0.50	0.50
F^-	0.51	1.88	0.00	0.00
Cl^-	14,000	51,536	90.67	90.67
Br^{-1}	0.00	0.00	0.00	0.00
SO_4^{-2}	2,141	7,916	1.19	1.19
PO_4^{-3}	0.90	3.32	0.00	0.00
SiO_2	0.83	3.04	0.01	0.01
Boron	0.00	0.00	0.00	0.00
CO_2	195.5	311.0	211.0	211.2
TDS[a]	29,516	108,511	160.9	160.9
Cond. µS/cm	41,970	130,097	334	334
pH	7.0	7.8	5.3	5.3

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Design Warnings

Design Warning		Limit	Value	Pass	Stage	Element	Product
Permeate Flow Rate > Maximum Limit	(m³/h)	0.24	0.28	1	1	1	SW30-4040
Concentrate Flow Rate < Minimum Limit	(m³/h)	0.91	0.30	1	1	1	SW30-4040
Concentrate Flow Rate < Minimum Limit	(m³/h)	0.91	0.18	1	1	2	SW30-4040
Concentrate Flow Rate < Minimum Limit	(m³/h)	0.91	0.16	1	1	3	SW30-4040
Feed Pressure > Maximum Limit	(bar)	69.0	80.2	1	1	1	SW30-4040
Element Recovery > Maximum Limit	(%)	13.0	49.0	1	1	1	SW30-4040
Element Recovery > Maximum Limit	(%)	13.0	38.3	1	1	2	SW30-4040
Element Recovery > Maximum Limit	(%)	13.0	14.6	1	1	3	SW30-4040

Special Comments

None

RO Flow Table (Element Level) - Pass 1

Stage	Element	Element Name	Recovery (%)	Feed Flow (m^3/h)	Feed Press (bar)	Feed TDS (mg/L)	Conc Flow (m^3/h)	Perm Flow (m^3/h)	Perm Flux (LMH)	Perm TDS (mg/L)
1	1	SW30-4040	49.0	0.58	80.2	29,620	0.30	0.28	35.8	60.10
1	2	SW30-4040	38.3	0.30	80.2	57,685	0.18	0.11	14.4	211.3
1	3	SW30-4040	14.6	0.18	80.2	92,941	0.16	0.03	3.4	1,017

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Solubility Warnings

Warning	Pass No
Stiff & Davis Stability Index > 0	1
$BaSO_4$ (% saturation) > 100	1
$SrSO_4$ (% saturation) > 100	1
Anti-scalants may be required. Consult your anti-scalant manufacturer for dosing and maximum allowable system recovery.	1

RO Chemical Adjustments

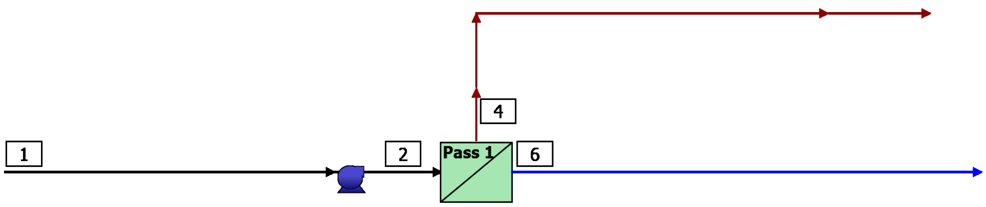
	Pass 1 Feed	RO 1st Pass Conc
pH	7.0	7.8
Langelier Saturation Index	1.1	2.92
Stiff & Davis Stability Index	0.20	1.95
TDS[a] (mg/l)	29,516	108,511
Ionic Strength (molal)	0.57	2.18
HCO_3^- (mg/L)	2,965	10,508
CO_2 (mg/l)	195.5	311.0
CO_3^{-2} (mg/L)	20.38	292.9
$CaSO_4$ (% saturation)	17.3	93.0
$BaSO_4$ (% saturation)	31.6	145.5
$SrSO_4$ (% saturation)	12.7	100.6
CaF_2 (% saturation)	2.2	78.0
SiO_2 (% saturation)	0.80	6.6
$Mg(OH)_2$ (% saturation)	0.00	0.14

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Summary Report

RO System Flow Diagram



#	Description	Flow (m^3/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	0.58	22,456	0.0
2	Net Feed to Pass 1	0.58	22,505	48.1
4	Total Concentrate from Pass 1	0.20	63,864	47.8
6	Net Product from RO System	0.38	107.1	0.0

RO System Overview

Total # of Units	1	Online =	1	Standby =	0	RO Recovery	65.0 %
System Flow Rate	(m^3/h)	Net Feed =	0.58	Net Product =	0.38		

Pass		Pass 1
Stream Name		Stream 1
Water Type		Sea Water (Conventional pretreatment,SDI<5)
Number of Elements		3
Total Active Area	(m^2)	23.7
Feed Flow per Pass	(m^3/h)	0.58
Feed TDS[a]	(mg/L)	22,505
Feed Pressure	(bar)	48.1
Flow Factor Per Stage		1.00
Permeate Flow per Pass	(m^3/h)	0.38
Pass Average flux	(LMH)	15.9
Permeate TDS[a]	(mg/L)	107.1
Pass Recovery		65.5 %
Average NDP	(bar)	19.7
Specific Energy	(kWh/m^3)	2.55
Temperature	(°C)	14.0
pH		7.0
Chemical Dose		-
RO System Recovery		65.0 %
Net RO System Recovery		65.0%

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Flow Table (Stage Level) - Pass 1

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow (m^3/h)	Recirc Flow (m^3/h)	Feed Press (bar)	Boost Press (bar)	Conc Flow (m^3/h)	Conc Press (bar)	Press Drop (bar)	Perm Flow (m^3/h)	Avg Flux (LMH)	Perm Press (bar)	Perm TDS (mg/L)
1	SW30-4040	1	3	0.58	0.00	47.8	0.0	0.20	47.8	0.1	0.38	15.9	0.0	107.1

RO Solute Concentrations - Pass 1

Concentrations (mg/L as ion)				
		Concentrate	Permeate	
	Feed	Stage1	Stage1	Total
NH_4^+	2.70	7.67	0.03	0.03
K^+	255.5	727.2	1.68	1.68
Na^+	6,450	18,366	37.40	37.40
Mg^{+2}	803.0	2,293	1.03	1.03
Ca^{+2}	285.0	813.9	0.35	0.35
Sr^{+2}	5.26	15.02	0.01	0.01
Ba^{+2}	0.00	0.01	0.00	0.00
CO_3^{-2}	14.46	161.3	0.00	0.00
HCO_3^-	2,940	8,148	6.57	6.38
NO_3^-	19.00	53.72	0.32	0.32
F^-	0.33	0.94	0.00	0.00
Cl^-	10,220	29,101	59.20	59.20
Br^{-1}	0.00	0.00	0.00	0.00
SO_4^{-2}	1,460	4,172	0.70	0.70
PO_4^{-3}	0.70	2.00	0.00	0.00
SiO_2	0.83	2.35	0.01	0.01
Boron	0.00	0.00	0.00	0.00
CO_2	215.1	282.2	225.6	225.7
TDS[a]	22,456	63,864	107.1	107.1
Cond. µS/cm	32,335	80,942	224	224
pH	7.0	7.3	5.0	5.0

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Design Warnings

Design Warning		Limit	Value	Pass	Stage	Element	Product
Concentrate Flow Rate < Minimum Limit	(m^3/h)	0.91	0.37	1	1	1	SW30-4040
Concentrate Flow Rate < Minimum Limit	(m^3/h)	0.91	0.25	1	1	2	SW30-4040
Concentrate Flow Rate < Minimum Limit	(m^3/h)	0.91	0.20	1	1	3	SW30-4040
Element Recovery > Maximum Limit	(%)	13.0	36.4	1	1	1	SW30-4040
Element Recovery > Maximum Limit	(%)	13.0	31.9	1	1	2	SW30-4040
Element Recovery > Maximum Limit	(%)	13.0	19.4	1	1	3	SW30-4040

Special Comments

None

RO Flow Table (Element Level) - Pass 1

Stage	Element	Element Name	Recovery (%)	Feed Flow (m^3/h)	Feed Press (bar)	Feed TDS (mg/L)	Conc Flow (m^3/h)	Perm Flow (m^3/h)	Perm Flux (LMH)	Perm TDS (mg/L)
1	1	SW30-4040	36.4	0.58	47.8	22,505	0.37	0.21	26.7	49.26
1	2	SW30-4040	31.9	0.37	47.8	35,287	0.25	0.12	14.9	117.4
1	3	SW30-4040	19.4	0.25	47.8	51,612	0.20	0.05	6.2	333.9

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Solubility Warnings

Warning	Pass No
Stiff & Davis Stability Index > 0	1
Anti-scalants may be required. Consult your anti-scalant manufacturer for dosing and maximum allowable system recovery.	1

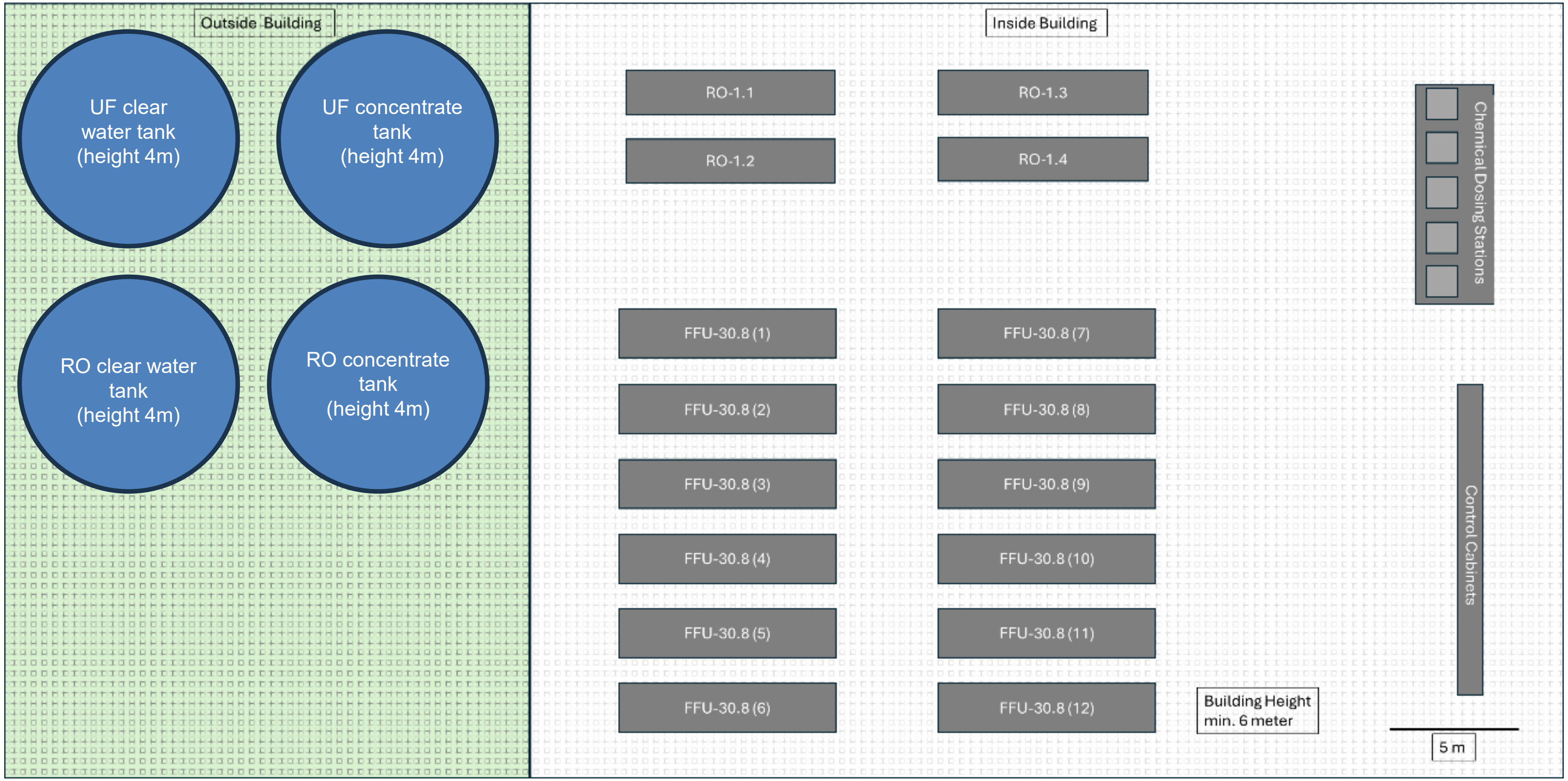
RO Chemical Adjustments

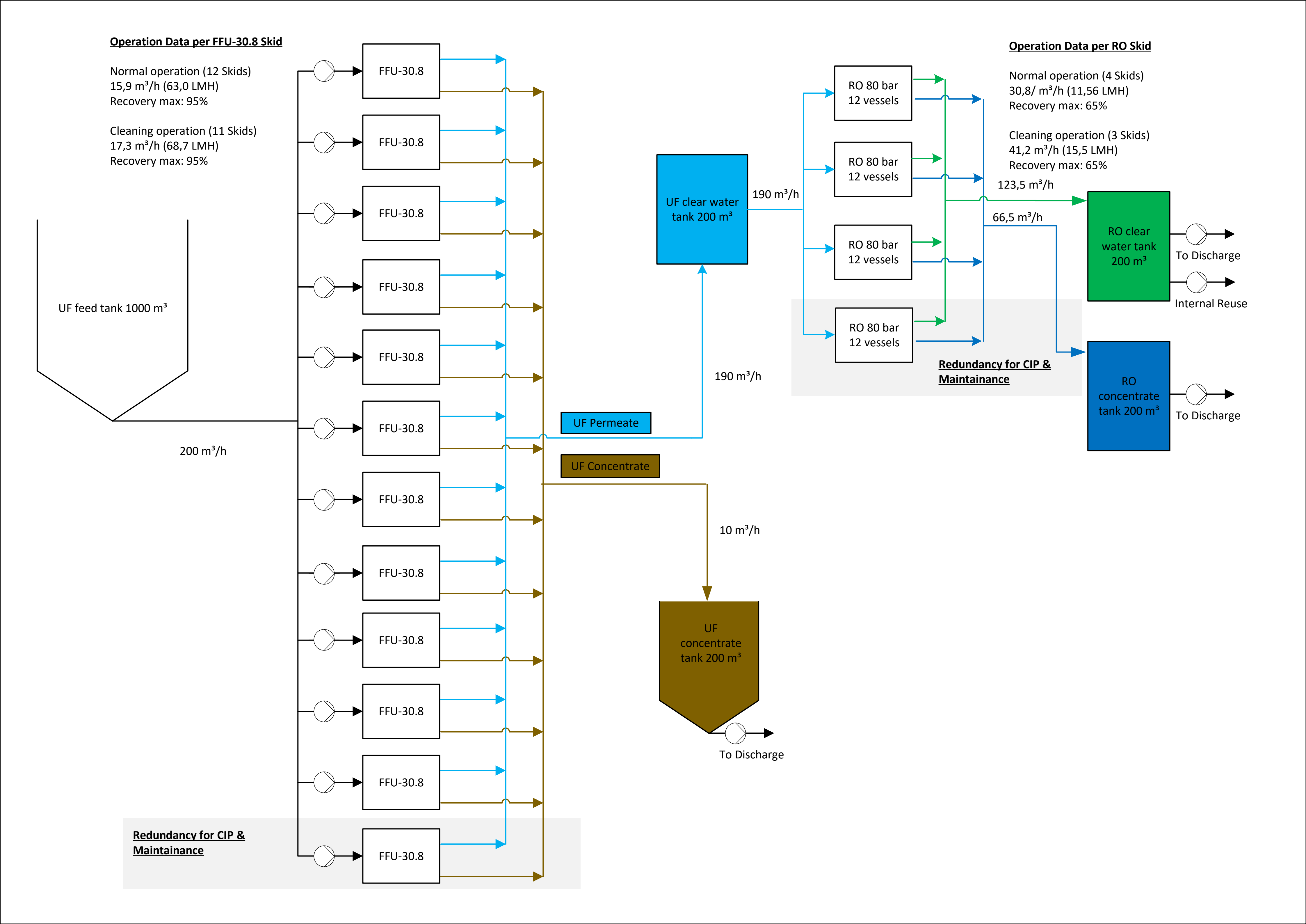
	Pass 1 Feed	RO 1st Pass Conc
pH	7.0	7.3
Langelier Saturation Index	0.98	2.16
Stiff & Davis Stability Index	0.24	1.12
TDS[a] (mg/l)	22,456	63,864
Ionic Strength (molal)	0.43	1.23
HCO_3^- (mg/L)	2,940	8,148
CO_2 (mg/l)	215.2	282.2
CO_3^{-2} (mg/L)	14.46	161.3
$CaSO_4$ (% saturation)	12.3	43.0
$BaSO_4$ (% saturation)	9.4	30.1
$SrSO_4$ (% saturation)	8.0	30.9
CaF_2 (% saturation)	0.84	14.3
SiO_2 (% saturation)	0.80	4.1
$Mg(OH)_2$ (% saturation)	0.00	0.01

Footnotes:

[a]Total Dissolved Solids and Conductivity includes ions, SiO_2 and B. It does not include NH_3 and CO_2

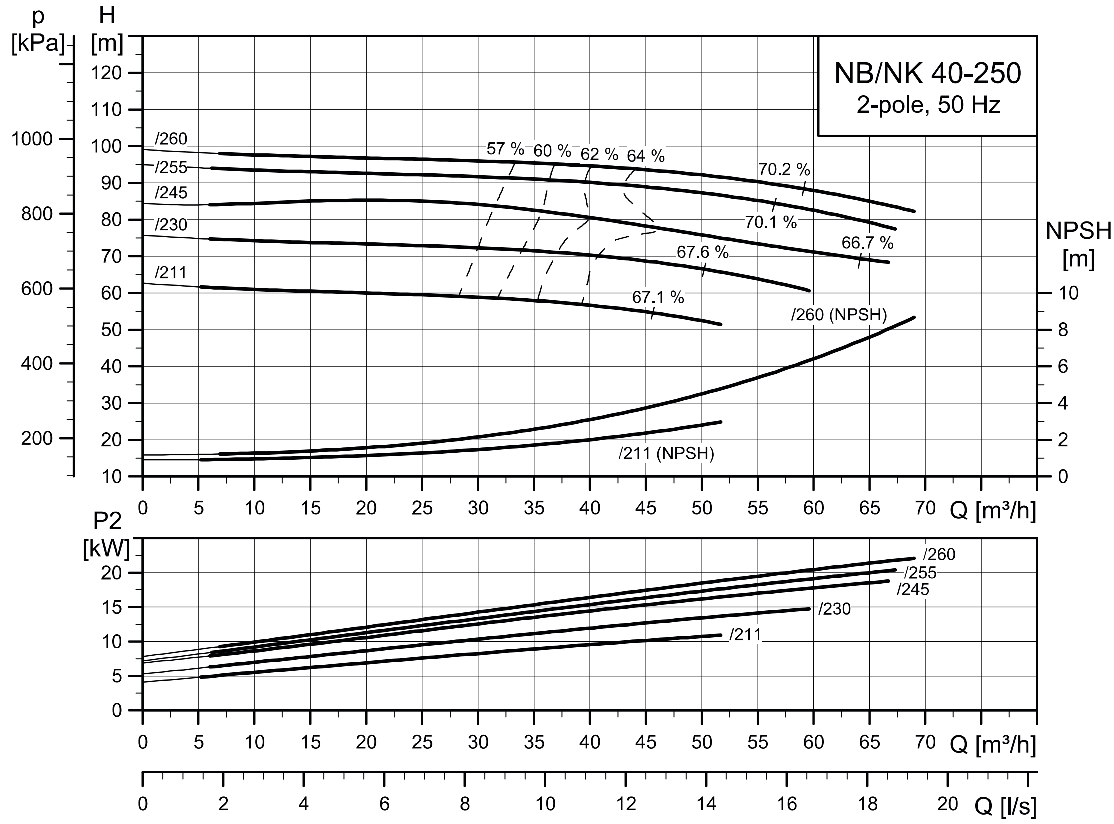
Basic lay-out drawings and area footprint TETRAS



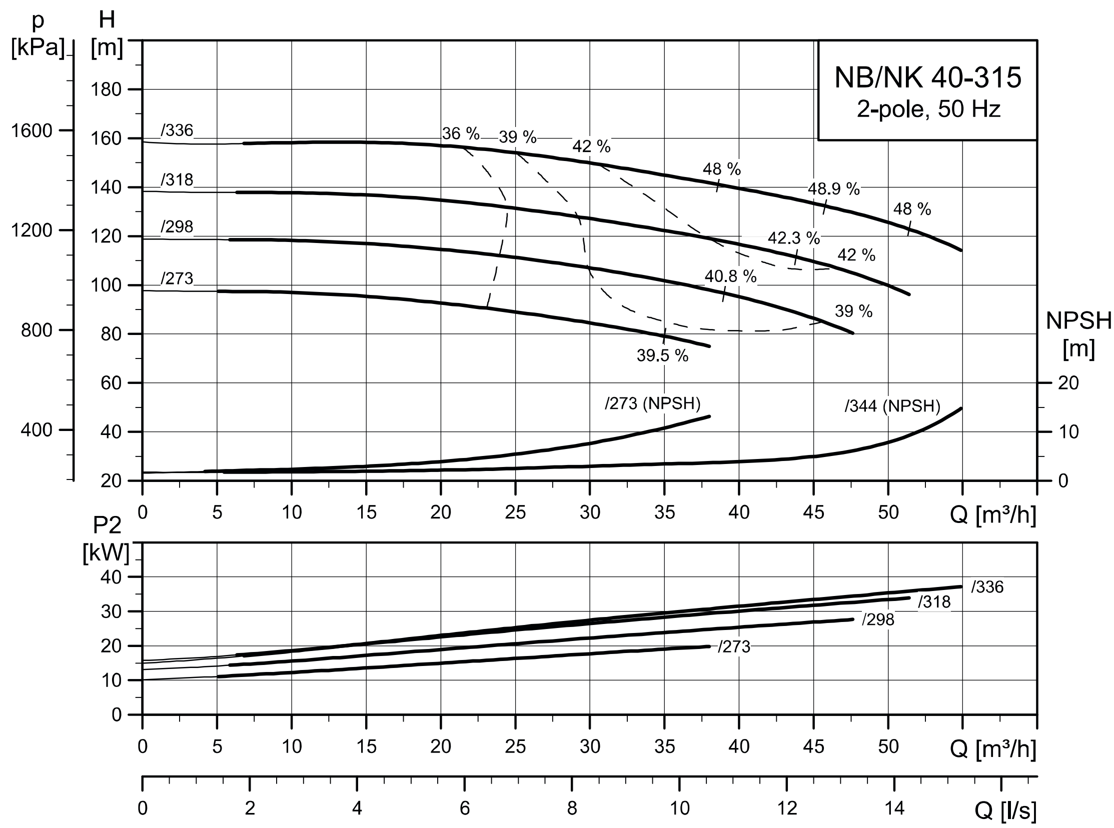


Operation Data per FFU-30.8 Skid
Normal operation (12 Skids)
15,9 m³/h (63,0 LMH)
Recovery max: 95%
Cleaning operation (11 Skids)
17,3 m³/h (68,7 LMH)
Recovery max: 95%
UF feed tank 1000 m³
200 m³/h
FFU-30.8
Redundancy for CIP & Maintainance
UF Permeate
UF Concentrate
190 m³/h
10 m³/h
UF concentrate tank 200 m³
To Discharge
UF clear water tank 200 m³
190 m³/h
RO 80 bar 12 vessels
Operation Data per RO Skid
Normal operation (4 Skids)
30,8/ m³/h (11,56 LMH)
Recovery max: 65%
Cleaning operation (3 Skids)
41,2 m³/h (15,5 LMH)
Recovery max: 65%
123,5 m³/h
66,5 m³/h
RO clear water tank 200 m³
To Discharge
Internal Reuse
Redundancy for CIP & Maintainance
RO concentrate tank 200 m³
To Discharge

NB, NK 40-250



NB, NK 40-315

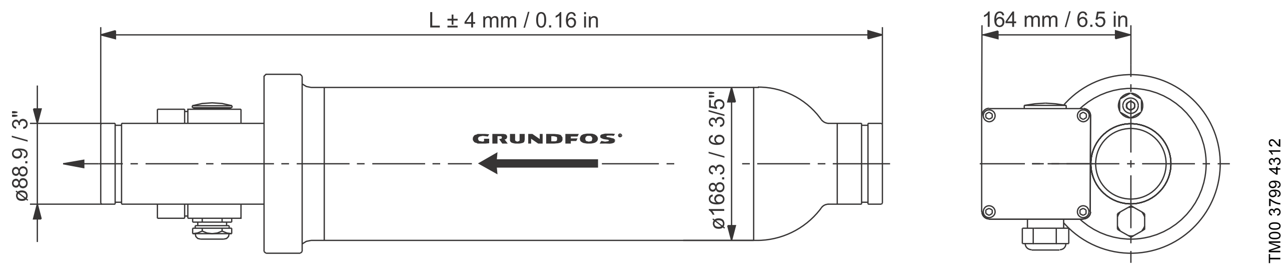


BM 6" (with straight pipe)

Type	Motor output [P2]		Rated current	Length [L]		Product number				Weight [kg]		Ship. vol.
	[kW]	[hp]	I_N [A]	[mm]	[in]	1.4301	N version	NE version	R version	Net	Gross	[m^3]
BM 17-3	3.0	4.0	7.40 - 7.75	1550	61.0	98490818	12 DJ 36 03	12 DH 36 03	12 DU 36 03	48.0	69.0	0.273
BM 17-4	4.0	5.5	9.45 - 9.45	1550	61.0	98490819	12DJ3604	12DH3604	12DU3604	53.0	76.0	0.273
BM 17-6	5.5	7.5	12.8 - 12.8	1850	72.8	98490820	12DJ3606	12DH3606	12DU3606	63.0	90.0	0.320
BM 17-8	7.5	10	17.4 - 17.0	1850	72.8	98490821	12DJ3608	12DH3608	12DU3608	79.0	113.0	0.320
BM 17-10	9.2	12.5	21.80 - 21.0	2100	82.7	98490822	12DJ3610	12DH3610	12DU3610	91.0	129.0	0.356
BM 17-12	11	15	25.5 - 24.0	2200	86.6	98490823	12DJ3612	12DH3612	12DU3612	97.0	138.0	0.374
BM 17-15	13	17.5	29.5 - 28.5	2500	98.4	98490824	12DJ3615	12DH3615	12DU3615	109.0	155.0	0.421
BM 17-17	15	20	33.5 - 32.5	2500	98.4	98490825	12DJ3617	12DH3617	12DU3617	115.0	163.0	0.421
BM 17-21	18.5	25	42.0 - 41.0	2850	112.2	98490826	12DJ3621	12DH3621	12DU3621	131.0	185.0	0.476
BM 17-25	22	30	48.0 - 46.5	3200	126.0	98490827	12DJ3625	12DH3625	12DU3625	147.0	208.0	0.530
BM 17-30	26	35	57.5 - 54.5	3800	149.6	98490828	12DJ3630	12DH3630	12DU3630	167.0	236.0	0.624
BM 30-2	3.0	4.0	7.40 - 7.75	1550	61.0	98490829	13DJ3602	13DH3602	13DU3602	47.0	68.0	0.273
BM 30-3	4.0	5.5	9.45 - 9.45	1650	65.0	98490830	13DJ3603	13DH3603	13DU3603	54.0	78.0	0.289
BM 30-4	5.5	7.5	12.8 - 12.8	1850	72.8	98490831	13DJ3604	13DH3604	13DU3604	64.0	92.0	0.320
BM 30-5	7.5	10	17.4 - 17.0	1850	72.8	98490832	13DJ3605	13DH3605	13DU3605	78.0	111.0	0.320
BM 30-7	9.2	12.5	21.8 - 21.0	2100	82.7	98490833	13DJ3607	13DH3607	13DU3607	91.0	129.0	0.356
BM 30-8	11	15	25.5 - 24.0	2200	86.6	98490834	13DJ3608	13DH3608	13DU3608	96.0	136.0	0.374
BM 30-10	13	17.5	29.5 - 28.5	2500	98.4	98490835	13DJ3610	13DH3610	13DU3610	108.0	153.0	0.421
BM 30-11	15	20	33.5 - 32.5	2500	98.4	98490836	13DJ3611	13DH3611	13DU3611	113.0	160.0	0.421
BM 30-14	18.5	25	42.0 - 41.0	2850	112.2	98490837	13DJ3614	13DH3614	13DU3614	129.0	183.0	0.476
BM 30-17	22	30	48.0 - 46.5	3200	126.0	98490838	13DJ3617	13DH3617	13DU3617	145.0	205.0	0.530
BM 30-20	26	35	57.5 - 54.5	3800	149.6	98490839	13DJ3620	13DH3620	13DU3620	165.0	233.0	0.624
BM 30-23	30	40	66.5 - 63.0	4250	167.3	98490840	13DJ3623	13DH3623	13DU3623	185.0	261.0	0.694
BM 46-2	5.5	7.5	12.8 - 12.8	1650	65.0	98490841	15E03602	15E13602	15E63602	59.0	85.0	0.289
BM 46-3	7.5	10	17.4 - 17.0	1750	68.9	98490842	15E03603	15E13603	15E63603	75.0	107.0	0.304
BM 46-4	9.2	12.5	21.8 - 21.0	1850	72.8	98490843	15E03604	15E13604	15E63604	85.0	121.0	0.320
BM 46-5	13	17.5	29.5 - 28.5	2100	82.7	98490844	15E03605	15E13605	15E63605	98.0	139.0	0.356
BM 46-6	15	20	33.5 - 32.5	2200	86.6	98490845	15E03606	15E13606	15E63606	105.0	149.0	0.374
BM 46-8	18.5	25	42.0 - 41.0	2500	98.4	98490846	15E03608	15E13608	15E63608	121.0	171.0	0.421
BM 46-9	22	30	48.0 - 46.5	2700	106.3	98490847	15E03609	15E13609	15E63609	132.0	187.0	0.452
BM 46-11	26	35	57.5 - 54.5	3050	120.0	98490848	15E03611	15E13611	15E63611	148.0	209.0	0.507
BM 46-13	30	40	66.5 - 63.0	3200	126.0	98490849	15E03613	15E13613	15E63613	163.0	230.0	0.530
BM 60-5	15	20	33.5 - 32.5	2100	82.7	98490850	14DE3605	14DJ3605	14E63605	102.0	145.0	0.356
BM 60-6	18.5	25	42.0 - 41.0	2200	86.6	98490851	14DE3606	14DJ3606	14E63606	111.0	157.0	0.374
BM 60-8	22	30	48.0 - 46.5	2500	98.4	98490852	14DE3608	14DJ3608	14E63608	127.0	180.0	0.421
BM 60-9	26	35	57.5 - 54.5	2700	106.3	98490853	14DE3609	14DJ3609	14E63609	138.0	195.0	0.452
BM 60-10	30	40	66.5 - 63.0	2850	112.2	98490854	14DE3610	14DJ3610	14E63610	150.0	212.0	0.476

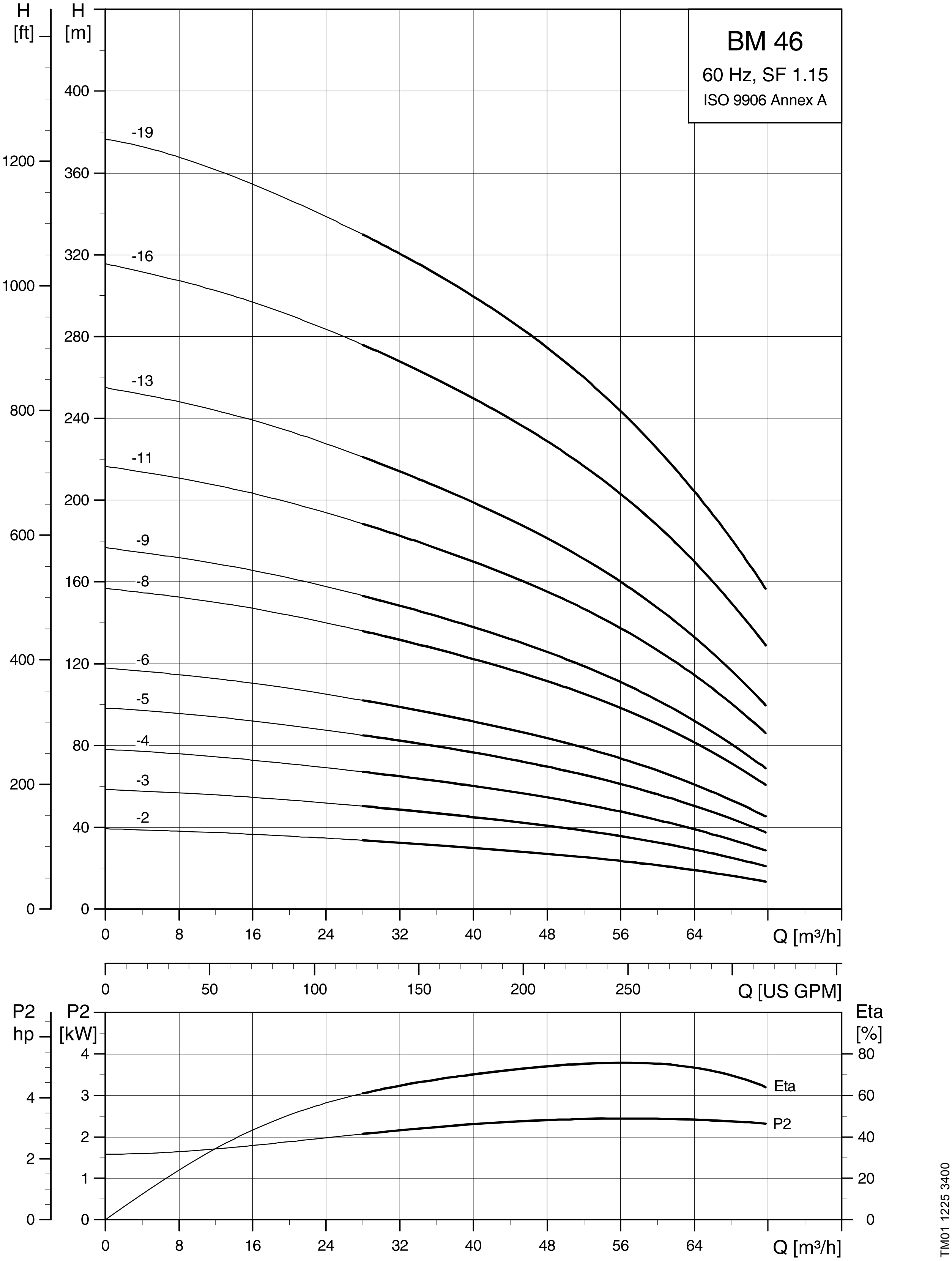
On request, the BM is available in other voltages and with all stages indicated in the standard SP pump range.

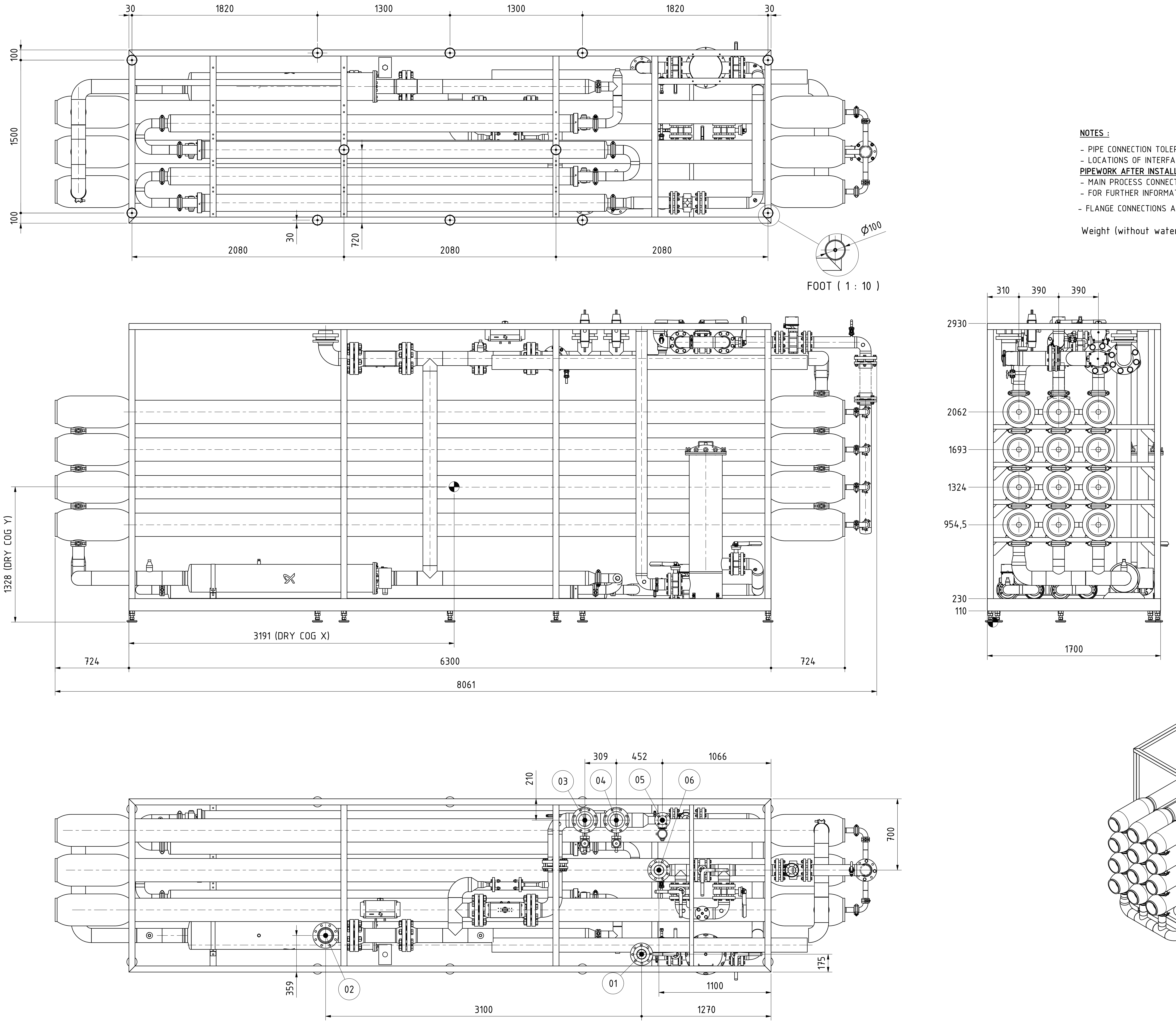
Dimensional sketch



One set of connecting fittings is required for each system. See section *13. Accessories*, page 71.

BM 46


BM 46
60 Hz, SF 1.15
ISO 9906 Annex A
H [ft]
H [m]
-19
-16
-13
-11
-9
-8
-6
-5
-4
-3
-2
Q [m³/h]
Q [US GPM]
P2 hp
P2 [kW]
Eta [%]
Eta
P2
TM01 1225 3400



CONNECTIONS		
REF.	DESCRIPTION	SIZE
01	FEED INLET	DN 100
02	CIP INLET	DN 125
03	TO CIP TANK 1	DN 125
04	TO SUMP PUMP	DN 125
05	TO CONCENTRATE TANK	DN 40
06	TO RO2 FEED	DN 100

NOTES :

- PIPE CONNECTION TOLERANCES AT BOUNDARY LIMITS ±10mm
- LOCATIONS OF INTERFACE CONNECTIONS SHOWN ARE APPROXIMATE, INSTALLER SHOULD MAKE INTERFACING PIPEWORK AFTER INSTALLATION.
- MAIN PROCESS CONNECTION REFERENCES ARE INDICATED BY A BALLOON, SEE TABLE.
- FOR FURTHER INFORMATION SEE RELEVANT ELECTRICAL AND PNEUMATIC DIAGRAMS SUPPLIED SEPARATELY
- FLANGE CONNECTIONS ACCORDING TO ISO 7005-1 / EN 1092-1

Weight (without water)≃ 5 t. ± 0.5 t.

PRELIMINARY DRAWING : DIMENSIONS ARE PROVISIONAL AND MIGHT BE SUBJECT TO CHANGE

REV.	DESCRIPTION	DRAWN	CHECKED	DATE
0	FIRST ISSUE	GP	GP	12/04/2014

Alle Maßangaben in Millimeter / dimensions are in millimeters
Änderungen nur über CAD zulässig! / modification only with CAD!
Tolerierung ISO 8015 / toleration ISO 8015
Schutzvermerk ISO 16016 beachten / refer to protection notice ISO 16016
Projektionsmethode 1 / projection method 1 / DIN ISO 5456-2
Werkstückkanten nach / corners per DIN EN ISO 13715 -0,5 +0,5
Oberflächen / surfaces ISO1302 Rauheitsgr. RZ / roughn. par. RZ ISO 4287
Allgemeintoleranzen / general tolerances DIN ISO 2768-mK Schweisskonstruktionen / welded constructions EN ISO 13920-CF
Werkstoff / material
Maßstab / scale
Benennung / title: R01

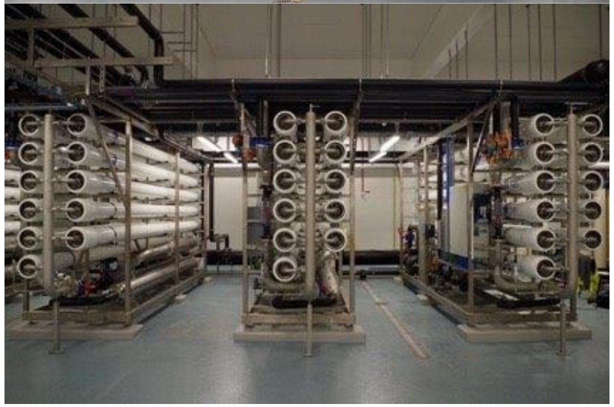
BOLLFILTER Protection Systems
Boll & Kirch Filterbau GmbH
Siemensstraße 10-14, 50170 Kerpen

	Datum / date	Name / name
Erstellt / created	12/04/24	GP
Geändert / changed		
Genehmigt / approved	12/04/24	GP
Freigegeben / released		

Ursprung: / origin:
Ersetzt durch: / substitute:
Zeichnung-Nr. / drawing-no.: CU0616_R01
Zust. / index: 0
Blatt / sheet: 1/1
09 Zeichnungsvorlage / drawing template
Letzter Änderungsgrund / last reason for change:

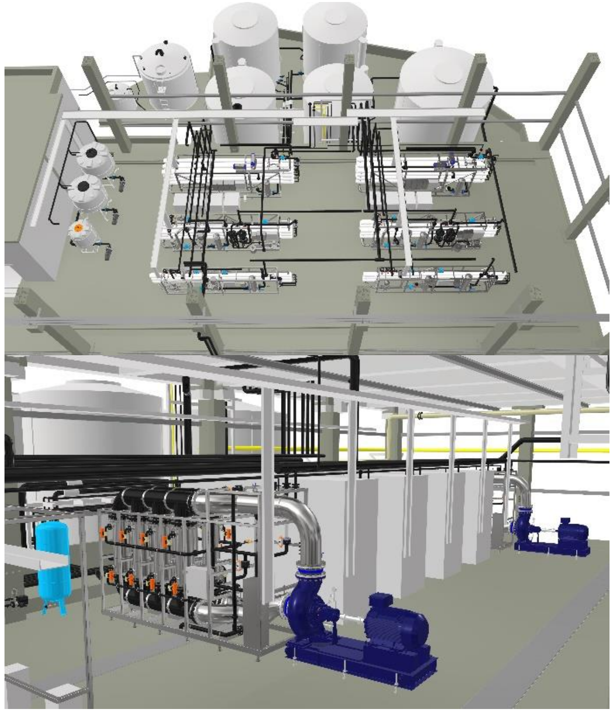
BOLL & KIRCH Inventor A1

BOLLFILTER Protection Systems

Project Location	Year	Scope	Capacity	Description
Schweden	2019	○ Ultrafiltration system including cartridge filter and backwash system; ○ Combined CIP / Neutralisation system; ○ Ferric chloride storage and dosing; ○ Tenside storage and dosing; ○ Hydrochloric acid storage and dosing; ○ Mixing pump and reaction piping ○ Ultrafiltration streets including feed pump and cartridge filter; ○ Ultrafiltration backwash system; ○ Neutralisation system for UF and RO waste streams; ○ CIP system for UF and RO cleaning; ○ Reverse osmosis system including feed pump, cartridge filter, high pressure pump, internal recirculation pump and 2 stage reverse osmosis system; ○ Antiscalant storage and dosing; ○ Sodium bisulfite strorage and dosing ○ Tenside storage and dosing; ○ Hydrochloric acid storage and dosing;	4000 m^3/day	The purpose of the Treatment Plant is to provide drinking water for the Kommun. The plant has two source waters: brackish groundwater and waste water and and industrial waste water stream (Chicken Slaughter House).  

Project Location	Year	Scope	Capacity	Description
China	2006	○ Storage tank for equalising the feed ○ Preheating to at least 25 °C ○ Fixed bed biology for BOD degradation ○ Precipitation/flocculation to reduce COD that is difficult to degrade ○ Flotation for solids removal with integrated multi-layer filter for ○ multi-layer filter for turbidity separation ○ Ultrafiltration as pre-treatment before reverse osmosis ○ 2-stage reverse osmosis for demineralisation ○ Redundant pumps and control system	30000 m^3/day	The purpose of the Treatment plant is to provide boiler feed water and cooling tower make-up water to the petrochemical industry. Due to the locally restrictions in water availability the effluent of the local sawage treatment plant is treated by the mean of membrane filtration.  

BOLLFILTER Protection Systems

Project Location	Year	Scope	Capacity	Description
Poland / Germany	2024	○ All (intermediate) sotorage tanks ○ All installation works ○ Pre-treatment by Chamber Filter Press for solid removal ○ Ceramic Ultrafiltration as pre-treatment for RO ○ 3-stage reverse osmosis for demineralisation ○ Membrane degasing stage ○ Chemical dosing stations	1584 m^3/day	The purpose of the Treatment plant is to treat digestae after the secondary digester of a biogas plant. The final effluent after the 3-stage RO has a high quality and can be discharged to the local river or can be reused in the process to close the water cycle. The concentrate streams of the CFP and RO-1 can be used as a fertilizer. 

Appendix 3
Economic assessment of full-scale plant

CAPEX – Overview of Components and Costs

Category	Description	Quantity / Size	Comment	Estimate (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)	1 unit	Automatic self-cleaning filter, 100 µm	
	BOLL FineFilterUnit 30.8 UF-skids	12 pcs.	3,050 m² total membrane area (SiC tubular), incl. dosing, control, software Piping material: GRVE Membrane module material: Duplex Pump material: Superduplex	
	Total UF system			**€ 7.500.000**
RO system	RO pre-treatment		Pretreatment and RO	
	BOLL RO-skids including chemical dosing stations, software and control cabinets.	4 pcs.		**€ 2.500.000**
Building and fortified area	Light building	30 x 35 m (6 m high)		**€ 1.759.000**
	Foundation - fortifies area	20 x 20 m		**€ 268.000**
Consultancy		10% of total CAPEX		**€ 1.509.240**
Miscellaneous and unforeseen expenses		14% of total CAPEX		**€ 1.760.780**
Total CAPEX				**EUR**
				€ 15.847.020
Uncertainty (+30%)				€ 20.601.126
Uncertainty (–30%)				€ 11.092.914

OPEX – Overview of Operating Costs

Category	Description	Consumption	Unit	Estimate (EUR)
Electricity	Total: 11,000 MWh/year UF: ~5,500 MWh/year (cross-flow) RO: ~5,500 MWh/year Assumed price: 1.0 DKK/kWh (EUR 0.134/kWh)	11.000.000	kWh/year	**€ 1.474.531**
Chemicals	BollClean 1550 (acid-based cleaning agent)	6000	L	**€ 24.000**
	BollClean 3300 (alkaline cleaning agent)	6000	L	**€ 24.000**
	Antiscalant (dosing)	5	ml/m³	**€ 74.898**
	Caustic soda (50%)	80	L/year	**€ 200**
	Sulfuric acid (96%)	30	L/year	**€ 200**
Membrane replacement (UF)	Replacement of UF membranes	10 year lifespan	EUR/membrane	**€ 980**
Membrane replacement (RO)	Replacement of RO membranes	4 year lifespan	EUR/membrane	**€ 980**
Miscellaneous OPEX	Various operational maintenance costs (standard and repairs)	7%	%	**€ 111.848**

Building and fortified area	**Foot print [m2]**	**Cost [EUR]**
Foundation and light building	1050	1.759.383
Foundation - fortifies area	400	268.097

Cost for foundation, building and containers		
Drilled well foundations	670	EUR/m2
Light building	1.676	EUR/m2

	Year Count	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
	Year count	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	NPV																					
CAPEX	**15.847.020**	15.847.020																				
OPEX	**28.095.032**		1.743.870	1.778.748	1.814.323	1.854.852	1.887.621	1.925.374	1.963.881	2.007.752	2.043.222	2.098.422	2.125.768	2.173.255	2.211.649	2.255.882	2.301.000	2.352.401	2.393.960	2.441.840	2.490.676	2.563.790

Total NPV	**43.942.052**

Net price increase	2%
Discount rate	4%

Produced water (20 year total)	21.637.200	m3
Cost per m3 (NPV)	2,03	EUR/m3

Appendix 4
Reject water cost estimate

SOURCE DOCUMENT

Reject water treatment type	CAPEX		OPEX		TOTEX		Specific cost	
	50 MW anlæg	1 GW anlæg	50 MW anlæg	1 GW anlæg	50 MW anlæg	1 GW anlæg	50 MW anlæg	1 GW anlæg
	mio. DKK	mio. DKK	mio. DKK	mio. DKK	mio. DKK	mio. DKK	DKK/m3 ultrarent vand	DKK/m3 ultrarent vand
Wastewater - Reject water treatment for recipient with PFAS challenges	8	40	1,5	10	2,5	15	32	10
Wastewater - Reject water treatment for recipient with no PFAS treatment requirement	6,5	28	1,5	7,5	2	10	29	7

Source: Rejektvand MST rapport 2024

Flow assumed:

	68.965,52	m3/year ultrapure water 50 MW
70% recovery	29.556,65	m3/year reject water 50 MW
	1.428.571,43	m3/year ultrapure water 1GW
	612.244,90	m3/year reject water 1GW

TETRAS CALCULATIONS

Technical water plant feed volume	200	m3/h
Technical water plant feed volume	1.728.000,00	m3/year
Reject water plant feed volume	660.960,00	m3/year
Reject water plant feed volume	76,50	m3/h

	CAPEX	OPEX	TOTEX		Specific TOTEX cost	
TETRAS - Reject water plant no PFAS challenges (DKK)	**30,23**	**8,10**	**10,80**	**mio DKK**	**16,33**	DKK/m3 reject water
TETRAS - Reject water plant no PFAS challenges (EUR)	**4,06**	**1,09**	**1,45**	**mio EUR**	**2,19**	EUR/m3 reject water

**calculated based on costs estimated for reject water treatment of a 1 GW P2X plant (NIRAS, 2024) corresponding to 612.245 m3/year of reject water with 70% recovery, in the same ballpark as the TETRAS plant*

Table - assumptions for cost estimate extrapolation

Parameter (Unit)	Value
Technical water plant feed volume (m3/year)	1.728.000,00
Reject water plant feed volume (m3/year)	660.960,00
Requirement to remove PFAS from reject water	None

Tabel til Rapport (+/- 50% estimates)

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/m3 reject water)	1,10	3,29