Power-to-X
Feasibility study

Interreg
Baltic Sea Region

Co-funded by
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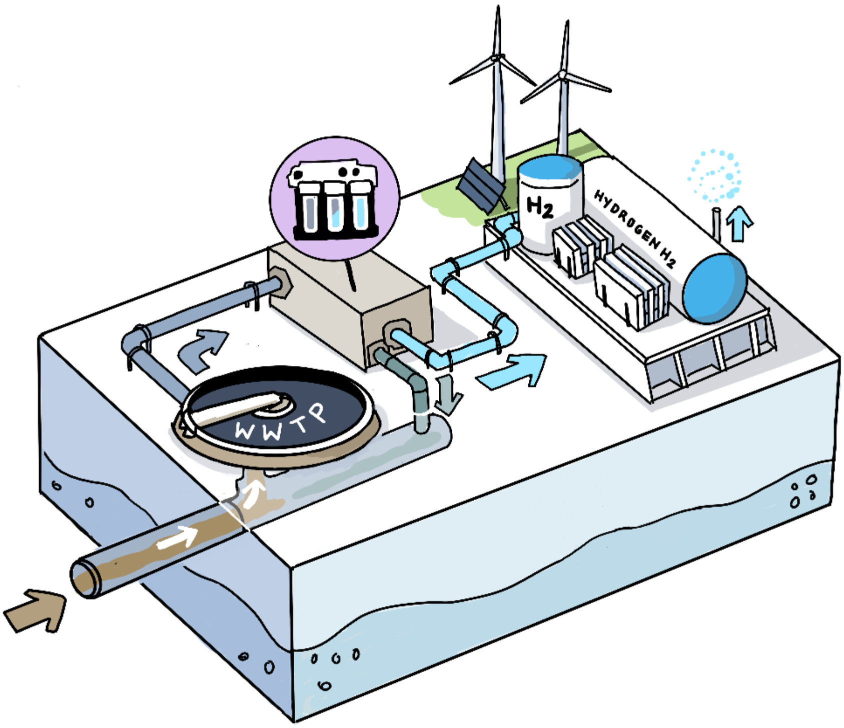
SUSTAINABLE WATERS
WaterMan

2025

Water for PtX - Feasibility Study Bornholm case - WaterMan project



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Executive summary

This feasibility study assesses the potential of utilizing treated wastewater as a source for process water in a Power-to-X (PtX) project on Bornholm. PtX technologies enable the conversion of renewable electricity into chemical energy carriers such as hydrogen, methane, and methanol, supporting the transition to a sustainable energy system.

The study evaluates the technical, economic, environmental, and regulatory dimensions of integrating wastewater reuse into PtX production. Key considerations include water quantity and quality requirements for electrolysis, treatment technologies, energy consumption, brine management, and compliance with Danish and EU regulations.

By comparing wastewater with alternative sources such as brackish Baltic Sea water, the report provides insights into cost implications, infrastructure needs, and environmental impacts. The findings aim to inform strategic decisions for Bornholm's Energy Island vision and support the development of a robust business case for technical water supply in PtX applications.

Key Conclusions and Recommendations

- Wastewater is a viable source for PtX process water on Bornholm, offering competitive advantages in sustainability and cost compared to brackish water, provided adequate treatment technologies are implemented.
- Seasonal variations in wastewater flow and quality require adaptive treatment strategies and storage solutions to ensure continuous supply for large-scale electrolysis.
- Advanced treatment technologies (e.g., reverse osmosis, electrodeionization) combined with energy-efficient designs can minimize operational costs and environmental impacts.
- Regulatory alignment and stakeholder engagement are critical: establishing a dedicated technical water entity under Danish water sector regulations will enable compliance and long-term viability.

Introduction

This feasibility study is conducted by Bornholms Energi og Forsyning (BEOF) as part of the INTERREG Baltic Sea Region project WATERMAN (#C017), which runs from January 1, 2023, to December 31, 2025. The study contributes to Deliverable 2.2: "Set of validated and complementary local measures for the reuse of treated water in the Baltic Sea Region."

WaterMan promotes water reuse across the Baltic Sea Region, introducing an innovative element to water management that enhances climate resilience. For most local authorities and water companies, water reuse remains a relatively new concept. WaterMan aims to provide these stakeholders with knowledge and practical tools to develop strategic approaches and implement concrete measures that bring water reuse into practice.

This study focuses on the feasibility of reusing treated wastewater for hydrogen electrolysis in Power-to-X (PtX) applications. The key questions addressed include:

- **What is PtX and what plans exist for PtX on Bornholm?**
- **What water quantity and quality are required for PtX electrolysis plants?**
- **What water sources are available on Bornholm and what are their characteristics?**
- **What treatment technologies are needed to achieve the required water quality, and what are the associated CAPEX and OPEX costs?**
- **Can BEOF establish a separate entity to supply water for PtX, and how would this be regulated?**
- **What risks are associated with entering the PtX market?**
- **Is there a sound and viable business case for BEOF?**

What is PtX?

Power-to-X (PtX) refers to processes that convert renewable electricity (power) into chemical energy carriers (X). These carriers can be:

- Gaseous fuels such as hydrogen or methane (synthetic natural gas, *Power-to-Gas*).
- Liquid synthetic fuels such as methanol, ammonia, synthetic diesel, or kerosene (*Power-to-Liquid*).

Liquid fuels from PtX are often referred to as electrofuels or e-fuels (Rambøll, 2024). For this study, we assume hydrogen as the primary product, as it appears to be the most likely scenario based on current research and market trends.

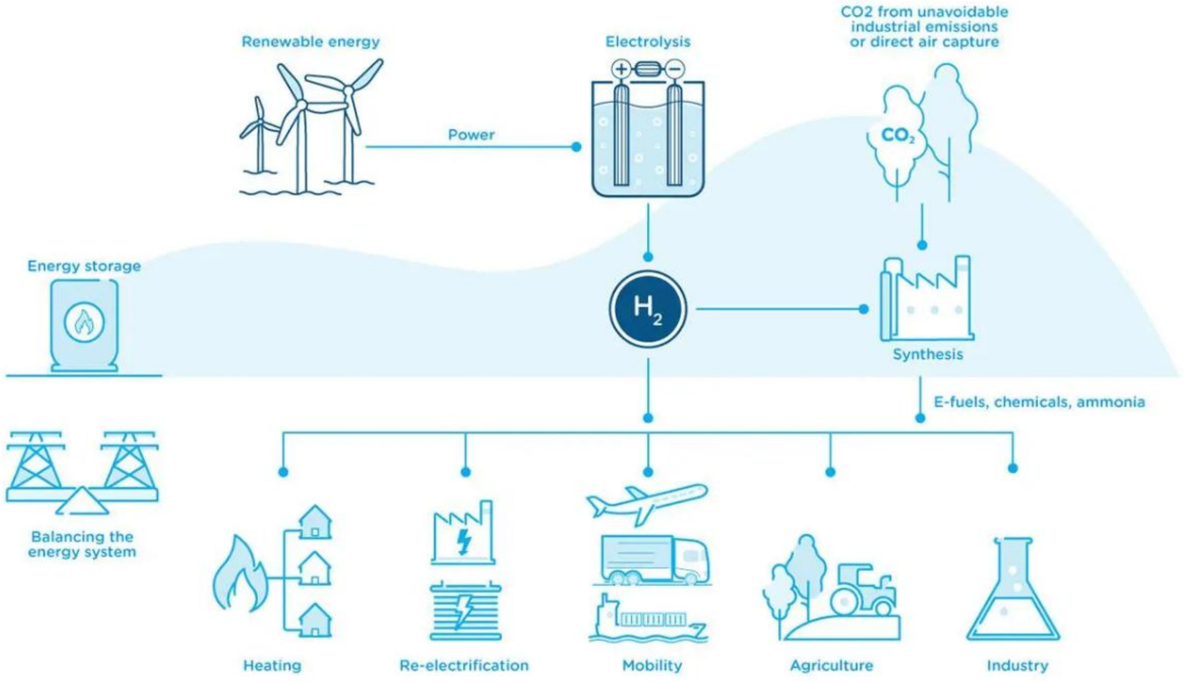


Figure 1 - Hydrogen production and utility (Rambøll, 2024)

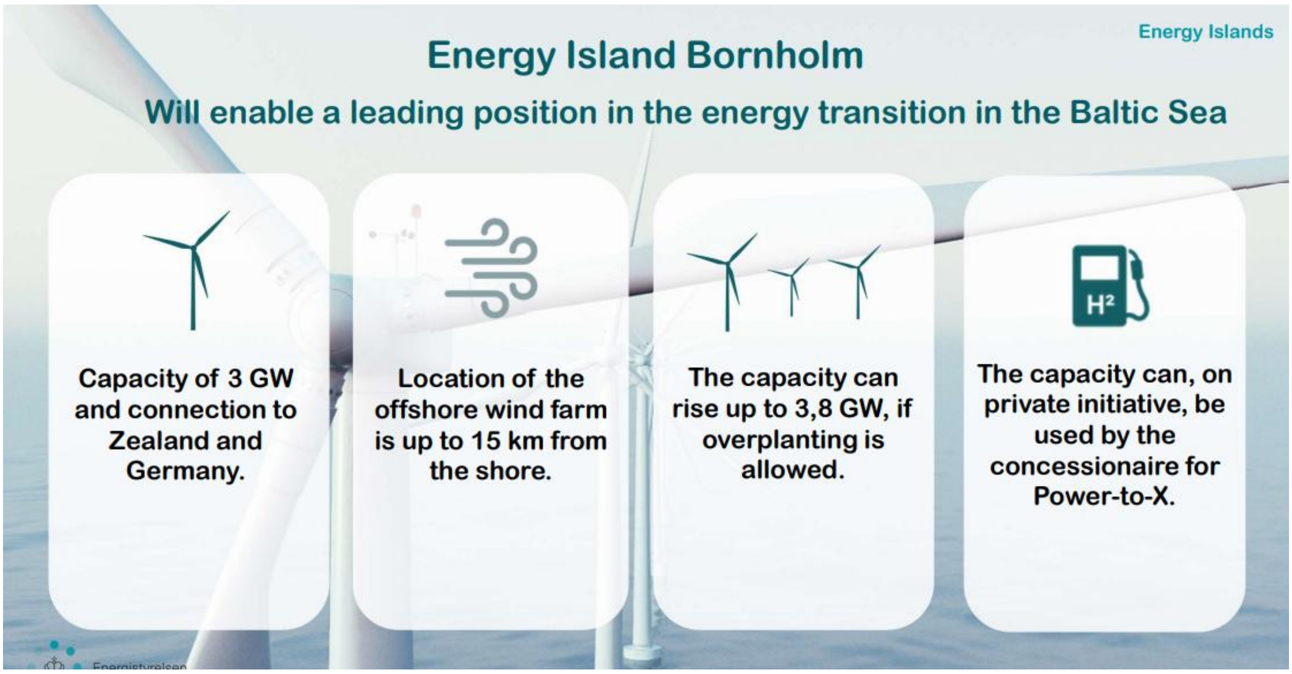
PtX plans on Bornholm – Energy Island perspective.

The Energy Island Bornholm agreement was adopted by the Danish Parliament on February 20, 2020. The Energy Island in the Baltic Sea will comprise:

- Two offshore wind farms.
- A high-voltage direct current (HVDC) converter station on Bornholm.
- Transmission cables connecting turbines, the converter station, and energy recipients in Zealand and abroad.

A similar converter station will be constructed in Zealand to receive power from the Energy Island. Additionally, a separate energy island is planned for the North Sea. The Danish Energy Agency and Energinet are responsible for construction, while Bornholm's Regional Municipality (BRK) collaborates with local and national actors to foster green innovation and job creation on Bornholm (Bornholm Regional Municipality, 2024).

The offshore wind capacity is expected to reach 3 GW, with potential overplanting of 0.6–0.8 GW (Energistryrelsen, 2023). Excess power from overplanting could be utilized for PtX production (Skøt, 2023). A PtX plant could be located in an industrial park adjacent to the transformer station and would likely be established and operated by a private company.



Energy Islands

Energy Island Bornholm

Will enable a leading position in the energy transition in the Baltic Sea

Capacity of 3 GW and connection to Zealand and Germany.

Location of the offshore wind farm is up to 15 km from the shore.

The capacity can rise up to 3,8 GW, if overplanting is allowed.

The capacity can, on private initiative, be used by the concessionaire for Power-to-X.

Figure 2 - Accelerating energy transition with the first energy island in the Baltic Sea (Energistryrelsen, 2023).

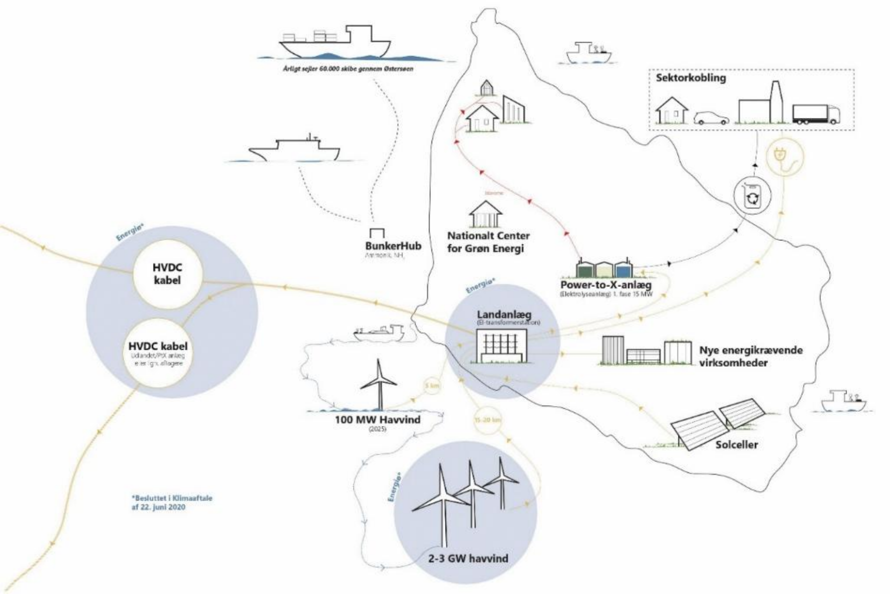


Figure 3 - Baltic Sea green hub (KTC, 2023)[1]

Benchmarking PtX Projects and Source Water Choices

Overview of PtX Development in Denmark

According to the Danish Energy Agency (Energistyrelsen, data as of 30/10/2023), more than 34 PtX projects are planned across Denmark, representing a combined electrolysis capacity of approximately 9 GW. Figure 4 illustrates the geographical distribution of publicly announced projects (Ebbehøj, 2023). It is important to note that most projects are still in early development stages, and their realization remains uncertain.

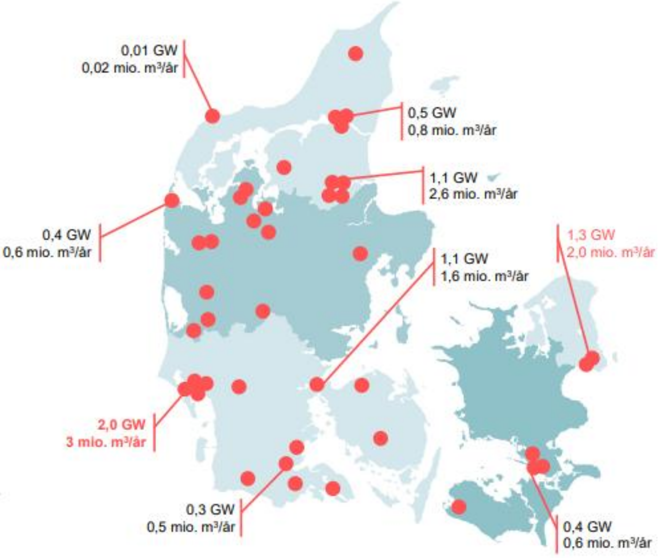


Figure 4 - Overview of public announced projects in Denmark

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[1] Energiø Bornholm - vi tænker nyt "Lykkeland" | ktc.dk

Publicly Announced PtX Projects

Several PtX projects in Denmark have adopted wastewater reuse as a primary source for producing ultra-pure water required for hydrogen electrolysis. This approach aligns closely with Bornholm's case, although Bornholm also has the unique option of utilizing brackish Baltic Sea water, which will be explored later in this report.

Case Study: HØST PtX Esbjerg

HØST PtX Esbjerg is a large-scale ammonia plant under development, deploying electrolysis technology at gigawatt scale. The facility aims to produce approximately 600,000 tonnes of green ammonia annually, serving as feedstock for fertilizer production and as a green maritime fuel.
With an estimated capital investment exceeding €2 billion, HØST PtX Esbjerg will rank among Denmark's largest PtX projects and one of Europe's first gigawatt-scale facilities (HØST PtX Esbjerg, 2024).

Water Source Strategy:

"The water which will be used for the production has to be extremely clean, and we have decided not to use drinking water as this is a limited resource which we must uphold for drinking water purposes. We have considered if seawater could be an option, but the desalination of seawater is a very energy-consuming and expensive process. This leaves us with the option of selecting either technical water—i.e., groundwater unfit for drinking—or wastewater."
— Marco Haubjerg, Engineer, HØST PtX Project

Ultimately, demineralized wastewater was identified as the most environmentally attractive solution compared to groundwater or seawater, despite the need for advanced purification beyond standard demineralization (HØST PtX Esbjerg, 2024) (NIRAS, 2024).

Case Study: Lolland

Facing increasing water scarcity and stricter regulations, Lolland Municipality announced that local industries can no longer rely on unlimited access to drinking water due to limited groundwater reserves.
To address this challenge, Lolland Utility plans to establish a water treatment facility in Nakskov to deliver up to 800,000 m^3/year of drinking-water-quality water from treated wastewater. A significant share of this technical water will be allocated to an upcoming PtX plant, supporting Denmark's decarbonization goals.
Rambøll is conducting a feasibility study for the project, focusing on water quality requirements and sustainability across environmental, social, and economic dimensions (Rambøll, 2023).

Comparison: HØST PtX Esbjerg & Padborg PtX

Both Esbjerg and Aabenraa (Padborg) municipalities are developing PtX projects with water supply strategies based on treated wastewater. Commissioning is expected around 2027.
Table 1 summarizes key project data, including production capacity, water supply volumes, and treatment technologies.

Key Insight:

- Wastewater offers a lower cost per cubic meter of ultrapure water compared to seawater, particularly at large scales due to economies of scale.
- While process wastewater treatment adds costs, it remains more economical than seawater desalination.

Tabel 1 - Ongoing PtX Projects in Esbjerg and Aabenraa (Design Stage) (NIRAS, 2024)

	H2-Energy og Høst	Padborg PtX
Production		
Owner of PtX	H2-Energy Høst	European Energy
Year of establishment	2027; 2030	2027
Hydrogen	90.000 t	
E-methanol		100.000 t
Ammonia	600.000 t	
Energy supply	2,0 GW	150 MW
Wind	x	x
Solar cells		x
Net	x	x
Water supply	DIN Forsyning	ARWOS
Treated wastewater	3.900.000 m3/år	250.000 m3/år
Clean water production	3.200.000 m3/år	200.000 m3/år
Discharge		
Water system	Vadehavet	Aabenraa Fjord
Public sewer	700.000 m3/år	20.000 – 40.000 m3/år
Direct discharge	x	
Requirements	Connection permit, Sewage treatment plant Øst	Connection permit, Stegholt Wastewater treatment plant on the way
Purification of process water	AOP, coagulation, advanced biological treatment, adsorption	Not determined

Lessons for Bornholm from Benchmarking PtX Projects

The experience of leading PtX projects in Denmark and Europe highlights the importance of early integration of water strategy into project design, particularly for large-scale electrolysis. Successful projects have prioritized securing reliable water sources, implementing advanced treatment technologies, and aligning with regulatory frameworks from the outset. Bornholm can leverage these insights by adopting a proactive approach to water planning, ensuring that technical water supply is treated as a critical infrastructure component alongside renewable energy generation. Collaboration with established water utilities and technology providers will further reduce implementation risks and accelerate project timelines.

Water Demand and Quality Requirements

Water quantities required for Ptx

This section examines the quantities of water needed for hydrogen production via electrolysis in Power-to-X (PtX) systems.

Electrolysis splits water (H_2O) into hydrogen (H_2) and oxygen (O_2). Based on molecular weights, 9 liters of ultrapure water are required to produce 1 kg of hydrogen.

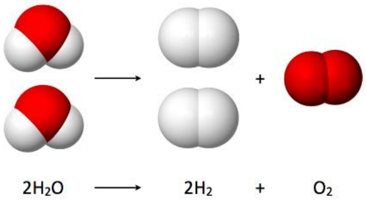


Figure 5 – splitting the H2O molecule

The amount of ultrapure water per MW depends on the electrolyser's energy consumption. Most electrolysers require 45–55 kWh per kg of hydrogen, which translates to approximately:

- 0.16–0.20 liters of ultrapure water per kWh, or
- 163–200 liters per hour per MW of electrolyser capacity.

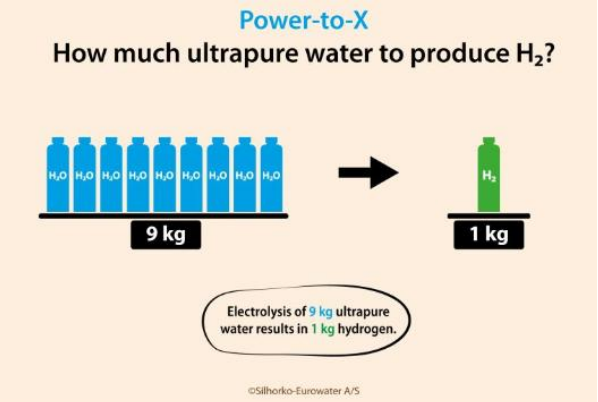
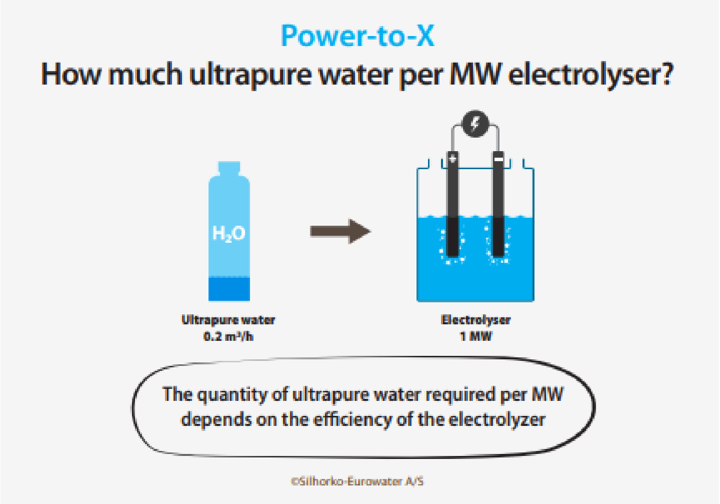


Figure 6 – how much water to produce H2



The quantity of ultrapure water required per MW depends on the efficiency of the electrolyzer

Figure 7 – how much ultrapure water per MW electrolyser

Example:
A PtX plant with 0.6–0.8 GW capacity would require 120–160 m³/h of ultrapure water, equivalent to 1.0–1.4 million m³/year.

Note: Cooling water is also needed to manage heat generated during electrolysis, but this aspect is outside the scope of this report (Silhorko - Eurowater, 2023).

Benchmark Data from NIRAS

To supplement these calculations, Table 2 (adapted from NIRAS, 2024) illustrates the relationship between PtX plant size, hydrogen output, water consumption, and potential water sources. Data is based on market dialogue and professional estimates, assuming:

- **Specific energy consumption:** 5.8 kWh per m³ of ultrapure water
- **Operating time:** 5,300 hours/year (≈61% utilization)
- **Hydrogen density:** 0.09 kg/Nm³
- **Water density:** 999.9 kg/m³ at 8°C

Tabel 2 - Overview. Grouping of Power-To-Hydrogen (PtH) plants based on size, potential water source and clean water technologies, and electricity supply. Data based on market dialogue and key figures for the PEM electrolysis process. (NIRAS, 2024)

Power-To-Hydrogen (PtH)			
Plant size	1 - 50 MW	50 - 200 MW	200 MW - 1 GW
Hydrogen production (t/year)	90 - 4.500	4.500 - 18.000	18.000 - 90.000
Ultrapure water			
Annual water volume (m^3/year)	750 - 37.000	37.000 - 150.000	150.000 - 750.000
Hourly water volume (m3/hour)	0,15 - 7	7 - 30	30 - 140
Potential water source(s)	Public water supply. Field drilling. Surface water.	Public water supply. Contaminated groundwater. Treated wastewater. Surface water.	Contaminated groundwater. Treated wastewater. Seawater.
Electricity supply	Local electricity supply	Local	
Wind	X	X	X
Sun	X	X	X
Net	X	X	X
Desalination Technology [1]	Reverse Osmosis, Ion Exchange	Reverse Osmosis, (Ion Exchange)[2]	Reverse Osmosis

1 The leading technology for water treatment. The technology is excl. pre- and post-treatment.

2 Ion exchange: Surface water and groundwater

Quality requirements for process water – Alkaline vs. PEM electrolysers

PtX electrolysis requires ultrapure water with extremely low concentrations of dissolved ions. Even trace impurities can cause scaling and fouling, reducing efficiency and damaging electrodes (Binhazzaa, 2023).

Typical conductivity limits (EUROWATER, 2023) (Becker, Hans; et. al., 2023) (Laguna-Bercero, 2012):

- **Alkaline electrolysers:** < **1 µS/cm**
- **PEM electrolysers:** < **0.1 µS/cm**
- **SOEC (Solid Oxide Electrolysis Cells):** < **1 µS/cm**

Potential water sources on Bornholm

This section examines and maps potential water sources in Bornholm suitable for PtX.

Ground water

Bornholm's annual drinking water production is approximately 3 million m³, with an estimated total groundwater resource of 5 million m³ per year. Given these limited reserves, allocating a significant portion for PtX production is highly unlikely.

In theory, up to 1 million m³/year (≈80 m³/h) of low-quality drinking water could be diverted for PtX. However, this volume would need to be aggregated from numerous wells across different catchment areas, making the solution logistically complex and economically unfeasible.

Ethical Consideration:
Groundwater is a critical resource for human consumption and ecosystem health. Diverting significant volumes for industrial purposes such as PtX could compromise drinking water security, increase vulnerability during droughts, and conflict with sustainability principles. Therefore, prioritizing groundwater for PtX would raise ethical concerns regarding resource stewardship and public interest.

Brackish Water (Baltic Sea water)

Brackish water from the Baltic Sea represents another potential source for PtX electrolysis. The seawater surrounding Bornholm has a salinity of approximately 7–8 g/kg, which is significantly lower than ocean water but still requires advanced treatment for ultrapure water production. While wastewater remains the primary focus for water supply, the feasibility of using brackish water is acknowledged as a backup option if circumstances demand it.

Current and future characteristics of raw brackish water from the Baltic Sea

Salinity

Surface salinity in the Bornholm Basin is relatively stable, with interannual variability being very low. Salinity decreases gradually across all Baltic subdivisions due to freshwater inflows from rivers and precipitation. The Baltic Sea's salt content originates from the North Sea, but inflows of denser, saline water occur only under specific meteorological and oceanographic conditions. These Major Baltic Inflow (MBI) events are rare and temporary, raising bottom salinity levels significantly before returning to normal.

- Historical MBIs: 1993, 2002, and 2014
- After the 2014 event, bottom salinity in the Bornholm Basin peaked at 20 g/kg, then declined to 16 g/kg over seven years (Copernicus, 2023).
- Typical salinity range: 7.5 g/kg at 0–20 m depth to 16 g/kg at 100 m depth.

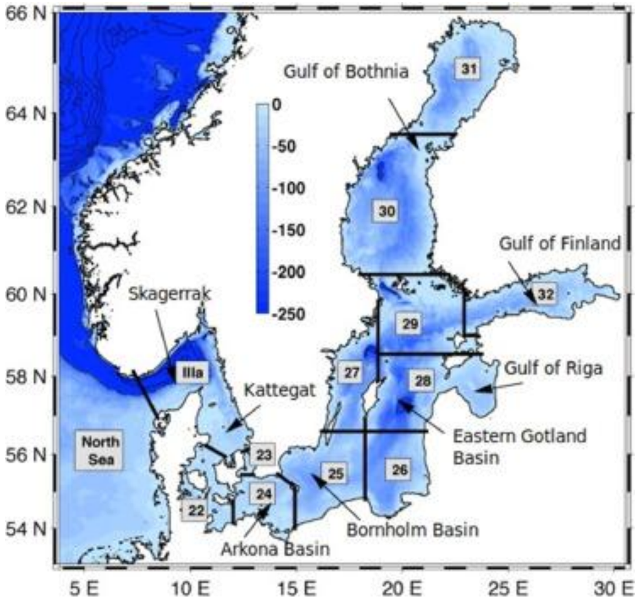


Figure 8 - The Baltic Sea region with ICES subdivisions. Colour scale shows sea depth in m (Stockmayer, Vera; et. al., 2023) [2]

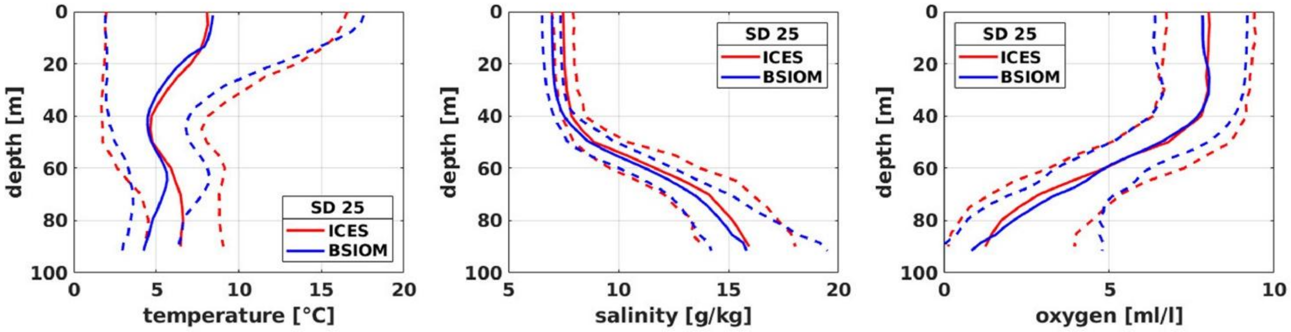


Figure 9 - Percentiles (5% and 95%: dashed line, 50%: solid line) of temperature, salinity and oxygen profile for SD 25 (period 1956–2018), based on monthly means of ICES observational data and BSIOM model output (Stockmayer, Vera; et. al., 2023).

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[2] [Variations of temperature, salinity and oxygen of the Baltic Sea for the period 1950 to 2020 - ScienceDirect]

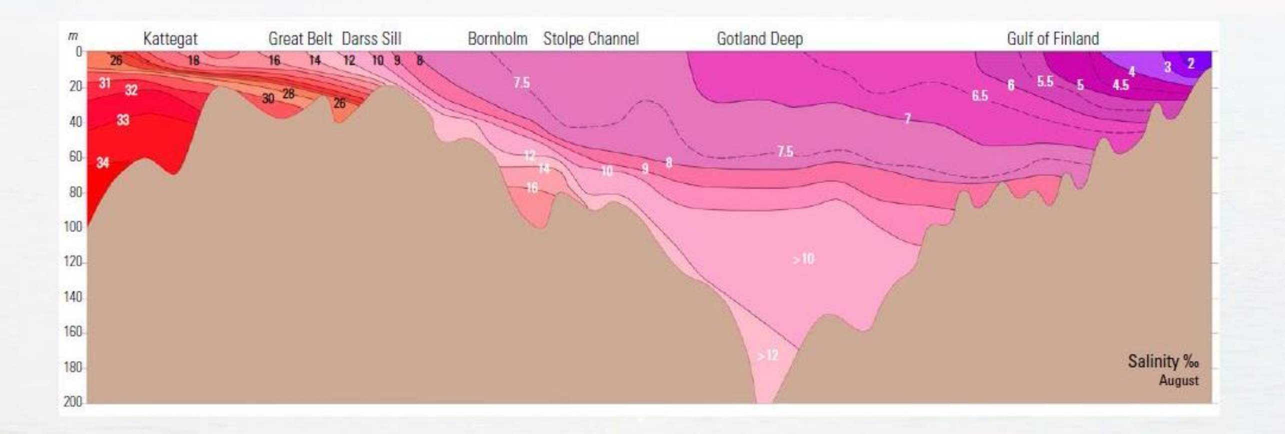

Figure 10 - The picture shows how salinity of the Baltic Sea changes, during summer, from the Danish straits to the Gulf of Finland (MarineFinland.fi, 2024).

Depth

Optimal pumping depth for PtX water intake is 10–20 meters, balancing water quality and temperature stability while avoiding surface contaminants. Deeper layers have higher salinity and lower oxygen, which complicates treatment and increases energy demand.

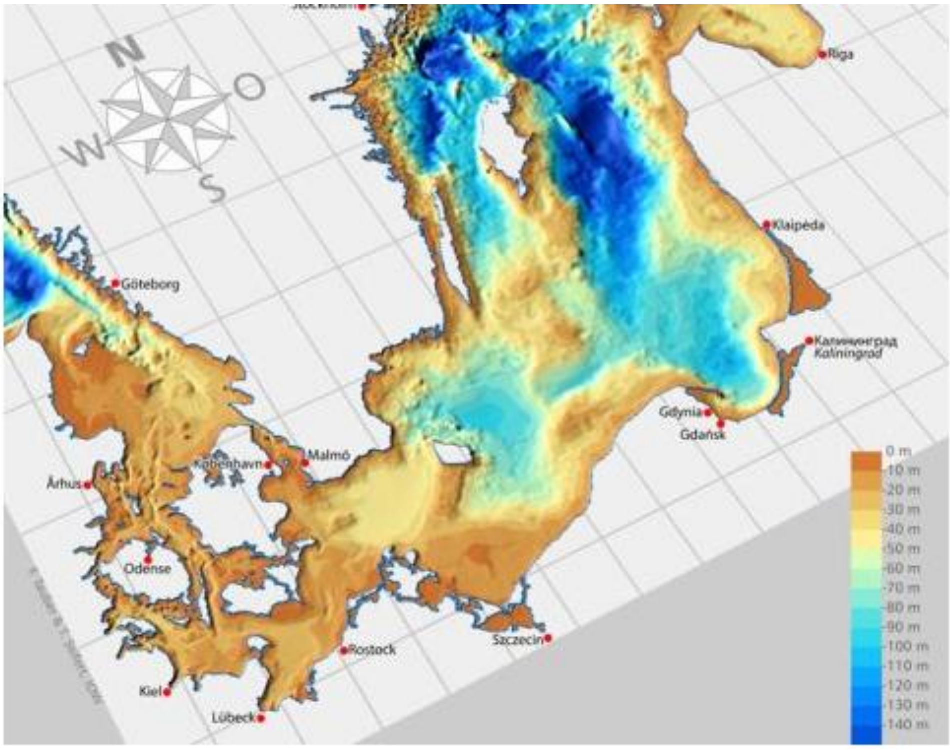

Figure 11 - Depth profile of the Baltic Sea (Leibniz Institute for Baltic Sea Research Warnemünde, 2018)[3]

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[3] [Baltic Sea in brief - IOW (io-warnemuende.de)]

Temperature

Temperature affects reverse osmosis (RO) performance:

- **Higher temperatures** → faster water flux, lower energy use, but higher salt passage and fouling risk.
- **Lower temperatures** → slower flux, higher energy use, but better salt rejection and membrane longevity.

At 20 m depth near Bornholm, water temperature typically ranges 6–10°C year-round, requiring energy input to reach the RO reference temperature of 25°C for optimal performance.

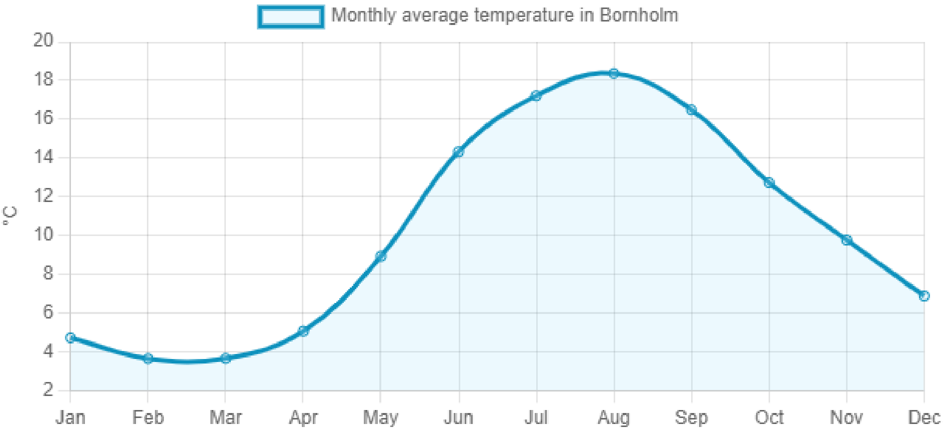

Figure 12 - Monthly average water temperature in Bornholm (Sea temperatures, 2024)

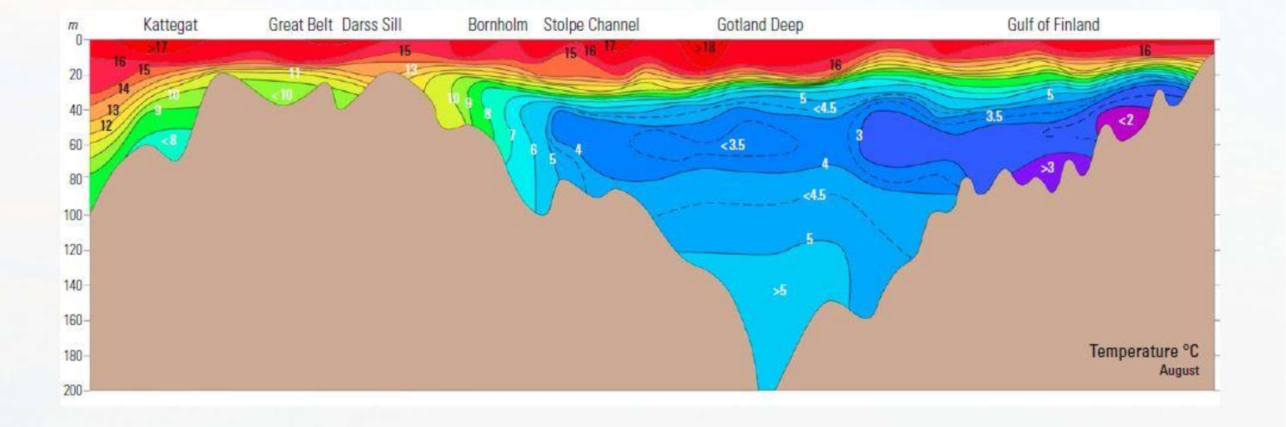

Figure 13 - The picture shows how summer temperatures of the Baltic Sea change from the Danish straits to the Gulf of Finland (MarineFinland.fi, 2024).

Key Takeaways:

- Salinity in the Bornholm Basin is stable at the surface but influenced by rare inflows of North Sea water at depth.
- Optimal intake depth: 10–20 m, balancing stability and avoiding surface pollutants.
- Water temperature (6–10°C) will require heating for RO systems, adding to energy costs.
- While technically feasible, brackish water treatment for ultrapure water is energy-intensive and costlier than wastewater reuse, making it a secondary option for Bornholm.

Wastewater

Reusing wastewater offers significant benefits, including supporting the circular economy agenda and reducing the discharge of treated effluent into local water bodies. This approach aligns with sustainability principles and minimizes environmental impact.

Bornholm's wastewater treatment plants (WWTPs) collectively handle almost 7 million m³ per year, making wastewater the most abundant and practical water source for PtX applications.

Table 1 - Quantities of water available for use in Power-to-X production

Source	Quantity (BEOF estimate)	Conductivity µS/cm
Drinking water	< 100.000 m3/year	500-600
Low-quality drinking water	< 1 mio. m3/year	500-600
Stormwater/rainwater	> 1 mio. m3/year	5-30
Wastewater	~7 mio. m3/year	850-1200
Surface water Baltic Sea	Infinite	~8000
Surface water North Sea	Infinite	28000-35000

Wastewater treatment on Bornholm and seasonal variations

Bornholm currently operates seven WWTPs, each serving different areas. Households outside these zones rely on private treatment systems or septic tanks.

Table 2 - WWTPs & respective outflow per year in m3

WWTPs	Outflow per year in m3 (2021)
Rønne	2,900,000
Nexø	1,250,00
Boderne	1,250,000
Tejn	800,000
Svaneke	580,000
Melsted	160,000
Vestermarie	N/A
Total	6,890,000

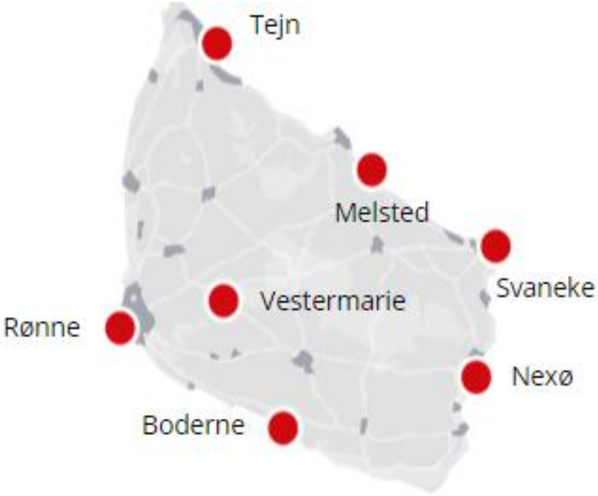

Figure 14 - Wastewater treatments plants on Bornholm

Figure 15 - Wastewater treatment sewer system layout (Bornholms Regionskommune, 2024)[4]

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[4] Bornholm - Spildevandsplan 2023-2027 - Bornholm Kommune (niras.dk)

Seasonal Variations
Wastewater flow and characteristics vary seasonally:

- **Summer (June–August):**
    - Rønne WWTP: ~150,000 m³/month
    - Boderne WWTP: ~50,000 m³/month
    - Nexø WWTP: ~50,000 m³/month
- **Winter (Nov–Jan):**
    - Up to **800,000 m³/month** treated due to rainwater infiltration at Rønne, Boderne, and Nexø WWTPs.

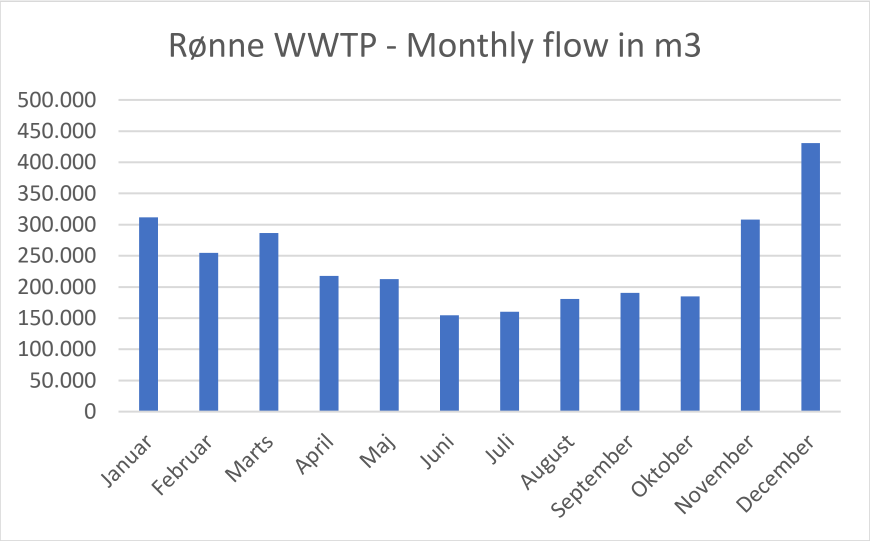

Figure 16 - Rønne WWTP - Monthly flow in m3

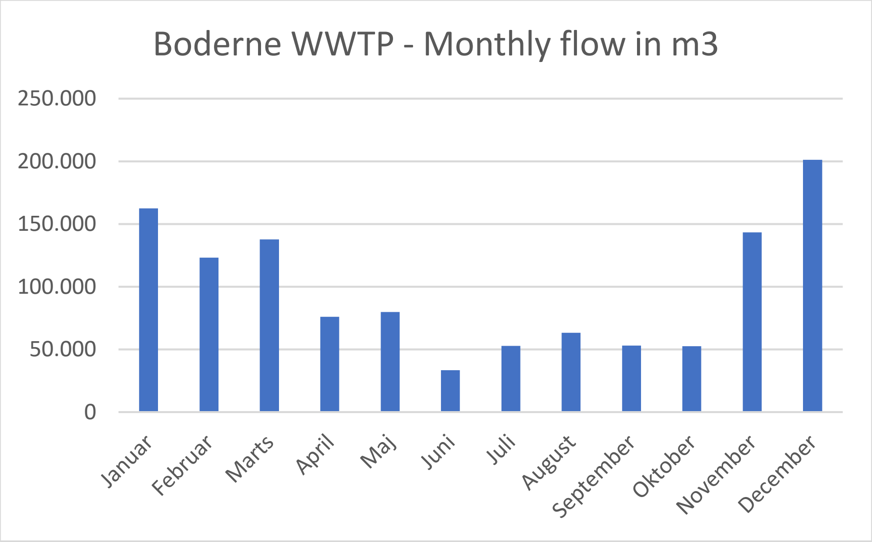

Figure 17 - Boderne WWTP - Monthly flow in m3

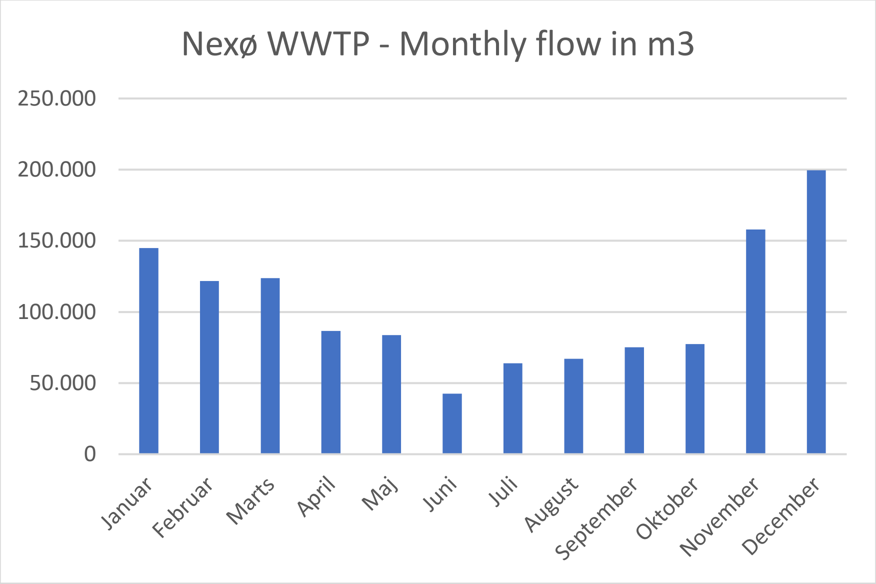

Figure 18 - Nexø WWTP - Monthly flow in m3

Capacity Analysis

The three largest WWTPs (Rønne, Nexø, Boderne) can collectively deliver ~275 m³/h of feed water for further treatment. Assuming a 70% recovery rate, this equates to ~190 m³/h of ultrapure water.

Table 3 - Required UPW quantity for PtX

	0,6GW PTX	0,8GWPTX
Required UPW quantity	120 m3/h	160 m3/h
Feed water quantity required at 70% recovery rate	**170 m3/h**	**230 m3/h**
Feed water quantity required at 80% recovery rate	150 m3/h	200 m3/h
Rønne, Nexø and Boderne (summer)	**~275 m3/h**	
Rønne (summer)	**150-160 m3/h**	

Key Insight:

- Rønne WWTP alone cannot meet the demand for a 0.8 GW PtX plant during summer.
- Collecting wastewater from multiple WWTPs would require significant investment in pipelines, reservoirs, and pumping stations.
- Rønne WWTP is the most suitable source due to its size (≈3 million m³/year) and proximity to the planned energy park near the transformer station. Boderne and Nexø are also relevant secondary sources.

Effluent Quality and Conductivity

To design an effective treatment solution for PtX, it is essential to understand the quality of effluent from Bornholm's WWTPs. This section focuses on Rønne, Boderne, and Nexø plants and outlines discharge limits, conductivity data, and other critical parameters.

Table 4 - National discharge limits for COD, BI5, Nitrogen and Phosphorus (Environmental Protection Agency, 2024).

Parameter	Limit
COD	< 75 mg/
BI5	< 15 mg/l
Total N	< 8 mg/l
Total P	< 1,5 mg/l

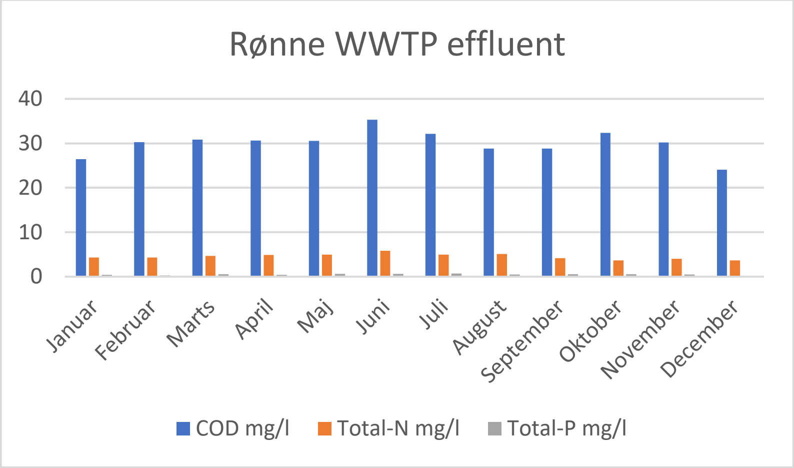

Figure 19 - Effluent quality from Rønne WWTP 2022.

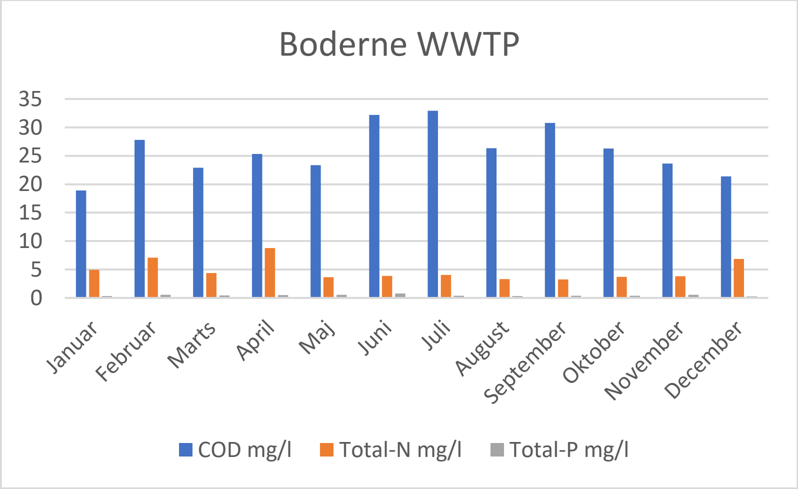

Figure 20 - Effluent quality from Boderne WWTP 2022.

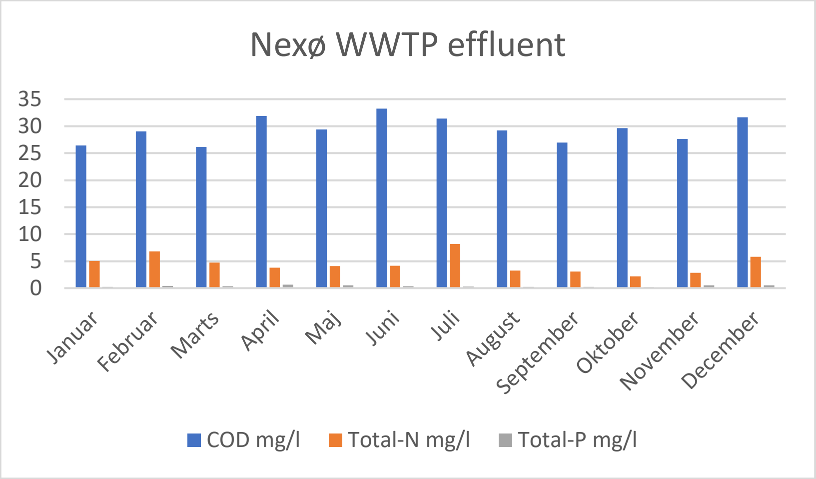

Figure 21 - Effluent quality from Nexø WWTP 2022.

Conductivity

Conductivity is a key indicator of dissolved salts in wastewater effluent.

- **Rønne WWTP:** Internal measurements tend to be higher than external measurements by Eurofins.
- **Nexø WWTP:** Shows higher conductivity values, with peaks above 1,800 µS/cm, likely due to Baltic Sea water intrusion during floods or road salt runoff in winter.

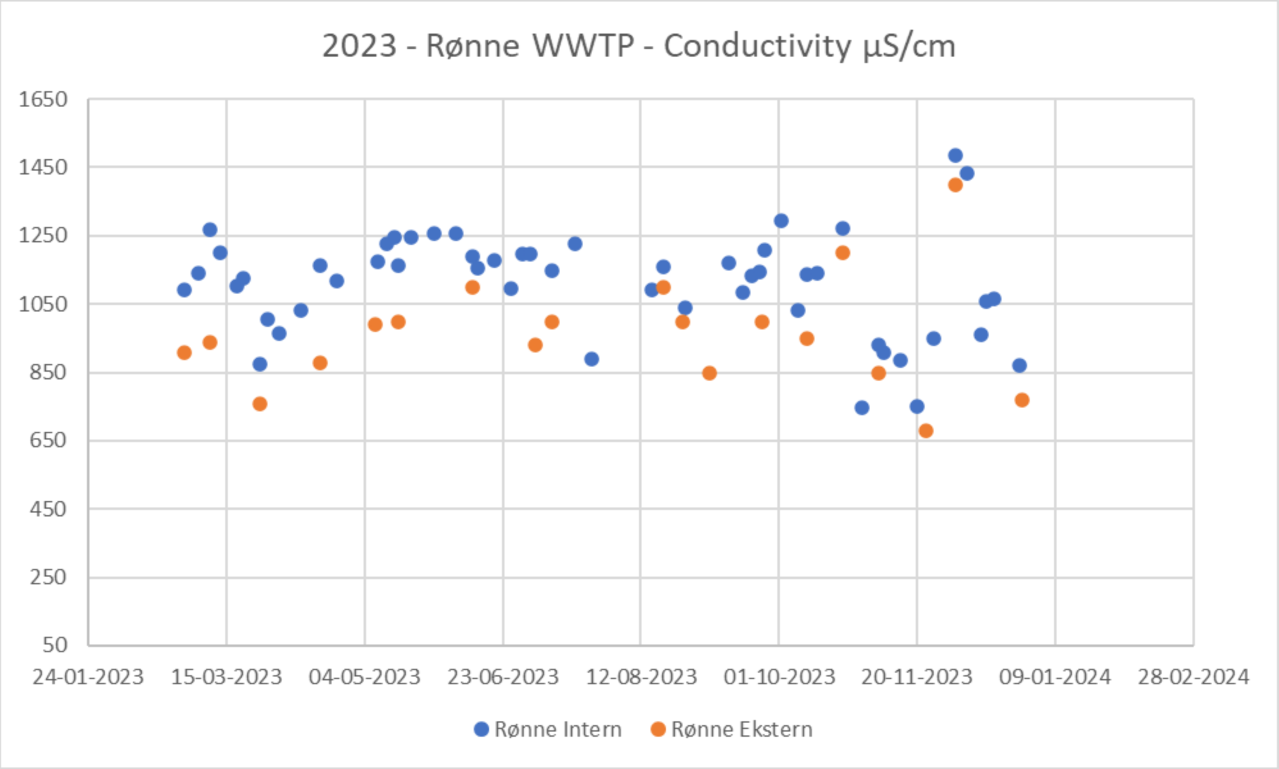

Figure 22 - Rønne WWTP Conductivity 2023

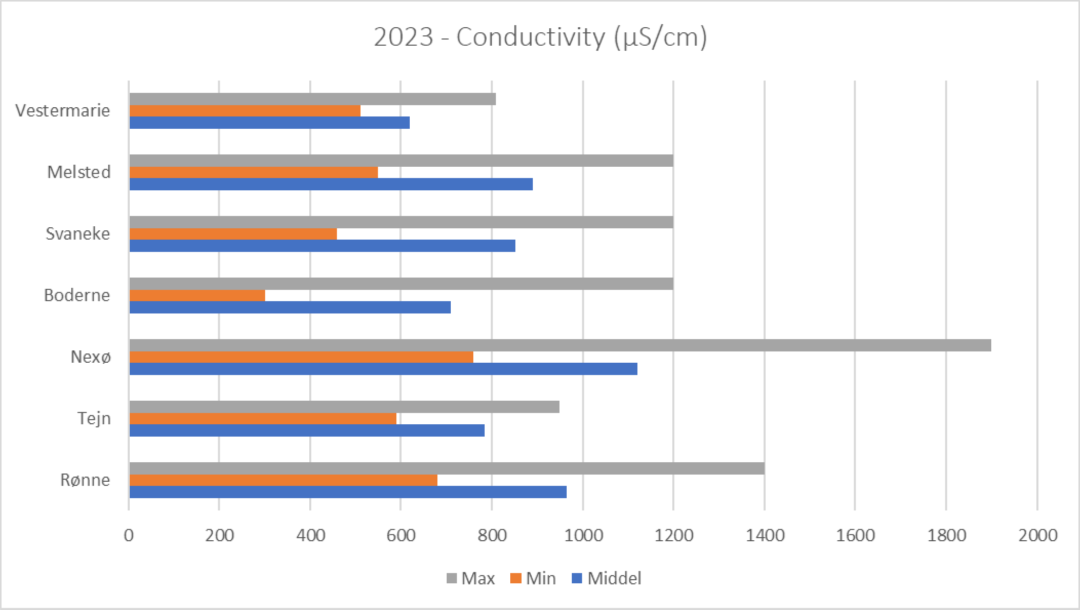

Figure 23 - conductivity values for all BEOF WWTPs 2023

Table 5 - average conductivity values for all BEOF WWTPs 2023

2023	**Rønne**	**Tejn**	**Nexø**	**Boderne**	**Svaneke**	**Melsted**	**Vester marie**
Average Conductivity (µS/cm)	964	783	1120	710	852	890	620

Other Key Analyses for Treatment Design

Beyond COD, BOD, and nutrients, a comprehensive water analysis is essential to predict fouling and scaling risks in reverse osmosis (RO) systems and determine pretreatment needs. Critical parameters include:

- **Total Dissolved Solids (TDS):** Primary target for RO systems.
- **pH:** Ideal range for RO membranes is **6.5–8**.
- **Temperature:** Affects permeate flow and membrane life.
- **Turbidity:** High levels increase fouling risk.
- **COD/BOD:** Indicates organic load; high values require pretreatment.
- **Oil and Grease:** Must be removed to prevent membrane fouling.
- **Heavy Metals:** Lead, mercury, arsenic may need additional treatment.
- **Microbial Contaminants:** RO removes most microorganisms, but disinfection may be required.
- **Scale-Forming Compounds:** Calcium, magnesium require anti-scaling measures.
- **Silt Density Index (SDI):** Indicates fouling potential; high SDI requires pretreatment.

Future Quantities and Quality of Wastewater

Several factors will influence the future availability and quality of wastewater on Bornholm:

1. **BEOF Strategy – Centralized WWTP**

BEOF is considering restructuring the current wastewater system by replacing the seven existing WWTPs with one centralized facility.

- **Impact:** A centralized WWTP would enable higher treatment efficiency, resulting in better effluent quality and potentially reducing the cost of producing ultrapure water for PtX.

2. **Sewer System and Rainwater Separation**

In September 2023, Bornholm Municipality decided to halt sewage separation projects, opting instead for retention basins to manage overflows.

- **Impact:** Rainwater will continue entering the wastewater system, maintaining seasonal flow variations and influencing effluent composition.

3. **EU Wastewater Treatment Directive**

The proposed recast of the Urban Wastewater Treatment Directive (European Commission, 2022) introduces stricter requirements:

- Advanced treatment for micro-pollutant removal
- Enhanced nutrient removal standards
- Extended Producer Responsibility (EPR) for pharmaceuticals and cosmetics
- **Impact:** These measures will improve effluent quality, reducing pretreatment needs and lowering costs for ultrapure water production.

4. **Climate Change**

Changing precipitation patterns will affect wastewater volumes:

- **Dry summers** → lower inflow, wastewater mainly from households and industry
- **Wet winters** → higher inflow due to rainwater infiltration
  Despite these variations, effluent quality remains relatively stable, with only minor seasonal fluctuations.

Water Consumption for Clean Water Production

Producing ultrapure water generates reject wastewater, and its volume depends on recovery rates and treatment level. Table 7 (adapted from NIRAS, 2024) summarizes water consumption, reject volumes, and efficiency for different sources and treatment levels.

Table 6 - Water Consumption and Reject Volumes per 1 m³ of Ultrapure Water.

Characterization of wastewater production	Unit	Water source			
		Treated wastewater	Groundwater	Surface water	Seawater
Level 1					
- Water consumption	m3/m3	1,7 - 1,3	1,7 - 1,3	1,7 - 1,3	5,0 - 2,5
- Wastewater production	m3/m3	0,7 - 0,3	0,7 - 0,3	0,7 - 0,3	4 - 1,5
- Water efficiency	%	60 - 80%	60 - 80%	60 - 80%	20 - 40%
- Concentration factor	-	2,5 - 5	2,5 - 5	2,5 - 5	1,3 - 1,7
Level 2					
- Water consumption	m3/m3	1,3 - 1,2	1,3 - 1,2	1,3 - 1,2	2,5 - 1,5
- Wastewater production	m3/m3	0,3 - 0,2	0,3 - 0,2	0,3 - 0,2	1,5 - 0,5
- Water efficiency	%	80 - 86%	80 - 86%	80 - 86%	40 - 67%
- Concentration factor	-	5 - 7	5 - 7	5 - 7	1,7 - 3
Level 3					
- Water consumption	m3/m3	<1,2	<1,2	<1,2	<1,5
- Wastewater production	m3/m3	<0,2	<0,2	<0,2	<0,5
- Water efficiency	%	>86%	>86%	>86%	>67%
- Concentration factor	-	>7	>7	>7	>3

Key Insight:

- **Level 1:** Lower recovery, simpler operation, but higher reject volumes.
- **Level 2:** Optimized recovery, smaller reject volume, suitable for most PtX plants.
- **Level 3:** Near-zero liquid discharge (ZLD), reject becomes solid waste, highest complexity and cost.

Feasibility of Mixing Treated Wastewater with Brackish Water

Technical Considerations

Blending treated wastewater with brackish Baltic Sea water could theoretically optimize treatment by balancing certain water quality parameters before reverse osmosis (RO). For example:

- **Dilution of salinity:** Mixing brackish water (7–8 g/L salinity) with low-salinity treated wastewater (≈850–1,200 µS/cm) reduces overall salt load, potentially lowering energy demand for desalination.
- **Hardness and scaling risk:** Brackish water typically contains higher concentrations of calcium and magnesium, increasing scaling potential in RO systems. Mixing with wastewater may reduce or increase hardness depending on ratios, requiring pretreatment strategies such as softening or antiscalant dosing to prevent membrane fouling.
- **Variability:** Seasonal changes in wastewater composition and occasional saltwater intrusion into sewers (e.g., Nexø WWTP) could complicate blending ratios and operational stability.

Treatment Process Implications

A blended feed stream would require a customized treatment train, likely including:

- **Coagulation and filtration** to remove suspended solids and organics from wastewater.
- **Softening or antiscalant dosing** to manage hardness and prevent scaling.
- **High-recovery RO** followed by polishing steps at the PtX plant (e.g., electrodeionization) to achieve ultrapure water quality (<0.1 µS/cm for PEM electrolysers).

While blending could reduce overall salinity compared to pure seawater, it introduces complexity in pretreatment design, monitoring, and chemical dosing.

Legislative and Regulatory Aspects

Under Danish law, treated wastewater remains classified as wastewater, even after advanced treatment, until it meets discharge or reuse standards. Mixing wastewater with brackish water may trigger additional regulatory requirements:

- Wastewater discharge permits under the Danish Environmental Protection Act (Order No. 1448) apply when effluent is introduced to natural waters or reused in industrial processes.
- Blending could be interpreted as a discharge activity, requiring permits and compliance with nutrient and pollutant limits.
- Future EU Urban Wastewater Treatment Directive revisions will impose stricter standards for nutrient removal and micro-pollutant control, which could affect blending feasibility.

Key Risks

- **Operational complexity:** Managing variable feedwater chemistry and scaling risk.
- **Regulatory uncertainty:** Blended water may fall under wastewater regulations, complicating approval for PtX use.
- **Cost implications:** Additional pretreatment steps and monitoring increase CAPEX and OPEX compared to single-source strategies.

Summary:

Blending treated wastewater with brackish water is technically possible but introduces significant design and regulatory challenges. While it may reduce salinity and optimize treatment in theory, hardness management, seasonal variability, and compliance with wastewater regulations make this approach less attractive than using a single, well-characterized source.

Treatment technologies for electrolysis

The choice of treatment technology depends on:

- **Feed water quality** (wastewater effluent vs. brackish water)
- **Electrolysis technology** (PEM, AWE, SOEC)
- **Required water purity** for the electrolyser

Treatment systems typically combine multiple technologies, each targeting specific contaminants. Danish water treatment company Silhorko-Eurowater, a leading provider of ultrapure water solutions for PtX, illustrates a general treatment train for different water sources:

- **Final polishing step** (common to all sources)**:**
  - Softening
  - Demineralization (Reverse Osmosis – RO)
  - Degassing
  - Electrodeionization (EDI)
- **Pre-treatment:**
  - **Wastewater effluent:** Ultrafiltration (UF) and UV disinfection
  - **Brackish water:** Reverse Osmosis (primary desalination)

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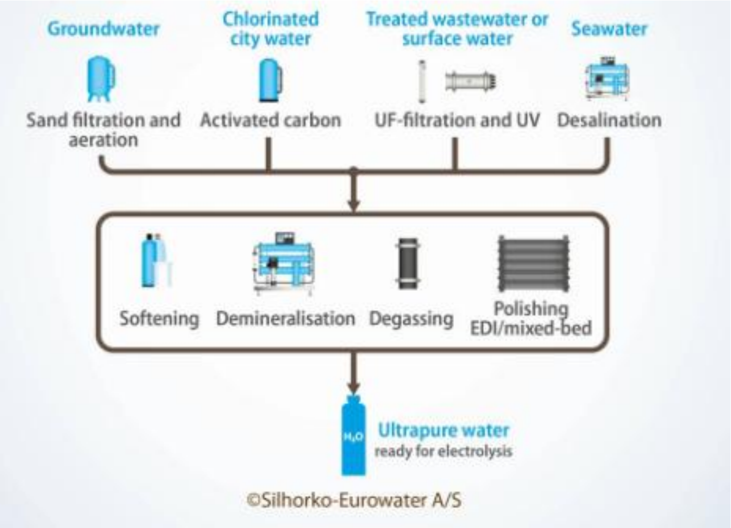


Figure 24 - How is water treated for green H2?

Overview of Electrolysis Technologies: Membrane-Based and Thermal Techniques for Hydrogen Production

Various Electrolysis technologies fall into two main categories: membrane-based and thermal techniques, each with distinct advantages and challenges.

1. Membrane-Based Electrolysis

These technologies use ion-conductive membranes to separate hydrogen and oxygen gases.

A. Proton Exchange Membrane (PEM) Electrolysis

- **Overview:** Uses a solid polymer electrolyte (e.g., Nafion) to conduct protons while blocking gases.
- **Advantages:**
    - High efficiency and fast startup
    - Compact design, ideal for space-constrained applications
    - Flexible operation with intermittent renewables
- **Challenges:**
    - High cost (membranes and platinum-group catalysts)
    - Durability issues under high temperature/pressure

B. Alkaline Electrolysis (AWE)

- **Overview:** Uses liquid electrolyte (KOH or NaOH) and a porous diaphragm.
- **Advantages:**
    - Mature, proven technology
    - Lower capital cost
    - Uses inexpensive catalysts (nickel-based)
- **Challenges:**
    - Lower efficiency and slower startup
    - Lower operating pressure, affecting hydrogen purity

C. Anion Exchange Membrane (AEM) Electrolysis

- **Overview:** Combines features of PEM and alkaline systems, using a solid membrane that conducts hydroxide ions.
- **Advantages:**
    - Potentially lower cost (non-precious catalysts)
    - Operates in alkaline environment, improving safety

- **Challenges:**
    - Early-stage development, limited commercial data
    - Membrane durability concerns

2. Thermal Techniques

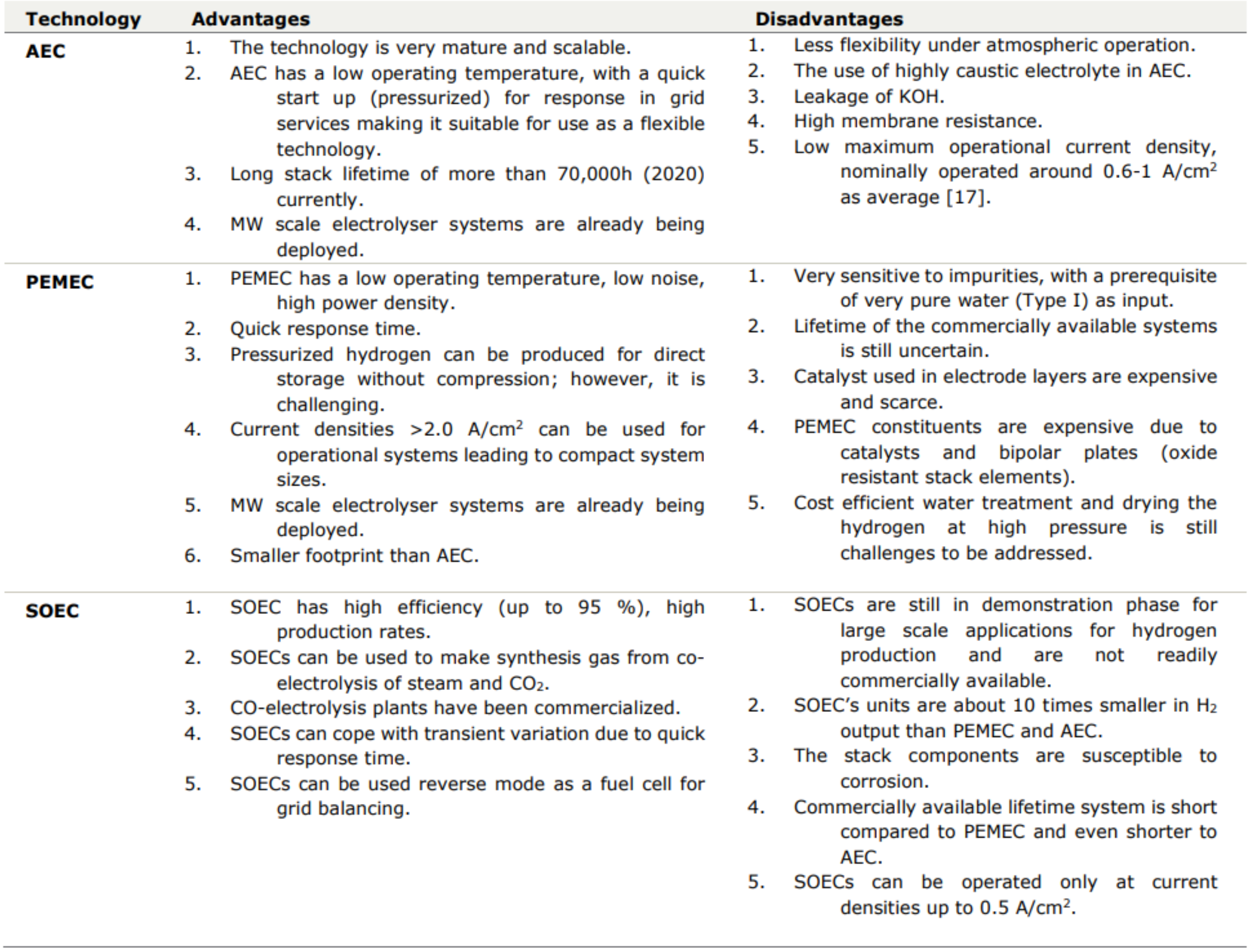
These methods use heat to reduce electrical energy demand for water splitting.

A. High-Temperature Steam Electrolysis (HTSE)

- **Overview:** Operates at 700–1,000°C using steam and solid oxide electrolyser cells (SOEC).
- **Advantages:**
    - High efficiency (up to 90%)
    - Integration with industrial waste heat or solar thermal systems
- **Challenges:**
    - Material degradation at high temperatures
    - Complex and costly system design

B. Thermochemical Water Splitting Cycles

- **Overview:** Uses high temperatures (>1,000°C) to drive chemical reactions (e.g., Sulfur-Iodine cycle).
- **Advantages:**
    - High theoretical efficiency
    - Scalable for large hydrogen production
- **Challenges:**
    - Extreme operating conditions
    - Complex chemical handling
    - Mostly experimental



Technology	Advantages	Disadvantages
AEC	1. The technology is very mature and scalable. 2. AEC has a low operating temperature, with a quick start up (pressurized) for response in grid services making it suitable for use as a flexible technology. 3. Long stack lifetime of more than 70,000h (2020) currently. 4. MW scale electrolyser systems are already being deployed.	1. Less flexibility under atmospheric operation. 2. The use of highly caustic electrolyte in AEC. 3. Leakage of KOH. 4. High membrane resistance. 5. Low maximum operational current density, nominally operated around 0.6-1 A/cm^2 as average [17].
PEMEC	1. PEMEC has a low operating temperature, low noise, high power density. 2. Quick response time. 3. Pressurized hydrogen can be produced for direct storage without compression; however, it is challenging. 4. Current densities >2.0 A/cm^2 can be used for operational systems leading to compact system sizes. 5. MW scale electrolyser systems are already being deployed. 6. Smaller footprint than AEC.	1. Very sensitive to impurities, with a prerequisite of very pure water (Type I) as input. 2. Lifetime of the commercially available systems is still uncertain. 3. Catalyst used in electrode layers are expensive and scarce. 4. PEMEC constituents are expensive due to catalysts and bipolar plates (oxide resistant stack elements). 5. Cost efficient water treatment and drying the hydrogen at high pressure is still challenges to be addressed.
SOEC	1. SOEC has high efficiency (up to 95 %), high production rates. 2. SOECs can be used to make synthesis gas from co-electrolysis of steam and CO_2. 3. CO-electrolysis plants have been commercialized. 4. SOECs can cope with transient variation due to quick response time. 5. SOECs can be used reverse mode as a fuel cell for grid balancing.	1. SOECs are still in demonstration phase for large scale applications for hydrogen production and are not readily commercially available. 2. SOEC's units are about 10 times smaller in H_2 output than PEMEC and AEC. 3. The stack components are susceptible to corrosion. 4. Commercially available lifetime system is short compared to PEMEC and even shorter to AEC. 5. SOECs can be operated only at current densities up to 0.5 A/cm^2.

Figure 25 - Summary of advantages and disadvantages of AEC, PEMEC and SOEC (Danish Energy Agency, 2017).

Excess Heat Produced from Electrolysis: Overview and Potential Applications

Electrolysis, particularly water electrolysis for hydrogen production, involves passing an electric current through water to split it into hydrogen and oxygen. During this process, not all the input energy is converted into the chemical energy of hydrogen; a portion of it is lost as heat. This excess heat can arise due to the inherent inefficiencies in the electrolyser's components, such as the resistance of the electrolyte, the overpotentials at the electrodes, and other thermal losses.

Understanding the generation and potential uses of this excess heat is crucial for improving the overall efficiency and economics of electrolysis systems. In detail, these aspects are:

1. Generation of Excess Heat in Electrolysis

- **Thermodynamic Losses**: Electrolysis involves endothermic and exothermic reactions at the electrodes. The overall process is thermodynamically unfavourable, requiring an external energy supply. The electrochemical reactions at the anode and cathode are associated with overpotentials—extra energy required to drive the reactions beyond their thermodynamic requirements. This extra energy is primarily dissipated as heat (Laguna-Bercero, 2012).

- **Ohmic Losses**: Electrical resistance within the electrolyte, electrodes, and membrane (if present) generates heat. This is particularly relevant in high-current-density operations where resistive losses can be significant.
- **Heat from Compression**: In some cases, the electrolysers are designed to operate at high pressures to reduce downstream hydrogen compression needs. The energy required to compress the gas also contributes to excess heat.
- **Efficiency Factors**: Different electrolysis technologies (e.g., PEM, AEM, Alkaline, High-Temperature Steam Electrolysis) produce varying amounts of excess heat. For example, high-temperature steam electrolysis (HTSE) generates more excess heat because it operates at temperatures between 700-1000°C, whereas PEM and alkaline electrolysers typically operate at lower temperatures (around 50-80°C).

2. Potential Applications of Excess Heat from Electrolysis

Excess heat generated during electrolysis can be harnessed for various secondary applications, improving overall system efficiency and contributing to integrated energy systems. Here are some potential uses:

A. District Heating and Low-Temperature Applications

- **District Heating Systems**: In urban or industrial settings, excess heat from electrolysis can be used to supply district heating networks. The relatively low-temperature heat (around 50-80°C from PEM or alkaline electrolysers) can be effectively used for residential or commercial space heating or for providing hot water. This application is particularly viable where the electrolysis plant is located near the heat demand center.
- **Greenhouses and Agricultural Heating**: Excess heat can be redirected to greenhouses for controlled environment agriculture, providing a cost-effective heating source during colder months. This application can enhance agricultural productivity and reduce reliance on fossil fuels.

B. Preheating in Industrial Processes

- **Preheating Water or Feedstock**: In many industries, there is a need to preheat water or feedstock materials before they enter a primary heating process (such as boilers or reactors). The excess heat from electrolysis can be used to preheat these inputs, reducing the overall energy demand and improving process efficiency.)
- **Thermal Energy Storage (TES)**: Excess heat from electrolysis can be stored in thermal energy storage systems (like hot water tanks or phase change materials) and used later when demand for heat is higher or electricity prices are unfavourable. This application could help balance supply and demand in integrated renewable energy systems.

C. Enhancing Efficiency of High-Temperature Electrolysis (HTSE)

- **Internal Heat Recirculation**: For high-temperature steam electrolysis (HTSE) systems, the excess heat can be recycled within the electrolyser to maintain the high operating temperatures required. This reduces the need for additional external heating sources and can significantly improve the overall efficiency of the system. (Cavaliere, 2023)
- **Cogeneration Systems**: HTSE plants can be integrated into cogeneration (combined heat and power, CHP) systems, where the excess heat from the electrolysis process is used to generate

electricity or provide heating. This integration makes better use of the available thermal energy and can lead to higher overall system efficiencies. (Steinfeld, 2005)

D. Desalination and Water Purification

- **Thermal Desalination**: Excess heat from electrolysis can be utilized in thermal desalination processes like Multi-Effect Distillation (MED) or Multi-Stage Flash Distillation (MSF), which require a heat source to evaporate and condense water. This application is particularly relevant in coastal regions where seawater desalination is needed to provide freshwater.
- **Water Purification**: Low-grade heat can be used in processes such as membrane distillation or solar stills to purify contaminated or saline water. This approach is particularly beneficial in off-grid or remote locations where energy resources are limited.

E. Supporting Renewable Energy Integration

- **Grid Balancing**: Excess heat from electrolysis systems can be used to generate electricity through Organic Rankine Cycle (ORC) systems or other heat-to-power technologies during periods of high electricity demand or low renewable generation. This capability enhances the flexibility of the electrolysis plant, allowing it to participate more effectively in grid balancing services.
- **Energy Storage Support**: In cases where electrolysers are coupled with renewable energy sources (like solar or wind), the excess heat can be used to optimize the performance of battery storage systems or pumped hydro storage by maintaining temperature conditions that maximize their efficiency.

F. Hydrogen Refuelling Stations

- **Preheating for Hydrogen Compression**: Hydrogen produced by electrolysis is often compressed for storage or use in hydrogen refuelling stations. The excess heat can be used to preheat compressors or storage tanks, reducing the energy required for compression and enhancing the overall efficiency of the refuelling process.

3. Conclusion: Enhancing the Value of Excess Heat from Electrolysis

Harnessing the excess heat generated during electrolysis can significantly improve the overall energy efficiency and economics of hydrogen production systems. By integrating these systems into broader energy networks (such as district heating or industrial processes), or by using the heat for cogeneration and desalination, the value of the electrolyser’s output can be maximized. In a future energy system dominated by renewable sources, the ability to effectively utilize every available form of energy will be key to achieving sustainability and reducing carbon emissions.

Heat generation

To calculate the amount of heat generated by a 0.8 GW (800 MW) electrolysis plant, we need to consider the efficiency of the electrolysis process. The efficiency affects how much of the electrical energy is converted into useful hydrogen production versus how much is lost as heat.

General Calculation Approach

1. **Determine the Electrical Input**:
    - The plant has an electrical power input of 0.8 GW (800 MW).
2. **Estimate the Electrolysis Efficiency**:
    - The efficiency of water electrolysis systems varies, typically ranging from 60% to 80%. For our calculation, we used a mid-range efficiency of 70%.
3. **Calculate the Heat Loss**:
    - If the efficiency is 70%, then 30% of the electrical input energy is lost as heat.

Calculation Steps

1. **Electrical Input Power**:
    - Power input = 0.8 GW = 800 MW
2. **Efficiency**:
    - Efficiency = 70% (0.70)
3. **Heat Loss Percentage**:
    - Heat loss percentage = 100% - Efficiency = 100% - 70% = 30% (0.30)
4. **Calculate Heat Generated**:
    - Heat generated = Electrical input power × Heat loss percentage
    - Heat generated = 800 MW × 0.30 = 240 MW

Result

A 0.8 GW electrolysis plant, operating at an efficiency of 70%, would generate approximately 240 MW of excess heat. The calculation represents the instantaneous rate of heat generation, and it refers to the amount of heat produced at any given moment in time. For example:

Daily Heat Generation Calculation

1. **Determine the Heat Generation Rate**:
    - Heat generation rate = 240 MW
2. **Convert to Energy Over a Day**:
    - There are 24 hours in a day and 3600 seconds in an hour.

3. **Calculate Total Heat Energy per Day**:
    - Total energy (in MWh) = Power (MW) × Time (hours)
    - Total energy per day = 240 MW × 24 hours = 5760 MWh

Bornholm - Specific Opportunities for Excess Heat Utilization

A 0.8 GW electrolysis plant operating at 70% efficiency would generate approximately 240 MW of excess heat, equivalent to 5,760 MWh per day. This substantial thermal energy presents multiple opportunities for Bornholm:

- **District Heating Integration:** Rønne and other urban areas could utilize this heat to supply residential and commercial heating networks, significantly reducing reliance on fossil fuels and lowering heating costs.
- **Greenhouse Heating:** Agricultural sectors could benefit from low-grade heat for controlled-environment farming, supporting local food production and sustainability goals.
- **Industrial Preheating:** Heat could be used to preheat water or feedstock for local industries, improving energy efficiency and reducing operational costs.
- **Desalination and Water Reuse:** Excess heat could support thermal desalination or advanced water purification processes, complementing PtX water supply strategies.

Leveraging this heat would transform the PtX plant into a multi-energy hub, enhancing overall system efficiency and contributing to Bornholm's Energy Island vision.

Techno-Economic Analysis

Energy balance overview

This section presents the energy balance for three electrolysis technologies:

- **AEC (Alkaline Electrolysis Cell)**
- **PEMEC (Proton Exchange Membrane Electrolysis Cell)**
- **SOEC (Solid Oxide Electrolysis Cell)**

The data, based on Ramboll projects (2020) and the Danish Energy Agency (2017), reflects plant-level performance including Balance of Plant (BoP) components.

Key Differences in Energy Inputs

- **AEC and PEMEC:**
  - Input energy consists entirely of electricity.
- **SOEC:**
  - Operates at high temperatures (>600°C), requiring water to be converted into steam.
  - In 2020, 79.5% of input energy was electricity, while 20.5% came from heat supply.

This distinction is critical because SOEC systems can integrate waste heat from industrial processes or renewable thermal sources, improving overall efficiency.

Outputs and Heat Recovery

When water or steam enters the electrolysis cells, the process produces hydrogen (H_2) and oxygen (O_2), along with dissipated heat.

- Only part of this heat is usable for applications like district heating, as it must meet minimum temperature requirements for integration into heating networks.
- This analysis excludes the latent heat of vaporization of steam, focusing on Low Heating Value (LHV) and High Heating Value (HHV) of hydrogen for accurate energy accounting.

Figure 26 - The energy inputs from and outputs of an AEC (2020, 10MW hydrogen plants). Data is derived from Ramboll references.

Figure 27 - The energy inputs from and outputs of an PEMEC (2020, 10MW hydrogen plants). Data is derived from Ramboll references.

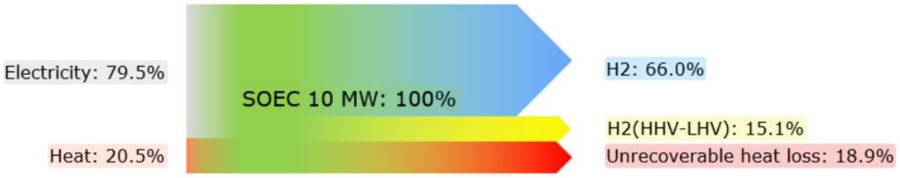


Figure 28 - The energy inputs from and outputs of an SOEC (2020, 10MW hydrogen plants). Data is derived from Ramboll references.

Which Technology Offers the Best Energy Balance for Bornholm?

For Bornholm’s PtX ambitions, PEM electrolysis stands out as the most suitable technology. While AEC offers lower CAPEX, its slower response time and lower efficiency make it less ideal for integration with intermittent offshore wind power. SOEC provides the highest theoretical efficiency and the ability to utilize waste heat, but its requirement for high-temperature steam (>600°C) and early-stage commercial maturity introduce complexity and risk.

PEM electrolysers combine high efficiency, fast load-following capability, and compact design, making them well-suited for Bornholm’s fluctuating renewable energy supply and space constraints near the Energy Island’s converter station. Additionally, PEM’s ability to operate dynamically supports grid balancing and maximizes hydrogen output during peak wind generation periods.

Capital and Operational Costs

This subsection summarizes economic estimates for ultrapure water production based on the NIRAS report “Process Wastewater Treatment” (2024). The analysis considers treatment solutions for different plant sizes (50 MW and 1 GW) using supplier quotes (2023–2024) and average water source profiles. Costs include:

- **Construction and installation**
- **Pre-treatment**
- **Reverse Osmosis (RO)**
- **Post-polishing**
- **Process wastewater treatment**

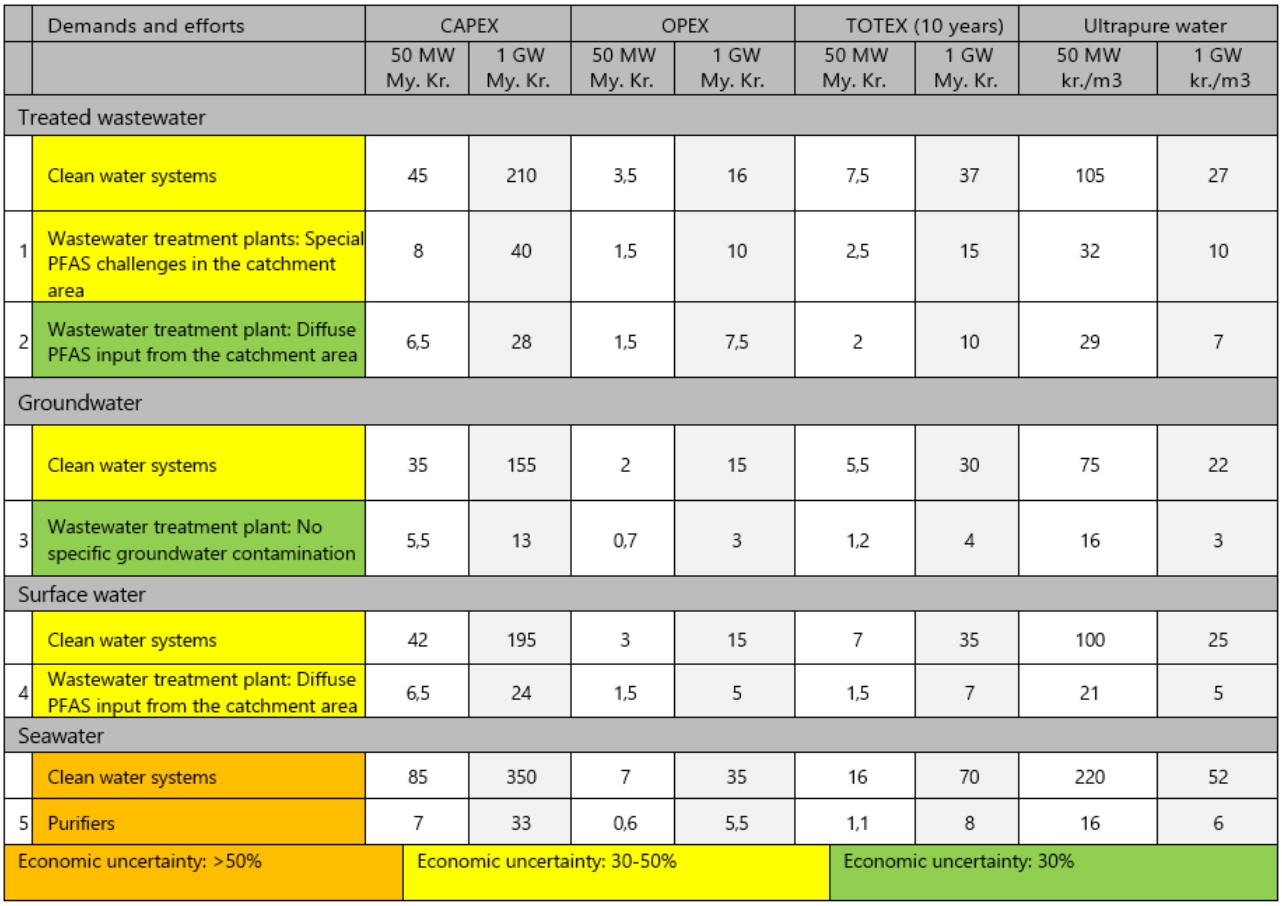
A 10-year depreciation period was applied for annual cost calculations (TOTEX).

Key Cost Drivers

- Water source (wastewater, groundwater, seawater)
- Recovery rate and treatment complexity
- Electrolysis process requirements (conductivity thresholds)

Cost Comparison by Source and Scale

- **Wastewater (treated effluent):**
    - **50 MW plant:** ~DKK **135/m³** (DKK 105/m³ for production + DKK 29/m³ for wastewater treatment)
    - **1 GW plant:** ~DKK **35/m³** (DKK 27/m³ for production + DKK 7/m³ for wastewater treatment)
- **Seawater (brackish):**
    - **50 MW plant:** ~DKK **220/m³**
    - **1 GW plant:** ~DKK **52/m³**
- **Groundwater:** Lowest cost option (~DKK 75/m³ for 50 MW; ~DKK 22/m³ for 1 GW), but limited availability and ethical concerns make it impractical for Bornholm.



	Demands and efforts	CAPEX		OPEX		TOTEX (10 years)		Ultrapure water	
		50 MW My. Kr.	1 GW My. Kr.	50 MW My. Kr.	1 GW My. Kr.	50 MW My. Kr.	1 GW My. Kr.	50 MW kr./m3	1 GW kr./m3
Treated wastewater									
	Clean water systems	45	210	3,5	16	7,5	37	105	27
1	Wastewater treatment plants: Special PFAS challenges in the catchment area	8	40	1,5	10	2,5	15	32	10
2	Wastewater treatment plant: Diffuse PFAS input from the catchment area	6,5	28	1,5	7,5	2	10	29	7
Groundwater									
	Clean water systems	35	155	2	15	5,5	30	75	22
3	Wastewater treatment plant: No specific groundwater contamination	5,5	13	0,7	3	1,2	4	16	3
Surface water									
	Clean water systems	42	195	3	15	7	35	100	25
4	Wastewater treatment plant: Diffuse PFAS input from the catchment area	6,5	24	1,5	5	1,5	7	21	5
Seawater									
	Clean water systems	85	350	7	35	16	70	220	52
5	Purifiers	7	33	0,6	5,5	1,1	8	16	6
Economic uncertainty: >50%			Economic uncertainty: 30-50%				Economic uncertainty: 30%		

Figure 29 - CAPEX (Capital Investment), OPEX (Annual Operation) and TOTEX (Total Annual Costs) of 50 MW and 1 GW installations for alternative water sources and technology trains, as well as prices per m3 of ultrapure water. The economic uncertainty is color-code (Niras 2024).

Economies of Scale

Unit costs decrease significantly with scale:

- **50 MW → 1 GW:** Cost per m³ drops by ~75%, driven by higher recovery rates and optimized infrastructure.

Uncertainty Factors

- Source variability (e.g., seasonal changes in wastewater composition)
- PFAS contamination risks in catchment areas
- Future regulatory requirements for advanced treatment

Why Wastewater is the Most Strategic Option for Bornholm

Wastewater emerges as the most cost-effective and sustainable water source for PtX on Bornholm. At 1 GW scale, ultrapure water production from treated wastewater costs approximately DKK 35/m³, compared to DKK 52/m³ for seawater—a 33% cost advantage. At smaller scales (50 MW), the gap widens further: DKK 135/m³ for wastewater versus DKK 220/m³ for seawater. Beyond economics, wastewater reuse supports circular economy principles, reduces environmental discharge, and avoids the high energy demand of seawater desalination. Combined with Bornholm's existing WWTP infrastructure, wastewater offers a strategic balance of cost, sustainability, and regulatory feasibility, making it the preferred source for PtX development.

Economic feasibility

Regulatory Framework of data retrieved from DIN Forsyning - Technical Water A/S

Economic feasibility for PtX water supply is assessed under the PIT model by DANVA, applying the same conditions as other water utilities—no special exemptions for PtX. Key assumptions include:

- **Inflation/price escalation:** 2.0% annually
- **Operational efficiency requirement:** 2.0% annually
- **Facility efficiency requirement:** 1.8% annually
- **Individual requirement:** 0% annually (best case)

Challenge:
Technical water companies rely on commercial agreements for revenue, unlike regulated utilities that can adjust tariffs or apply surcharges. This limits flexibility in covering rising costs.

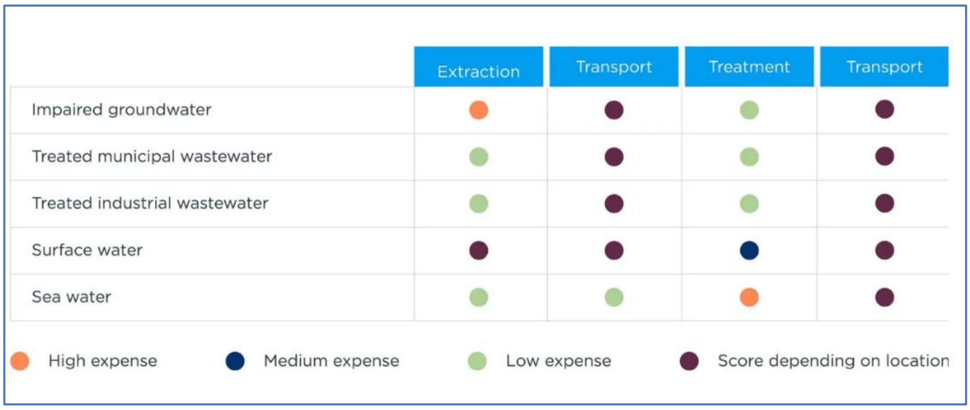
Indicative Treatment Costs

New Treatment Plant Øst (50,000 PE capacity):

- CAPEX: DKK 150 million
- OPEX: DKK 15–20 million
- TOTEX: ~DKK 25 million
- Output: 85 tons of nitrogen removed annually

Industry Feedback for Bornholm case – EUROWATER (Henrik Madsen)

- **CAPEX/OPEX estimates:** €1–3 million (excluding EDI), highly design-dependent
- **Additional costs:** Specialized wastewater processes (e.g., concentrated RO waste during dry summers)
- **Space requirements:** Compact RO units (~5 m² footprint), but multiple units needed for large-scale PtX



	Extraction	Transport	Treatment	Transport
Impaired groundwater	🟠	🟣	🟢	🟣
Treated municipal wastewater	🟢	🟣	🟢	🟣
Treated industrial wastewater	🟢	🟣	🟢	🟣
Surface water	🟣	🟣	🔵	🟣
Sea water	🟢	🟢	🟠	🟣

🟠 High expense 🔵 Medium expense 🟢 Low expense 🟣 Score depending on location

Figure 30 - Quantitative assessment of electrolysis water supply costs for four main water sources (Rambøll, 2024).

Bornholm Case – 0.8 GW PtX (PEM Electrolysis)

Table 7 - Economic comparison between the use of the wastewater or Brackish water (Baltic Sea). Based on the findings at this report.

Parameter	Wastewater Effluent	Brackish Seawater
Feed water (m³/h)	230	400 *(higher due to lower recovery)*
Recovery rate	70%	40–50% *(typical for seawater RO)*
Ultrapure water (m³/h)	160	160
Suggested treatment steps	UF + UV → Softening → RO → Degassing → (EDI)	Pre-treatment → Softening → RO → Degassing → (EDI)
CAPEX	~DKK 90–100 million *(based on NIRAS estimates for clean water facility)*	~DKK 150–180 million *(higher due to seawater desalination complexity)*
OPEX per year	~DKK 10–20 million	~DKK 20–30 million
Energy consumption (kWh/m³)	~5.8 *(RO + polishing)*	~8–10 *(due to high-pressure RO)*
Cost per m³	~DKK 35 *(at 1 GW scale)*	~DKK 52 *(at 1 GW scale)*
Lifetime	10–15 years	10–15 years
Brine/concentrate handling	Moderate *(lower salinity)*	High *(large brine volumes, disposal challenges)*

Key Insights:

- **Wastewater** offers a clear economic advantage: ~DKK 35/m³ vs. ~DKK 52/m³ for seawater at 1 GW scale.
- **Energy demand** for seawater treatment is 40–70% higher due to desalination pressure requirements.
- **Brine management** is significantly more complex for seawater, adding environmental and regulatory challenges.
- **PEM electrolysis** is chosen for Bornholm due to its ability to handle dynamic loads from offshore wind and its compatibility with ultrapure water requirements (<0.1 µS/cm).

Energy consumption assessment

Energy consumption for water treatment is often raised as a concern, especially for seawater desalination. However, it is important to note that while water treatment requires breaking ionic bonds between water molecules and dissolved salts, electrolysis must break the much stronger covalent bonds within water molecules. Consequently, the energy required for water treatment is negligible compared to electrolysis.

As illustrated in Figure 31, converting seawater to ultrapure water consumes 3–4 times more energy than treating wastewater or groundwater. Still, this represents only about 0.1% of the energy required for electrolysis.

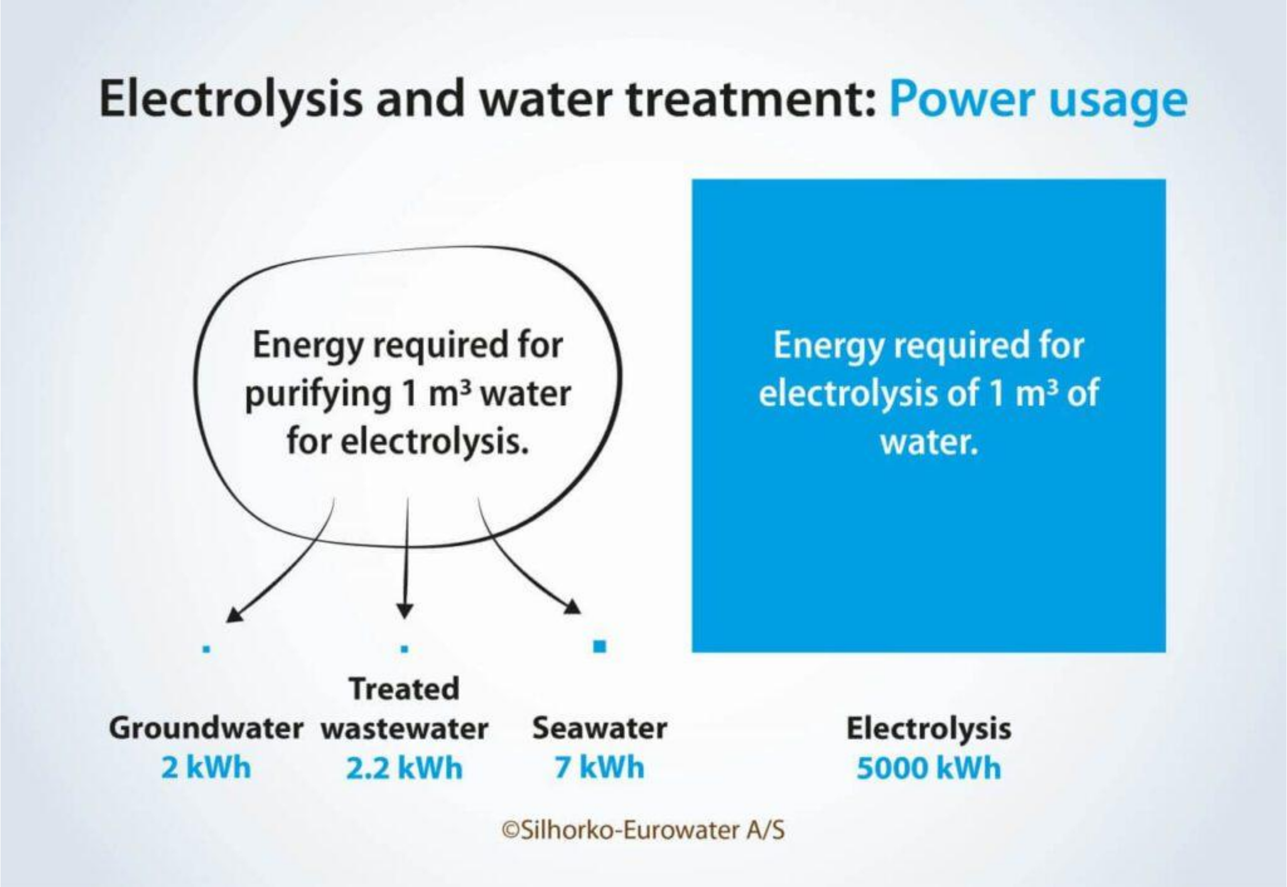


Figure 31 - The energy required to produce ultrapure water from different raw water sources (EUROWATER, 2023)

Specific Energy Consumption by Source

Wastewater:

- **~2.2 kWh/m³** for treatment to ultrapure water quality (EUROWATER, 2023).

Brackish Water (Baltic Sea):

- Energy demand varies with salinity and recovery rate.
- For Bornholm's salinity (~8 g/L), Reverse Osmosis (RO) requires approximately **1.2–1.5 kWh/m³** (Patel, Sohum K., et. al., 2021).
- Typical range for brackish water RO: **0.013–2.99 kWh/m³** depending on feedwater quality and salt removal efficiency.

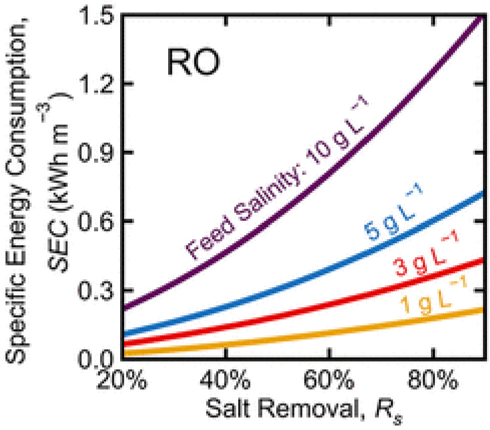


Figure 32 - Specific energy consumption (SEC) for RO as a function of salt removal (Rs). The water recovery and productivity are fixed at 80% and 20 L m–2 h–1, respectively. The various coloured lines show different feed salinities (Patel, Sohum K., et. al., 2021).[5]

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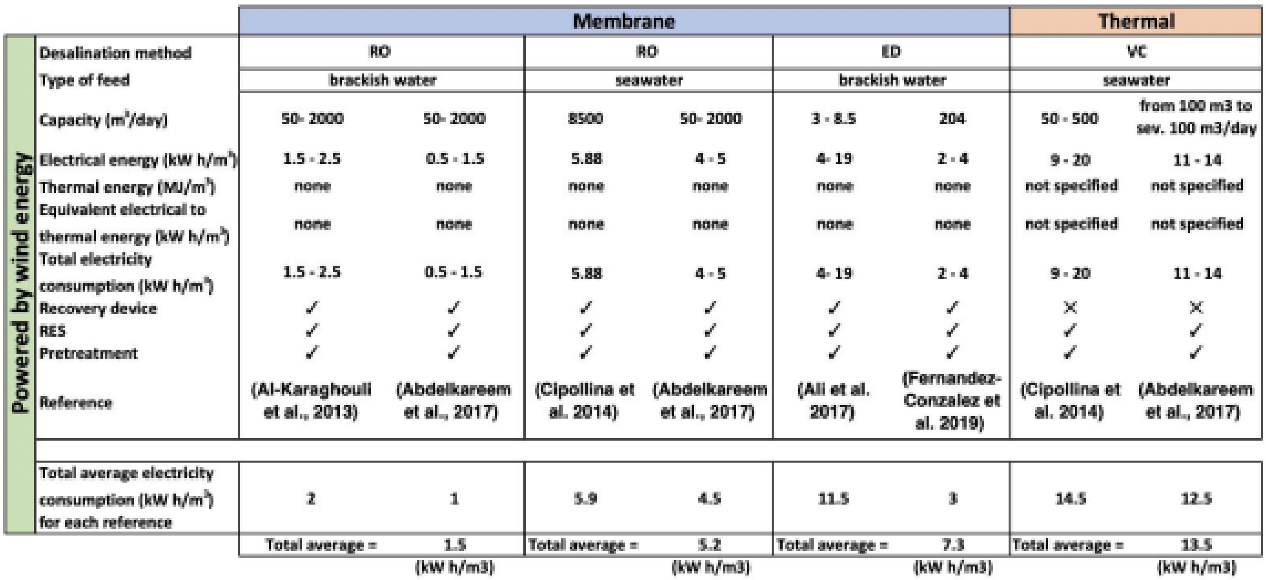
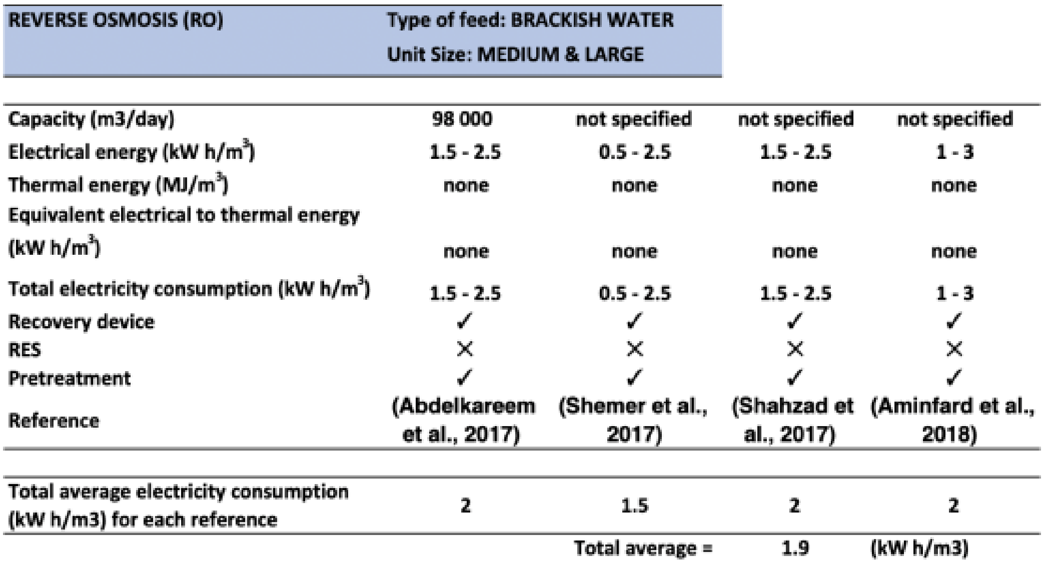
[5] Energy Consumption of Brackish Water Desalination: Identifying the Sweet Spots for Electrodialysis and Reverse Osmosis | ACS ES&T Engineering



		Membrane						Thermal	
Powered by wind energy	Desalination method	RO		RO		ED		VC	
	Type of feed	brackish water		seawater		brackish water		seawater	
	Capacity (m^3/day)	50- 2000	50- 2000	8500	50- 2000	3 - 8.5	204	50 - 500	from 100 m3 to sev. 100 m3/day
	Electrical energy (kW h/m^3)	1.5 - 2.5	0.5 - 1.5	5.88	4 - 5	4- 19	2 - 4	9 - 20	11 - 14
	Thermal energy (MJ/m^3)	none	none	none	none	none	none	not specified	not specified
	Equivalent electrical to thermal energy (kW h/m^3)	none	none	none	none	none	none	not specified	not specified
	Total electricity consumption (kW h/m^3)	1.5 - 2.5	0.5 - 1.5	5.88	4 - 5	4- 19	2 - 4	9 - 20	11 - 14
	Recovery device	✓	✓	✓	✓	✓	✓	✕	✕
	RES	✓	✓	✓	✓	✓	✓	✓	✓
	Pretreatment	✓	✓	✓	✓	✓	✓	✓	✓
	Reference	(Al-Karaghouli et al., 2013)	(Abdelkareem et al., 2017)	(Cipollina et al. 2014)	(Abdelkareem et al., 2017)	(Ali et al. 2017)	(Fernandez-Conzalez et al. 2019)	(Cipollina et al. 2014)	(Abdelkareem et al., 2017)
	Total average electricity consumption (kW h/m^3) for each reference	2	1	5.9	4.5	11.5	3	14.5	12.5
		Total average =	1.5	Total average =	5.2	Total average =	7.3	Total average =	13.5
			(kW h/m3)		(kW h/m3)		(kW h/m3)		(kW h/m3)

Figure 33 - The summary of desalination technologies powered by wind energy (Antonyan, 2019).



REVERSE OSMOSIS (RO)	Type of feed: BRACKISH WATER Unit Size: MEDIUM & LARGE			
Capacity (m3/day)	98 000	not specified	not specified	not specified
Electrical energy (kW h/m^3)	1.5 - 2.5	0.5 - 2.5	1.5 - 2.5	1 - 3
Thermal energy (MJ/m^3)	none	none	none	none
Equivalent electrical to thermal energy (kW h/m^3)	none	none	none	none
Total electricity consumption (kW h/m^3)	1.5 - 2.5	0.5 - 2.5	1.5 - 2.5	1 - 3
Recovery device	✓	✓	✓	✓
RES	✕	✕	✕	✕
Pretreatment	✓	✓	✓	✓
Reference	(Abdelkareem et al., 2017)	(Shemer et al., 2017)	(Shahzad et al., 2017)	(Aminfard et al., 2018)
Total average electricity consumption (kW h/m3) for each reference	2	1.5	2	2
		Total average =	1.9	(kW h/m3)

Figure 34 - RO energy consumption

Key Insight

Even though brackish water treatment is more energy-intensive than wastewater treatment, the difference is marginal compared to the 45–55 kWh/kg H_2 required for electrolysis. For Bornholm, using wastewater minimizes treatment energy demand and aligns with sustainability goals.

LCA study for water supply options for a Power-to-X project in Bornholm

The goal of this study is to analyse the environmental impacts of water supply for a Power-to-X (PtX) project in Bornholm. The study is based on the method of Life Cycle Assessment (LCA) as described in ISO 14040 (ISO 14040, 2006).

Goal and scope definition

The goal of this LCA is to compare two options for water supply for a Power-to-X project in their environmental impacts. The study focusses on two major aspects of environmental concern: 1) the impact on climate change ("carbon footprint") and 2) the emissions of nutrients into the aquatic environment, leading to eutrophication.

The function of the systems under study is the supply of feed water for an electrolyser unit. In terms of water quality, the feed water should be suitable to be fed to the electrolyser water treatment, where the water is polished and fully demineralized into ultrapure water. Relevant parameters for feed water quality are low conductivity (< 20 µS/cm), low organic content (TOC < 5 mg/L) and low hardness and ionic content. In terms of required water quantity, two different setups are analysed: water supply for a 25 MW PtX plant and b) water supply for an 800 MW PtX plant. Assuming a demand for ultrapure water of 200 L/h per MW at full load, the required feed water would amount to 210 L/h and MW with 95% recovery in the electrolyzer water treatment. Finally, this amounts to 126 m^3/d of feed water needs for 25 MW PtX and 4,032 m^3/d for the 800 MW PtX plant.

The functional unit of the LCA is defined as "per m^3 of feed water supplied at a sufficient quality".

The system boundaries include the water source, the treatment of water to the required quality, and the disposal of any brine that is produced in the treatment (Fig. 35). Delivery of water from the point of treatment to the PtX location is not included.

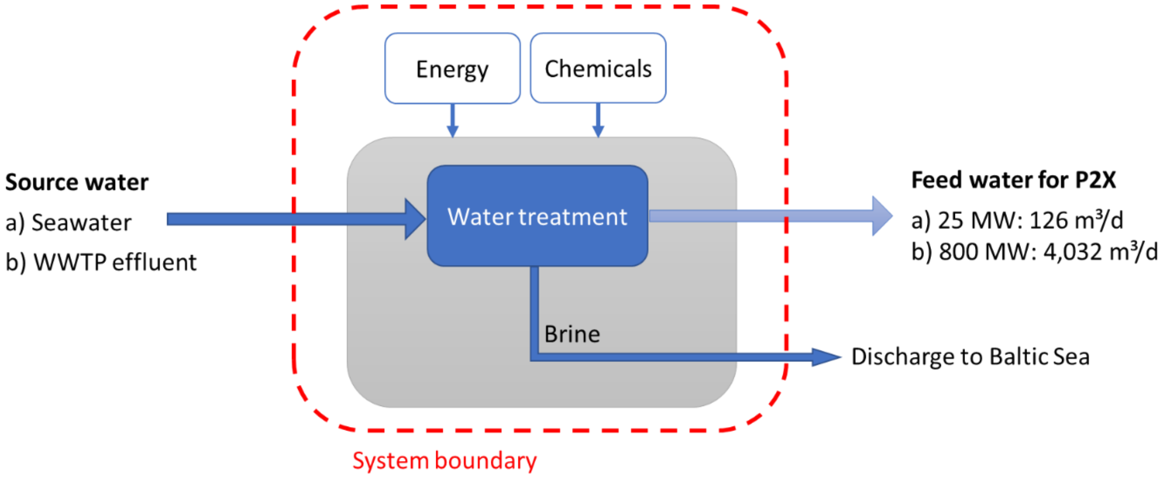


Figure 35 - System boundaries of the LCA study at Bornholm

Two different water sources are considered: 1) seawater from around Bornholm ("SW") and 2) effluent of the wastewater treatment plant Rönne ("WW"). Both water sources will be treated by a double-membrane process including ultrafiltration (UF) and reverse osmosis (RO). For the water treatment, only electricity and chemical demand are considered, whereas infrastructure (e.g. materials) and any other processes (e.g. water transport) are excluded in this LCA.

Input data for Life Cycle Inventory

Data for electricity and chemical demand of the water treatment processes (Table 9) is estimated based on comparable data from a similar LCA study (Jährig et al., 2025). This study conducted an LCA for water treatment for cooling water in Kalundborg from different water sources. As source water quality at Kalundborg is differing from conditions in Bornholm, data has been adjusted to reflect these differences adequately. However, quality data for source water in Bornholm is only limited to some basic parameters (e.g. conductivity, COD, nutrients), which made the transfer more challenging. To validate the assumptions and data for Bornholm, it would be helpful to have more detailed water quality data for both seawater and WWTP effluent.

Table 8: Electricity and chemicals demand for water treatment in the different scenarios

Parameter	**Unit**	**SW-25**	**SW-800**	**WW-25**	**WW-800**
Process		Pre-treatment + double membrane (UF/RO)		Pre-treatment + double membrane (UF/RO)	
Water recovery	%	45	45	65	65
Source water	m^3/d	280	8,960	194	6,200
Electricity	kWh/m^3	1*	1*	0.5	0.5
Chemicals					
NaOH (35%)	g/m^3	25	25	20	20
NaOCl (12%)	g/m^3	-	-	2	2
Citric Acid (40%)	g/m^3	7	7	10	10
HCl (25%)	g/m^3			30	30
NaHSO3 (18%)	g/m^3	23	23	-	-
FeCl (40%)	g/m^3	0.7	0.7	5	5

** estimated for salt content of Baltic Sea (0.8%)*

Background data for production of electricity and chemicals comes from the LCA database ecoinvent v3.10 ((Ecoinvent, 2023)). For electricity, the Danish grid mix was assumed (179 g CO_2e/kWh). For sensitivity, the use of wind power (DK, off-shore: 16 g CO_2e/kWh) was also analysed. Chemicals production was modelled with datasets for average European production.

Brine quantity and quality was modelled based on water recovery rates of the treatment trains (Table 10). It has to be noted that the brine from seawater desalination can most probably be discharged back into the ocean, while the brine from wastewater reclamation may not get a permission to be discharged to sea due to elevated concentrations of regulated substances (COD, N, P). Therefore, brine from wastewater reclamation needs a different handling. For the smaller amount of brine in scenario WW-25 (68 m^3/d), a direct recycling back to the inlet of the WWTP seems to be the best solution. This small flow accounts for only <1% of the total WWTP inlet, so that the WWTP is not overloaded with brine recycling and no negative effects of this brine on WWTP performance is expected. For the larger scenario WW-800, brine volume is at 2,168 m^3/d, which amount up to 25% of the WWTP inlet. Recycling this brine may exceed the hydraulic capacity of the WWTP, and also could have negative effects on WWTP performance. A separate brine treatment could be needed, but this is not included in the present LCA study. It has to be noted that brine management in the WW-800 scenario is a critical issue for the entire concept and should be addressed in future studies.

Table 9: Brine quantity and quality data for different scenarios

Parameter	Unit	SW-25	SW-800	WW-25	WW-800
Process		Pre-treatment + double membrane (UF/RO)		Pre-treatment + double membrane (UF/RO)	
Water recovery	%	45	45	65	65
Source water	m³/d	280	8,960	194	6,200
Product water	m³/d	126	4,032	126	4,032
Brine	m³/d	154	4,982	68	2,168
Relative to WWTP inlet (8,637 m³/d)				<1%	25%
Disposal		Sea	Sea	WWTP inlet	Sea (permission?) or treatment
COD in brine	g/m³			~ 75	~ 75
TN in brine	g/m³			~ 8	~ 8
TP in brine	g/m³			~ 0.8	~ 0.8

Results of the LCA

Global warming potential of feed water supply amounts to 0.12 kg CO_2e per m³ of feed water for reclaimed wastewater and 0,22 kg CO_2e/m^3 for seawater (Fig. 36). The main contribution to both footprints is the electricity needed for water treatment. Wastewater reclamation has a lower specific electricity demand and a higher water recovery than seawater desalination, which leads to a lower carbon footprint of this scenario (-44%). For the smaller and higher capacity (25 and 800 MW), specific carbon footprints are identical for each water source, as no "economies of scale" are included in the process data. The carbon footprint of chemical demand is comparable between wastewater and seawater scenarios and amounts to 19-27% of the total impact.

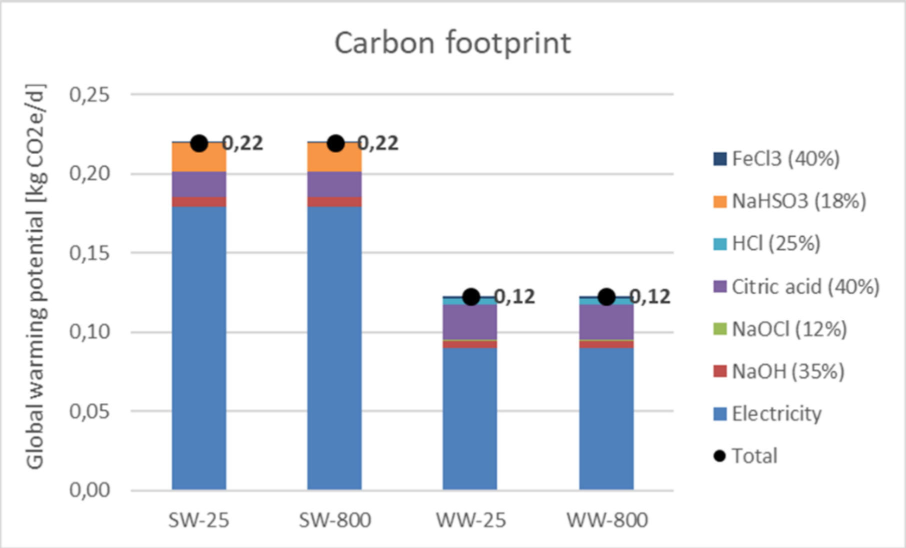


Figure 36 - Carbon footprint of feed water supply in the different scenarios (electricity as DK grid mix)

If electricity would be supplied by renewable sources only (DK wind power), the total carbon footprint of all scenarios is drastically reduced to 0.04-0.06 kg CO_2e per m³ feed water (Fig. 37). Still, seawater desalination has a higher carbon footprint that wastewater reclamation, but the absolute difference is relatively small.

With using wind power only, chemicals demand is now the major contributor to the total carbon footprint with 72-81%.

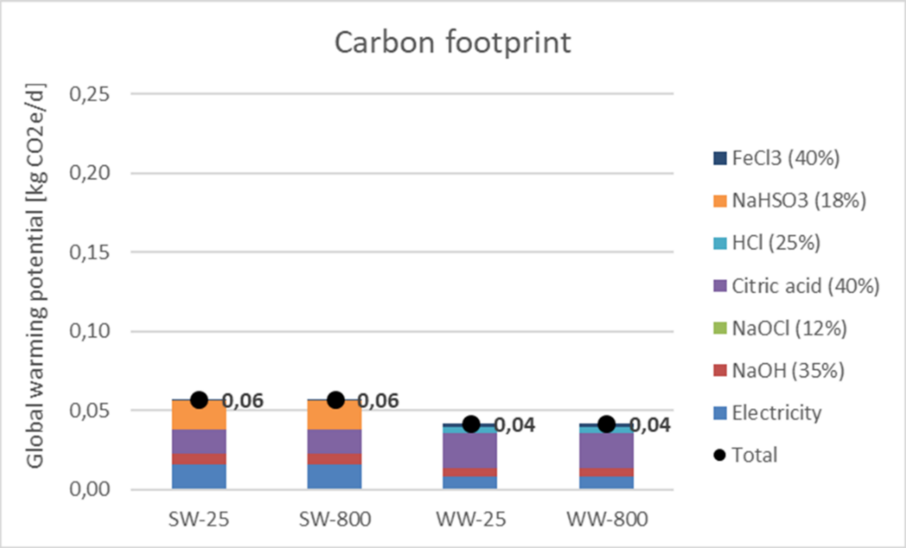


Figure 37 - Carbon footprint of feed water supply in the different scenarios (electricity as DK wind power mix)

For eutrophication, this LCA only considers direct emission of nitrogen and phosphorus into the aquatic environment for the scenarios with wastewater reclamation, neglecting any contributions from background processes such as electricity and chemicals production. The results only show the total nitrogen and phosphorus load per day for the scenarios with wastewater reclamation (Fig. 38), as seawater desalination will not lead to any “extra” emissions as brine is just returned to where it came from. The results show that the scenario WW-25 leads to a small (2%) reduction in N and P loads, as the brine is recycled back to the WWTP inlet. Scenario WW-800 results in no change in N and P emissions if brine is discharged to the sea (logically). However, if brine from WW-800 is separately treated and not discharged (e.g. by following a zero-liquid-discharge (ZLD) concept), nutrient loads could be substantially reduced (-65%). It has to be noted though that a ZLD concept for brine treatment is associated with high energy demand and related carbon footprint, which has been shown in the Kalundborg study (Jährig et al., 2025).

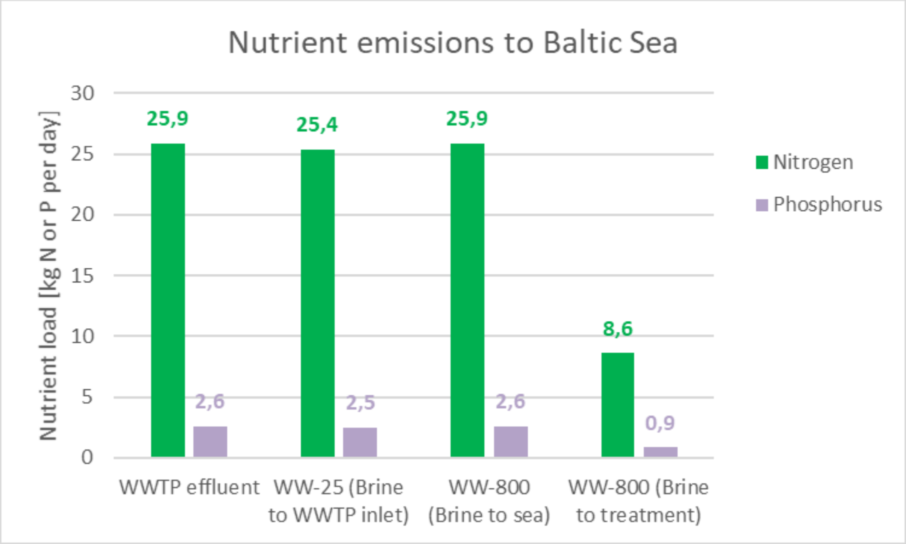


Figure 38 - Nutrient emission loads to Baltic sea in the scenarios with wastewater reclamation compared to the total nutrient loads in WWTP effluent.

Conclusions

From the LCA study of feed water supply options for a PtX unit in Bornholm, the following conclusions can be drawn:

- WWTP effluent volume is sufficient to produce feed water volumes for 25 MW and 800 MW PtX unit
- Brine disposal from wastewater reclamation is a critical problem for the 800 MW scenario (brine ~ 25% of WWTP inlet), as discharge to Baltic sea may not be permitted due to higher concentrations of pollutants
- Feed water from WWTP effluent has lower energy demand and carbon footprint (-44%) than desalinated sea water (to be confirmed with more water quality data for source waters)
- Benefits in carbon footprint are less important if wind power is used for water treatment
- Nitrogen and phosphorus loads to Baltic sea could only be substantially reduced if brine from 800 MW is treated separately (but this would increase energy demand and carbon footprint drastically)

In general, this LCA study builds on the transfer of process data from another study to the Bornholm conditions. For validating the results, more water quality data is needed to determine specific process performance and important parameters (e.g. water recovery, electricity demand) for the different options on a more solid basis.

Brine and Resource Management

Reject/Brine handling

The management of concentrate (brine) produced during desalination and ultrapure water treatment is a major technical and economic challenge for PtX projects. During filtration, a portion of the feedwater is rejected as brine, containing high concentrations of salts, solids, and other contaminants. Effective brine management is essential to prevent environmental harm and maintain system reliability.

Environmental and Technical Challenges

Reject brine can cause significant ecological impacts if discharged untreated, including:

- **Eutrophication** of water bodies
- **pH fluctuations** affecting aquatic life
- **Accumulation of heavy metals** in marine environments
- **Sterilizing effects** from residual disinfectants

These risks make brine handling and disposal a critical design consideration for PtX water treatment systems.

This **Recovery Rate and Concentration Factor**

- **Recovery rate (%):** Percentage of feedwater converted to product water
- **Concentration factor (CF):**

$$CF = \frac{1}{1 - \text{Recovery}}$$

- At 70% recovery, CF ≈ **3.3** (Figure 39).
- For ultrapure water systems operating at 75% recovery, CF ≈ **4**.
- Higher CF increases scaling and fouling risks, especially for minerals like carbonates and silica.

According to Silhorko-Eurowater, membrane systems typically have an overall recovery rate of 60-70%. As illustrated below the higher the recovery the higher the concentration factor.

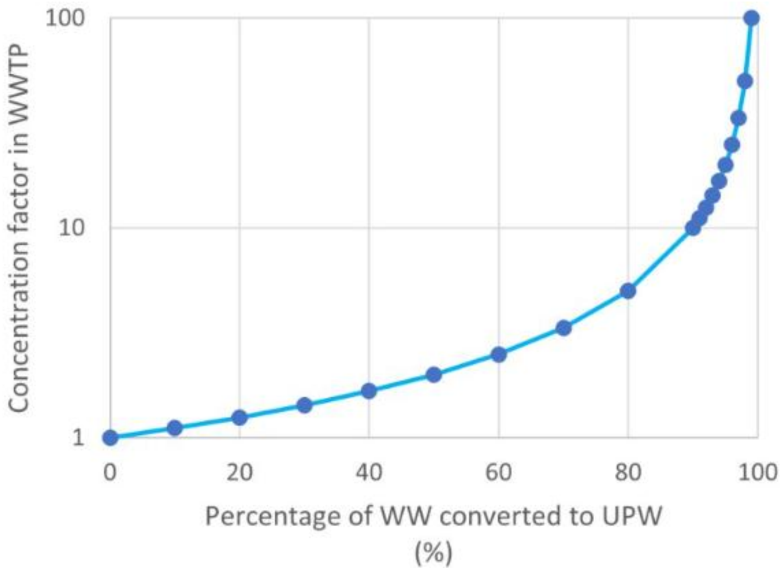


Figure 39 - How much will concentration in WWTP increase if water is used for PtX?

Impact of Recirculation

When concentrate is returned to the WWTP:

- Total CF = CF from WWTP × CF from UPW system
- Example:
  - If 50% of WWTP inflow is used for PtX and UPW recovery is 75%, CF_total ≈ 8×
  - If 90% of WWTP inflow is used, CF total can reach 40×
    This dramatically raises fouling and scaling risks, requiring lower recovery rates and higher cross-flow velocities, which increase energy demand and pressure losses.

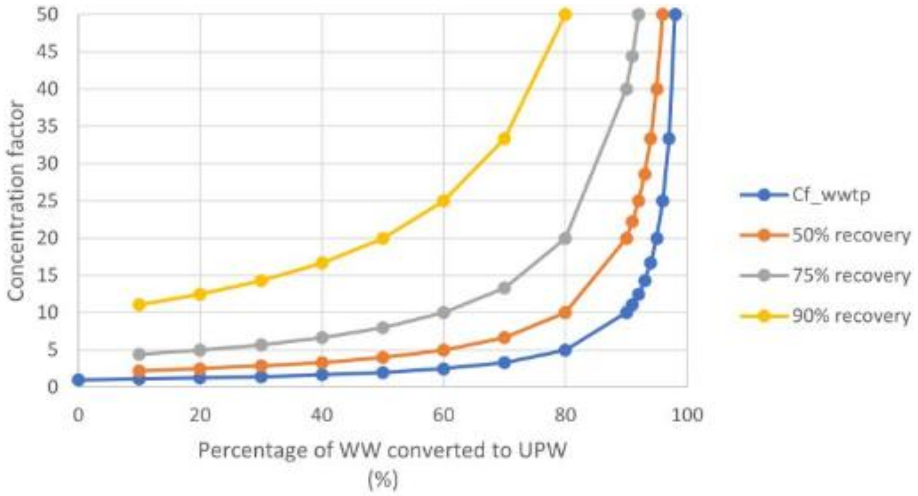


Figure 40 - Concentration factor increase in UPWTP due to PtX

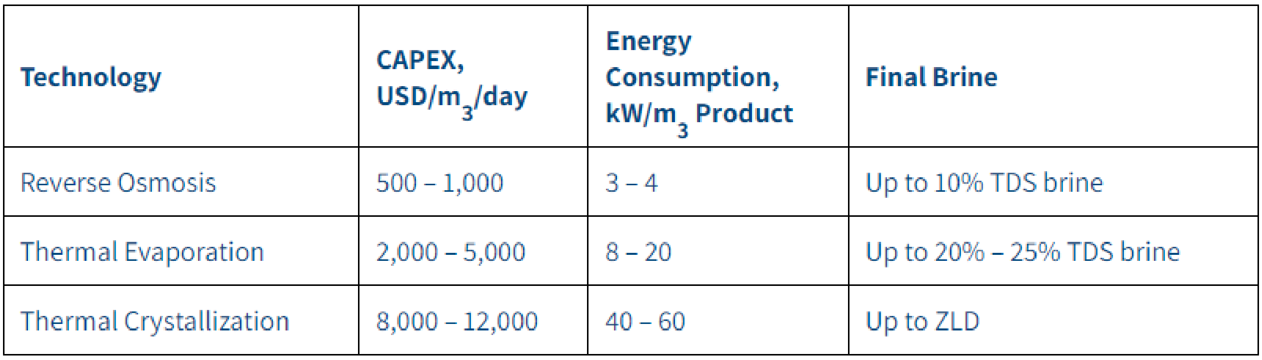
Reverse Osmosis (RO) and Brine Management

RO is the primary technology for freshwater production from brackish and seawater. It requires high operating pressures and a polishing post-treatment, typically through ion exchange or electrodialysis, to achieve the necessary water quality for PEM electrolysis.

Membrane based technologies and in particular reverse osmosis (RO) is with a market share of 69 % the market dominant desalination technology. Here water flows under high pressure (typically 52-82 bar) through a semipermeable membrane to separate the salts and minerals from the water. With an energy demand of 2.5-4.5 kWh/m^3 RO remains a highly energy intensive process, even though compared to thermal desalination, RO is more energy efficient. Independent of the technology used for the desalination process, a higher salinity is correlated with a higher energy demand. Consequently, the process of desalinating brackish water generally demands a lower energy input compared with the energy requirements of sea water desalination.

RO summary:

- RO dominates desalination (69% market share)
- Operating pressure: 52–82 bar
- Energy demand: 2.5–4.5 kWh/m^3
- Higher salinity → higher energy demand
- Brackish water requires less energy than seawater, but still generates significant brine volumes.



Technology	CAPEX, USD/m_3/day	Energy Consumption, kW/m_3 Product	Final Brine
Reverse Osmosis	500 – 1,000	3 – 4	Up to 10% TDS brine
Thermal Evaporation	2,000 – 5,000	8 – 20	Up to 20% – 25% TDS brine
Thermal Crystallization	8,000 – 12,000	40 – 60	Up to ZLD

Figure 41 - Comparison table of brine minimization technologies (IDE Technologies Group, 2019).

Key Takeaways

- **System Design:** Water treatment providers must account for recirculation effects and design for flexible recovery rates.
- **Operational Risk:** Owners should anticipate scaling and fouling risks during low-flow seasons and high PtX capacity periods.
- **Mitigation Options:**
    - Flexible systems with high cross-flow capability
    - Separate WWTP for brine handling
    - Advanced brine minimization technologies (e.g., Zero Liquid Discharge – ZLD)

Brine Handling: Wastewater vs Seawater

Brine management challenges differ significantly between wastewater and seawater sources. For wastewater, the main issue is the concentration factor increase when reject streams are recirculated to the WWTP, which can lead to severe fouling and scaling risks in both the WWTP and the ultrapure water treatment system. This requires flexible recovery strategies or dedicated brine treatment units.
In contrast, seawater desalination produces large volumes of high-salinity brine (up to 50–70% of feedwater), which cannot be discharged untreated into the Baltic Sea due to environmental regulations. Disposal options such as deep-sea discharge or Zero Liquid Discharge (ZLD) systems significantly increase CAPEX, OPEX, and energy demand, making seawater brine management more complex and costly than wastewater brine handling.
For Bornholm, wastewater offers a lower environmental risk and simpler brine management, provided that recirculation effects are carefully controlled.

Recent Innovations in Brine Management

Managing brine from ultrapure water production and desalination is a critical challenge for PtX projects. Recent technological advancements focus on minimizing brine volume, recovering valuable resources, and reducing environmental impacts.

1. Zero Liquid Discharge (ZLD) Technologies

ZLD systems aim to eliminate liquid waste, converting it into solid salts and purified water. Key innovations include:

- **Advanced Membrane Distillation:** Hydrophobic membranes separate water vapor from brine, concentrating salts.
- **Crystallizers and Evaporators:** Thermal processes recover water and produce solid salts.
- **Hybrid Systems:** Combine RO, electrodialysis, and evaporation for higher efficiency and lower costs.

2. Resource Recovery

Brine contains valuable minerals and chemicals that can be recovered:

- **Electrodialysis:** Selectively removes and recovers ions.
- **Adsorption and Precipitation:** Extracts metals such as lithium, magnesium, and rare earth elements.
- **Selective Membrane Processes:** Tailored membranes for targeted resource extraction.

3. Environmental Discharge Strategies

Controlled discharge methods aim to reduce ecological impact:

- **Diffusion Systems:** Enhance mixing and dispersion in seawater.
- **Blending with Other Effluents:** Dilutes brine concentration before discharge.
- **Constructed Wetlands:** Natural treatment systems to lower salinity and pollutants.

4. Brine Concentration and Reduction

Technologies to minimize brine volume:

- **Forward Osmosis:** Draw solution extracts water from brine.
- **Capacitive Deionization:** Electrically charged electrodes remove ions.
- **High-Recovery RO:** Maximizes water recovery, reducing brine output.

5. Innovative Desalination Techniques

New methods aim to reduce brine generation:

- **Batch Reverse Osmosis:** Cyclical process for higher recovery rates.
- **Pressure Retarded Osmosis (PRO):** Uses osmotic pressure differences to generate energy and reduce brine.
- **PtX-Powered Desalination:** Integrates renewable energy with advanced brine management.

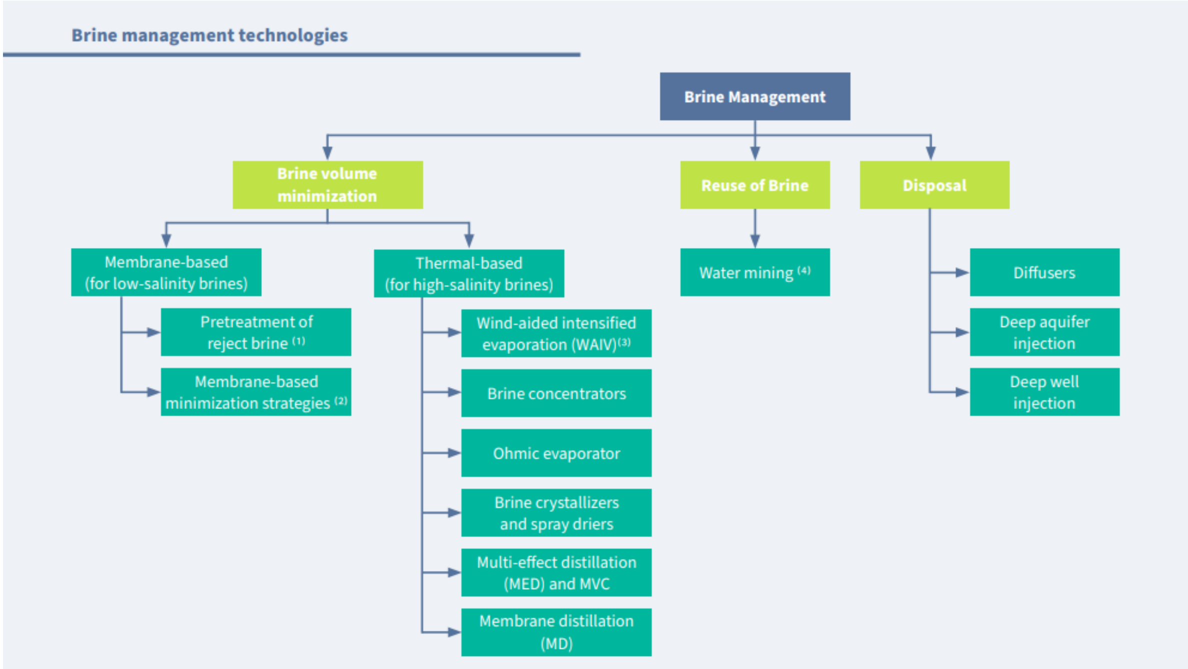


Figure 42 - Brine management technologies (International PtX Hub, 2024)

Table 10 - Brine Management Options vs Applicability for Bornholm

Brine Management Option	Description	Applicability for Bornholm
Zero Liquid Discharge (ZLD)	Converts liquid brine to solid salts and clean water	**High** – Ideal for large-scale PtX (800 MW) if Baltic discharge is restricted
Hybrid Systems (RO + Evaporation)	Combines RO, electrodialysis, and thermal processes	**High** – Suitable for wastewater brine minimization
Resource Recovery	Extracts nutrients (N, P) and minerals from brine	**High** – Aligns with circular economy and Baltic nutrient reduction goals
Constructed Wetlands	Nature-based brine dilution and treatment	**Medium** – Feasible for moderate brine volumes from wastewater
Forward Osmosis	Reduces brine volume using osmotic gradients	**Medium** – Promising for wastewater, less effective for seawater
High-Recovery RO	Maximizes water recovery, minimizes brine output	**High** – Critical for wastewater systems to reduce scaling risk
Batch RO / Pressure Retarded Osmosis	Innovative desalination with lower brine generation	**Low** – More relevant for seawater, less for wastewater
Blending with Other Effluents	Dilutes brine before discharge	**Low** – Limited by Baltic discharge regulations

This table shows **priority technologies for Bornholm**:

- **ZLD**, **Hybrid Systems**, **Resource Recovery**, and **High-Recovery RO** are most relevant for wastewater-based PtX.
- Seawater brine management options (Batch RO, PRO) are less applicable due to environmental restrictions and higher costs.

Valuable nutrients to recover

Handling concentrate from brackish water (brine) and wastewater (light brine) requires solutions that not only minimize disposal challenges but also enable resource recovery. Efficient and cost-effective technologies such as high-recovery RO, Minimal Liquid Discharge (MLD), and Zero Liquid Discharge (ZLD) are critical for economic viability.

One promising innovation, as an example, is the MAXH2O Desalter (IDE Technologies, 2024), which addresses brine reduction by:

- Operating RO at high velocity with natural shear forces to prevent scaling.
- Precipitating low-solubility salts on pellets, enabling maximum recovery without persistent fouling.
- Pushing brine volumes to new lows, improving overall system efficiency.

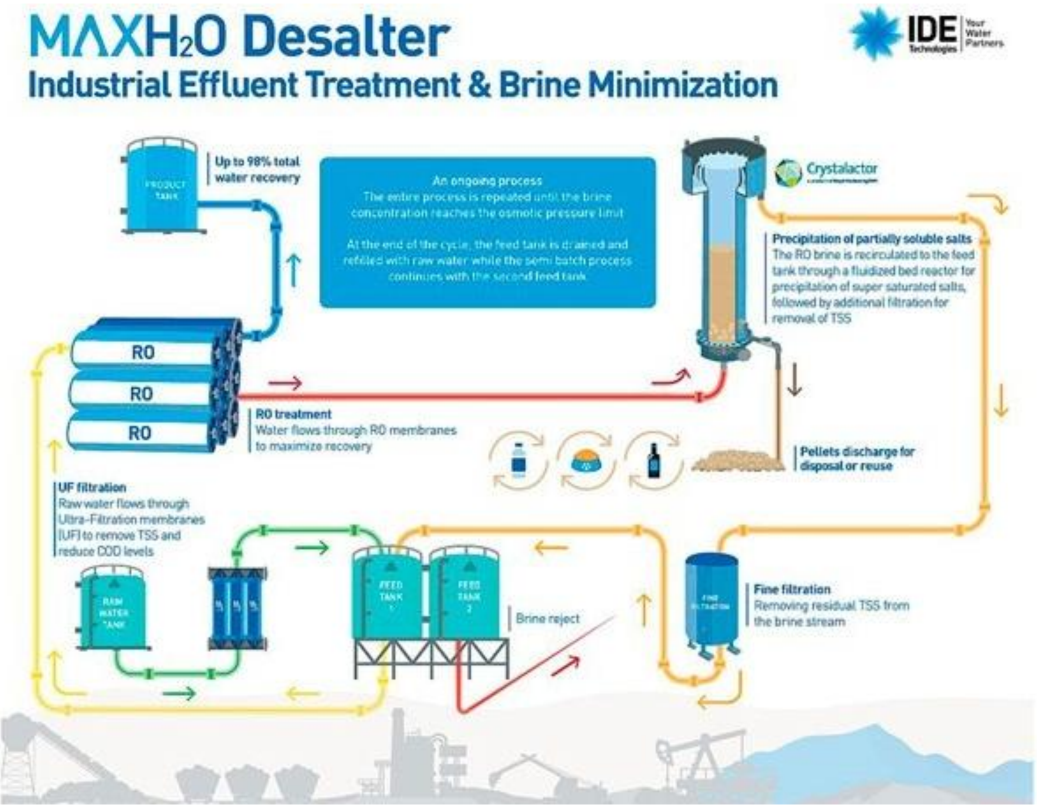


Figure 43 - MAXH2O Desalter (IDE Technologies, 2024)

Key Nutrients and Minerals for Recovery

Brine streams contain valuable compounds that can be recovered for industrial and agricultural use:

- **Sodium Hydroxide (NaOH):** Used in pretreatment for desalination and chemical industries.
- **Hydrochloric Acid (HCl):** Essential for industrial processes.
- **Magnesium:** Applications in alloys, batteries, and chemical production.
- **Calcium:** Used in cement, water treatment, and food/feed industries.
- **Potassium:** Critical for fertilizers and plant growth.
- **Sodium:** Important for soda ash production and chemical synthesis.
- **Sulphates:** Utilized in fertilizers, chemicals, and glass manufacturing.
- **Nitrate & Phosphate:** Key nutrients for agriculture.
- **Trace Elements (Iron, Zinc, Manganese):** Essential micronutrients for agriculture and industrial applications.

Why Nutrient Recovery Matters for Bornholm

Recovering nutrients and minerals from brine streams aligns with Bornholm’s circular economy goals and environmental commitments under the Baltic Sea Action Plan. By extracting compounds such as nitrogen, phosphorus, and trace elements, PtX water treatment can reduce nutrient discharge to the Baltic Sea, mitigating eutrophication risks. Additionally, recovered resources like magnesium, potassium, and calcium create opportunities for secondary revenue streams in agriculture and industry. This approach transforms brine from a waste challenge into a valuable resource, enhancing the sustainability and economic viability of Bornholm’s PtX strategy.

Types and Impacts of Contaminants in Brine

Brine disposal is a critical environmental and operational challenge for PtX water treatment systems. Reject streams from RO, ZLD, and other processes often contain concentrated contaminants that pose risks to ecosystems and infrastructure (Backer, Sumina; et al., 2022).

Key Contaminants in Brine

- **Microbial Disinfection Byproducts:**
  - Residual biocides and scavengers used in pretreatment can persist in brine, affecting aquatic microbiomes.
- **Coagulants and Flocculants:**
  - Chemicals like ferric chloride and alum increase metal concentrations in reject streams.

- **Heavy Metals:**
    - Commonly detected metals include Fe, Cu, Cr, Ni, Mo, which can accumulate in sediments and bioaccumulate in marine organisms.
- **Organic Residues:**
    - COD/BOD compounds from wastewater sources may remain concentrated in brine, increasing oxygen demand in receiving waters.
- **Salts and Scaling Compounds:**
    - High levels of calcium, magnesium, and silica can precipitate, causing fouling in treatment systems and altering water chemistry if discharged.
- **PFAS and Micropollutants:**
    - Persistent contaminants from industrial and household sources may concentrate in brine, requiring advanced treatment before disposal.

Environmental Impacts

- **Eutrophication:** Elevated nutrient levels (N, P) can trigger algal blooms and oxygen depletion.
- **pH Shifts:** Acidic or alkaline brine alters aquatic habitat conditions.
- **Toxicity:** Heavy metals and disinfectants harm marine life and disrupt food chains.
- **Long-Term Accumulation:** Persistent pollutants like PFAS pose chronic risks to ecosystems and human health.

Operational Risks

- **Scaling and Fouling:** High concentration factors increase precipitation of salts and minerals, reducing membrane life and efficiency.
- **Corrosion:** Aggressive brine chemistry accelerates equipment degradation.
- **Regulatory Compliance:** Discharge limits for metals, nutrients, and micropollutants require costly monitoring and treatment.

Economic Impact of Brine Management and Lessons from Danish Projects

Why Brine Management Costs Matter

Brine handling is not just an environmental challenge—it is a major cost driver in ultrapure water production for PtX. Technologies like Zero Liquid Discharge (ZLD) or advanced brine treatment can significantly increase CAPEX and OPEX, sometimes tipping the balance of economic feasibility for large-scale PtX plants. For example:

- ZLD systems can add 20–40% to total water treatment costs, depending on recovery targets and energy requirements.
- Brine disposal without treatment is not permitted under Danish and EU regulations, making advanced treatment unavoidable.

Insights from Danish Projects

Several Danish PtX and water reuse projects provide valuable lessons on brine management and regulatory compliance:

- **HØST PtX Esbjerg & DIN Forsyning**
    - Using treated wastewater instead of seawater avoids the extreme salinity of seawater brine, reducing treatment complexity and cost.
    - DIN Forsyning emphasizes reuse of municipal effluent to minimize environmental discharge and leverage existing infrastructure (HØST PtX Esbjerg, 2024).
- **Bornholm WaterMan LCA Study**
    - Highlights that brine disposal from wastewater reclamation becomes critical at large scales (e.g., 800 MW PtX), where reject volumes can equal 25% of WWTP inflow.
    - Discharge to the Baltic Sea may not be permitted without advanced treatment due to nutrient and pollutant concentration (Interreg - Baltic Sea Region, 2025).
- **PFAS and Micropollutant Removal Projects**
    - Danish utilities (e.g., Tune Waterworks, Fanoe Island) have implemented ion exchange and advanced oxidation for PFAS removal, showing that brine streams often require specialized treatment for hazardous substances (Eurowater, 2024).

Cost-Benefit Implications

- **Wastewater vs Seawater:**
    - Wastewater brine is less saline but contains nutrients and micropollutants, requiring chemical and biological treatment.
    - Seawater brine is highly saline and regulated for marine discharge, making ZLD or evaporation necessary—significantly more expensive.
- **Regulatory Pressure:**
    - EU Urban Wastewater Directive revisions will tighten discharge standards for nutrients and micropollutants, increasing compliance costs.
- **Recommendation:**
    - Engage with Danish projects (e.g., DIN Forsyning, NIRAS, Rambøll) to adopt best practices in brine minimization and resource recovery.

Key Takeaway

Brine management can make or break the business case for PtX water supply. Early integration of brine treatment strategies—including high-recovery RO, resource recovery, and ZLD options—is essential for Bornholm to ensure both economic viability and regulatory compliance.

Business case for Bornholm

Wastewater as a Strategic Resource

Wastewater is not just a byproduct of municipal and industrial activities—it represents a critical strategic resource for Bornholm's PtX ambitions. Leveraging treated wastewater for hydrogen electrolysis offers multiple benefits across economic, environmental, and regulatory dimensions.

1. Abundant and Reliable Supply

Bornholm's WWTPs collectively process ~7 million m^3/year, far exceeding the water demand for even large-scale PtX plants (e.g., 1.4 million m^3/year for 0.8 GW capacity). This ensures:

- **Security of supply** without competing with drinking water resources.
- **Scalability** for future PtX expansion.

2. Cost Advantage

Compared to seawater desalination:

- **Lower CAPEX and OPEX** due to reduced salinity and simpler treatment steps.
- **Unit cost at 1 GW scale:** ~**DKK 35/m³** for wastewater vs. **DKK 52/m³** for seawater.
- **Energy demand:** ~**2.2 kWh/m³** for wastewater vs. **1.5–4.5 kWh/m³** for brackish/seawater.

3. Environmental and Regulatory Alignment

- **Circular Economy:** Reusing wastewater reduces effluent discharge to the Baltic Sea, mitigating eutrophication risks.
- **Compliance:** Aligns with EU Urban Wastewater Directive goals for advanced treatment and resource recovery.
- **Carbon Footprint:** LCA shows wastewater reuse has **~44% lower carbon footprint** than seawater desalination (assuming similar operational conditions).

4. Integration with Existing Infrastructure

- WWTPs like Rønne, Nexø, and Boderne are strategically located near potential PtX sites.
- Existing sewer networks and treatment facilities reduce the need for new water intake infrastructure.

5. Opportunities for Resource Recovery

- Nutrients (N, P) and minerals (Mg, Ca, K) can be recovered from brine streams, creating secondary revenue streams and supporting Baltic nutrient reduction targets.

Strategic Implication

Positioning wastewater as the primary feedwater source for PtX transforms Bornholm's WWTPs into key enablers of the Energy Island vision, turning a waste stream into a high-value input for green hydrogen production.

Regulatory

Regulatory issues as a non-profit and regulated company?

This section deals with the regulatory issues and will try to answer the key question about the type of company to form when dealing with technical water for PtX and how the company is regulated. To begin with, this section will go more into details with the regulation of the Danish water and wastewater sector, as it is important to understand the regulatory framework that defines and sets the rules for the sector.

Both the drinking water and wastewater sectors in Denmark are natural monopolies. Therefore, both sectors are regulated according to a self-supporting principle by which companies can charge the price that corresponds to the necessary costs. In order to ensure efficient management of the sectors, in 2009 the Danish Parliament passed legislation under which the largest water supply companies and municipally owned water supply companies are subject to a number of requirements concerning economic regulation and organisation. Approximately 300 companies are subject to the regulation covered by the Danish Water Sector Act. The Act provides rules for the water supply companies to keep their revenues within a set limit (a revenue cap), and it stipulates rules for efficiency requirements. Benchmarking is used by the regulator to set individual requirements for efficiency improvements. The water sector legislation also regulates the activities which the water and wastewater companies are allowed to perform.

The Secretariat for Water Supply is the Danish economic regulator for water supply companies. The tasks of the Secretariat are stipulated in the water sector legislation. The Secretariat is a part of the Danish Competition and Consumer Authority under the Ministry of Industry, Business and Financial Affairs (Danish Energy Agency, 2024). [6]

The Danish Water Sector Act defines two types of companies that can be established and their definitions:

1) **Wastewater company**

Transports, treats, and discharges wastewater.

- Supply of technical water can be a limited part of a wastewater company's main activities, but it should not exceed the main activity which is to treat the wastewater. There are also some limitations to the degree of treatment allowed as applying extensive treatment will be considered not to be part of the main activity.

2) **Drinking water company**

Recovers, treats, transports, and distributes water. Primarily ground water.

- Supply of technical water is allowed.

Above definitions leads to the conclusion that in order to deliver technical water for PtX a separate drinking water company should be established.

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[6] Water | Energistyrelsen (ens.dk)

Self-supporting principle

According to the Danish Water Sector Act a water company is subject to economic regulation if it:

1. Supplies at least 10 households and
2. The yearly supplied/treated water quantity is > 200.000m3/year.

Water companies supplying/treating < 200.000 m3/year are only subject to the self-supporting principle (hvile-i-sig-selv-princippet) and no further economic regulation (Konkurrence- og Forbrugerstyrelsen, 2024).[7]

An important note is that a company that is part of a larger group must include and summarize figures from the whole group. In the case of BEOF, the figures from the subsidiary Bornholms Vand A/S and Bornholms Spildevand A/S would be merged.

In conclusion, a company that supplies technical water for PtX (drinking water company) will be regulated by the Danish Water Sector Act and thus must follow some basic rules:

- Must keep revenues within a set limit (a revenue cap)
- Must follow rules for efficiency requirements (DANVA, 2022). [8]

  The efficiency requirements consist of an index-based general efficiency requirement, which is supposed to reflect the expected overall productivity changes, and a benchmark-based individual efficiency requirement, which is supposed to reflect the acquisition of efficiency potential.

  The efficiency requirements are formulated as annual reductions of the revenue framework, and water and wastewater companies must therefore reduce their costs correspondingly over time, because there will be less revenue available to cover the total costs every year.

- Benchmarking and individual requirements for efficiency improvements (if supply is > 800,000 m3/year). This applies to BEOF.

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[7] Økonomiske rammer (kfst.dk)

[8] Legislation and Control Measurements (danva.dk)

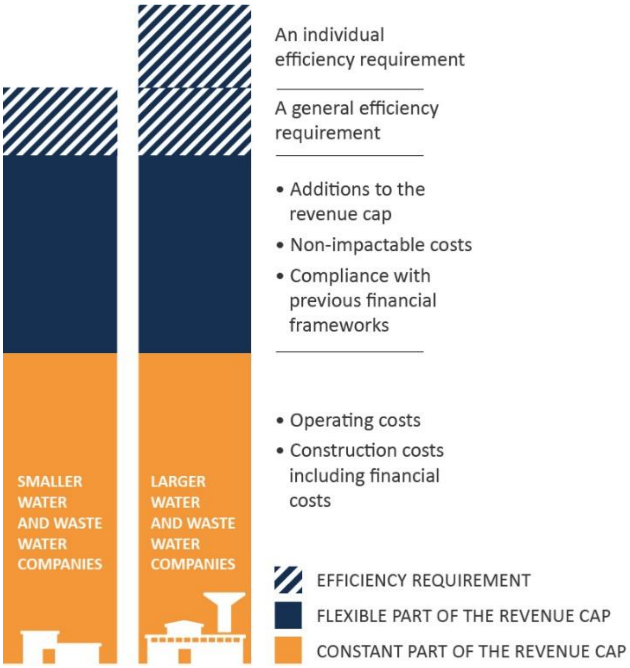

Figure 44 - Illustration of the revenue cap for small and large water companies (Konkurrence- og Forbrugerstyrelsen, 2024) [9]

Approvals and permits needed to establish new PtX plants.

The establishment and operation of PtX plants necessitates various approvals, permits, and regulatory processes to ensure that the facility is properly located and meets standards for environmental protection, safety, and other requirements.

The necessary permits for renewable energy plants in Denmark depend on the location and type of the facility, which can be established both at sea and on land. The Energistryrelsen website (Energistyrelsen, 2024) serves as a contact point for installers of such plants, in line with the implementation of the VEII and VEIII Directives, incorporated into Danish law on 1 July 2024.

A Council regulation to accelerate the deployment of renewable energy was adopted by the EU on 22 December 2022 and took effect on 30 December 2022. The regulation was later extended and amended on 19 December 2023, with some provisions directly applicable and others incorporated into Danish law on 1 July 2024 to support the expansion of renewable energy.

Energistyrelsen also provides an overview showing the majority of the rules that may come into play when establishing a PtX plant. See annexes 2.

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[9] Økonomiske rammer (kfst.dk)

Recent developments towards legislation

Danish Minister can grant exemptions from (some) requirements (2023)

Niras, an engineering consulting company, has contacted the Ministry of the Environment's special consultant in the area, Jóannes Jørgen Gaard, because it had become aware that the minister has the opportunity to grant exemptions from the requirements of the Wastewater Order. At least in terms of nitrogen and phosphorus.

"*The reject from the plant for the production of technical water actually contains a little less substance than there is today in the wastewater from the treatment plant's outlet, but at the same time is concentrated to a factor of 3-4. This means that the concentration of e.g. nitrogen is raised from 4 mg N/l to 12 mg N/l. It will be quite costly and probably technically challenging to get down to the requirements of the Wastewater Order*," writes chief consultant Claus Nickelsen from DIN Forsyning's consultant Niras to the Danish Environmental Protection Agency.

"*Since the project includes total substance reductions in terms of nitrogen and feed, there will be no problems with the Water Plans/Emergency Management Order (§8) on these substances. However, there may well be problems with the current emissions of PFOS/PFAS and other MFS (environmental pollutants, ed.) assessed in relation to the emission concentration*," writes the office, which therefore looks forward to DIN Forsyning and Niras completing a so-called Materiality Assessment Report. Among other things, it will calculate more precisely which concentrations may be problematic.

"*…DIN Forsyning should send your report to us (ministry), and that in addition to data for nitrogen and phosphorus, we also received data on what it is expected to look like for all the substances for which there are environmental quality requirements - not least PFOS/PFAS. Of course, it will be crucial for whether an exemption can be considered that the discharge does not affect the possibility of complying with all environmental quality requirements in the received water area*," writes Jóannes Jørgen Gaard (Ingeniøren, 2023).

Relevant topics that have been further encountered in research is that water utilities companies face two major challenges when engaging in PtX development (DANVA, 2024):

- The treatment of wastewater into technical water must be separated organizationally from the primary tasks of delivering drinking water and receiving wastewater, as mentioned in this section introduction. This separation maintains consumer safety for these core services. This can be achieved by establishing a separate technical water company. However, new legislation is needed to allow the formation of a technical water company outside the current water sector law.
- The overall process water from the treatment will often be of a quality that can be approved for pre-treated technical water. However, this might require collaboration from the water sector with the authorities to find a solution for a PtX facility. Without renewed legislation, this could take time.

E-mail from DANVA 17-04-2024

Special requirements for N and P in technical water (information from DANVA email 17-04-2024):

In the draft for a new executive order, more relaxed requirements are introduced for nitrogen and phosphorus in the wastewater from the production of ultrapure water. It is described in §22, subsection 3, page 18 of the draft.

In paragraph 1, no. 3, the requirement mentioned must however be < 1 mg/l at most. Paragraph 3. The limit values in subsection 1, can be exceeded in wastewater from the production of ultrapure technical water based on purified wastewater, if the total amount of nitrogen and phosphorus is reduced by 85% and 90%, respectively, during the purification process.

PFAS and Brine Management: Regulatory Uncertainty

PFAS removal is emerging as a critical compliance issue in Denmark. Current regulations impose strict PFAS limits for industrial wastewater discharge (e.g., PFOS and PFOA ≤ 2 ng/L) and mandate monitoring for over 20 PFAS compounds, but specific rules for brine from RO processes remain unclear. This creates a regulatory gap: while WWTP effluent discharge is well-defined under the Wastewater Order, concentrated brine from ultrapure water production may fall under stricter scrutiny due to its elevated PFAS levels and other micropollutants.

The Danish Environmental Protection Agency and recent PFAS Action Plan (2024–2027) signal tighter enforcement and possible EU-wide bans on non-essential PFAS uses, making proactive compliance essential. For Bornholm, this means (Danish Government, 2024) (State Of Green, 2024):

- **Legal ambiguity** on whether PFAS removal from brine is mandatory before discharge.
- **Potential cost escalation** if advanced PFAS treatment (e.g., activated carbon, ion exchange, or high-pressure membranes) becomes a requirement.
- **Strategic need for regulatory dialogue**: BEOF should engage with authorities and industry associations (e.g., DANVA) to clarify obligations, explore exemptions for industrial reuse, and advocate for consistent rules between WWTP effluent and RO brine.

Failure to address PFAS compliance early could jeopardize permits and increase operational costs, making this a priority risk factor for PtX water supply planning.

Regulatory Risk for Bornholm’s PtX Water Supply

The regulatory framework introduces several risks that could impact the economic viability and timeline of PtX water supply projects on Bornholm. Strict compliance with the Danish Water Sector Act limits pricing flexibility and imposes annual efficiency requirements, reducing revenue potential over time. Additional complexity arises from permit approvals, particularly for brine discharge and micropollutant control (PFAS, heavy metals), which may require costly advanced treatment or exemptions. Legislative uncertainty—such as pending rules for technical water companies and relaxed nutrient limits—means that early engagement with regulators and proactive planning for compliance costs are essential to avoid delays and safeguard the business case.

Risk analysis of becoming a process water supplier

The purpose of this risk analysis is to assess the most critical risks affecting the implementation of the reclaimed water supply project for PtX hydrogen production. It aims to identify, prioritize, and develop mitigation strategies to reduce both the likelihood and consequences of risks. As risks evolve throughout the project lifecycle, this analysis will be revisited periodically to integrate new insights and maintain project resilience.

Risk Identification

A comprehensive risk identification process was conducted using the PESTLE framework to cover external factors:

- **Political:** Changes in environmental policies, subsidies, or water sector regulations.
- **Economic:** Cost fluctuations in infrastructure, energy, and operational expenses.
- **Social:** Public perception and acceptance of wastewater reuse.
- **Technological:** Failures in treatment technology or new regulatory standards requiring adjustments.
- **Legal:** Compliance with the Danish Water Sector Act and other regulatory barriers.
- **Environmental:** Potential brine disposal challenges and water scarcity issues.

The risks were mapped along the critical path of the project to identify key threats to project milestones and deliverables.

Risk Assessment

The identified risks were assessed based on likelihood (L) and impact (I) using a 1-5 scale, with a risk rating (R) calculated as **R = L × I**.

Table 11 - Risk Analysis Table

Category	Risk	Description	Likelihood (1-5)	Impact (1-5)	Risk Score (R = L × I)	Risk Level
Technical	Water quality	Reclaimed water may not consistently meet RO standards for PtX production.	3	4	12	**High**
	Water composition	Variability in wastewater composition could impact treatment efficiency and compliance.	3	4	12	**High**
	Equipment failure	Unexpected breakdowns in RO systems, pumps, or storage facilities.	3	3	9	**Medium**
	Technology-related challenges	Unforeseen technical issues with RO, brine management, or desalination process.	3	3	9	**Medium**

Operational	Supply interruption (logistics)	Disruptions in pipeline or distribution system leading to water shortages.	2	3	6	**Low**
	Maintenance downtime	Planned/unplanned maintenance may cause temporary supply disruptions.	2	4	8	**Medium**
	Staff shortages	Lack of skilled personnel for plant operation and maintenance.	2	2	4	**Low**
	Natural disasters	Extreme weather events affecting infrastructure (floods, storms).	2	5	10	**High**
Regulatory & Compliance	Water use regulations	Compliance with evolving local/national water regulations.	2	4	8	**Medium**
	Wastewater discharge	Compliance risks regarding disposal and environmental limits.	2	4	8	**Medium**
	Environmental impact	Potential negative consequences from brine discharge, water use, or habitat disruption.	2	4	8	**Medium**
	Safety standards	Compliance with safety protocols in water treatment operations.	2	4	8	**Medium**
Financial	Fluctuations in water treatment costs	Rising operational costs due to energy prices, chemical use, and infrastructure upkeep.	3	3	9	**Medium**
	Fluctuations in water supply costs	Changes in wastewater treatment pricing or supply agreements.	3	3	9	**Medium**
	Unexpected expenses	Budget overruns due to unforeseen infrastructure or regulatory costs.	2	3	6	**Medium**
	Penalties for non-compliance	Fines or legal actions from regulatory violations.	2	5	10	**High**
Environmental	Contamination of natural water bodies	Improper brine disposal or leaks affecting surrounding ecosystems.	2	5	10	**High**
	Soil contamination	Chemical spills or seepage from wastewater treatment facilities.	2	5	10	**High**
	Non-compliance with sustainability goals	Failing to meet sustainability targets (e.g., water reuse efficiency, carbon footprint reduction).	2	3	6	**Medium**
Reputational	Supply interruptions	Public perception damage if reclaimed water supply is unreliable.	2	5	10	**High**
	Environmental incidents	Negative publicity from pollution, brine discharge, or ecosystem damage.	2	5	10	**High**
	Regulatory non-compliance	Reputation loss if the project is seen as failing to meet legal obligations.	2	5	10	**High**
Supply Chain	Dependence on single customer (1)	Risk if the PtX company reduces demand or cancels the agreement.	2	5	10	**High**
	Reliability of chemical suppliers	Delays or shortages in chemicals needed for water treatment.	2	2	4	**Low**
	Reliability of equipment suppliers	Delivery delays for critical treatment technology components.	2	2	4	**Low**

[1]PTX is an independent business, and it can decide to shut doors at any given time. A provider of technical water must be able to serve other purposes.

Revised Risk Analysis – Key Actions & Prioritization

1. Prioritizing the Largest Risks

The highest-priority risks are those with the highest risk scores (**10 or above**) and the greatest potential to impact the project. These include:

🔴 **Critical Risks (High Priority – Immediate Action Required)**

1. **Water quality & composition** *(Score: 12)* – Ensuring RO-treated water consistently meets PtX standards.
2. **Dependence on a single customer** *(Score: 10)* – Mitigating the risk of losing the PtX company as an off-taker.
3. **Regulatory non-compliance** *(Score: 10)* – Avoiding legal issues that could shut down operations.
4. **Environmental contamination** *(Score: 10)* – Preventing brine or wastewater spills that could harm ecosystems.
5. **Penalties for non-compliance** *(Score: 10)* – Financial consequences from regulatory breaches.
6. **Natural disasters** *(Score: 10)* – Ensuring infrastructure resilience to extreme weather events.
7. **Supply interruptions (reputational risk)** *(Score: 10)* – Preventing negative public perception.

🟡 **Medium Priority Risks (Require Monitoring & Contingency Planning)**

- **Equipment failure** *(Score: 9)* – Preventative maintenance and redundancy planning.
- **Fluctuations in operational costs** *(Score: 9)* – Budgeting for potential increases in treatment and supply costs.
- **Wastewater discharge compliance** *(Score: 8)* – Ensuring effluent meets environmental standards.
- **Maintenance downtime** *(Score: 8)* – Planning for scheduled maintenance without supply disruption.

🟢 **Low Priority Risks (Routine Monitoring & Low-Likelihood Events)**

- **Supply chain reliability (chemicals & equipment suppliers)** *(Score: 4)*
- **Staff shortages** *(Score: 4)* – Can be mitigated through training and recruitment.

Prioritization of Efforts – Mitigation & Contingency Strategies

For each high-priority risk, a **Plan A (prevention)** and a **Plan B (mitigation)** approach is suggested:

Risk	Plan A – Prevention (Reduce Likelihood)	Plan B – Mitigation (Reduce Impact)
Water quality & composition	Advanced monitoring & real-time quality control systems	Contingency treatment options (e.g., secondary polishing)
Dependence on single customer	Diversify customer base, explore alternative off-takers	Long-term contracts with volume flexibility
Regulatory non-compliance	Early stakeholder engagement & legal compliance checks	Dedicated compliance team & fast-response strategy
Environmental contamination	Strict brine & wastewater handling procedures	Emergency response plan & containment measures
Penalties for non-compliance	Active engagement with authorities, audits & self-reporting	Financial reserves for penalties
Natural disasters	Climate resilience built into infrastructure design	Emergency response plan & backup supply routes
Supply interruptions	Robust pipeline network & storage buffers	Communication strategy for customers & alternative supply

Conclusion

The feasibility study demonstrates that producing technical water for a PtX plant on Bornholm using treated wastewater is both technically viable and economically advantageous. Wastewater reuse offers a clear cost advantage over seawater desalination, particularly at large scales, and aligns with Denmark's sustainability objectives by promoting circular economy principles and reducing environmental discharge.

The Rønne WWTP emerges as the most strategic source due to its capacity and proximity to the proposed energy park. However, future water availability and quality may be influenced by factors such as WWTP restructuring, stormwater management decisions, and climate variability, requiring continuous monitoring and adaptive planning.

Economically, wastewater-based ultrapure water production is significantly cheaper than seawater treatment (DKK ~35/m^3 vs. ~52/m^3 at 1 GW scale), and energy demand for water treatment remains negligible compared to electrolysis. Integrating excess heat recovery from electrolysis into district heating or industrial processes can further enhance system efficiency and improve the overall business case.

The main challenges lie in regulatory compliance under the Danish Water Sector Act and environmental discharge limits for brine and micropollutants (including PFAS). Establishing a separate drinking water company for technical water supply is the most appropriate approach under current legislation, but legal ambiguities—especially regarding PFAS removal and brine management—necessitate early engagement with regulators and potential legislative amendments.

In summary, with careful planning, regulatory alignment, and strategic resource integration, wastewater reuse for PtX on Bornholm can become a cornerstone of Denmark's Energy Island vision and contribute significantly to national renewable energy goals.

Recommendations

To ensure successful implementation, the following actions are recommended:

- **Establish a Dedicated Technical Water Company**
  Form a regulated drinking water entity under the Danish Water Sector Act to supply ultrapure water for PtX, ensuring compliance with revenue caps and efficiency requirements.
- **Engage Early with Regulatory Authorities**
  Initiate dialogue with the Danish Competition and Consumer Authority, Environmental Protection Agency, and Energistyrelsen to clarify permit requirements, PFAS obligations, and brine discharge rules.
- **Advocate for Legislative Adjustments**
  Support amendments that allow greater flexibility for technical water production and industrial reuse of treated wastewater, including exemptions for nutrient and PFAS discharge where overall reductions are achieved.
- **Prioritize Wastewater as the Primary Source**
  Utilize Rønne WWTP as the main feedwater source due to its capacity, location, and cost advantage, while maintaining contingency plans for seasonal variations and future infrastructure changes.
- **Integrate Energy Efficiency Measures**
  Recover excess heat from electrolysis for district heating and industrial applications, transforming the PtX facility into a multi-energy hub.
- **Plan for Brine Management and Resource Recovery**
  Invest in high-recovery RO and explore ZLD or hybrid systems to minimize brine volumes. Implement nutrient recovery strategies to reduce Baltic nutrient loads and create secondary revenue streams.
- **New Treatment Plant on Bornholm**
  Future-proof water infrastructure by integrating PtX needs into the design of any new treatment plant. Consider synergies such as using PtX oxygen for wastewater treatment and CO_2 from biogas to optimize resource use and reduce emissions.
- **Conduct Detailed CAPEX/OPEX Analysis**
  Engage engineering consultants (e.g., NIRAS, Rambøll) to refine cost estimates for treatment technologies, brine handling, and integration with PtX operations.
- **Monitor Emerging Technologies and Risks**
  Continue evaluating advanced electrolysis and water treatment technologies, while tracking regulatory developments on PFAS and micropollutants to mitigate compliance risks.

Strategic Outlook for Bornholm

Bornholm is uniquely positioned to become a model for sustainable PtX development in Denmark and the Baltic region. By leveraging treated wastewater as a primary resource, integrating renewable energy from the Energy Island, and adopting advanced brine and nutrient recovery technologies, Bornholm can demonstrate how circular water management and green hydrogen production can coexist. This approach not only strengthens Bornholm’s role in Denmark’s climate and energy transition but also creates opportunities for regional innovation, new business models, and environmental leadership. With proactive regulatory engagement and strategic investments, Bornholm can set a benchmark for low-carbon, resource-efficient PtX systems that inspire similar initiatives across Europe.

Annexes:

Annex 1 – Stakeholder analysis

Primary Stakeholders (Directly Impacted and Involved)

Stakeholder	Role	Interest	Advantages	Disadvantages	Influence	Responsible	Handling
Bornholm Energi og Forsyning (BEOF)	Public wastewater utility, responsible for treating and supplying reclaimed water	Ensuring regulatory compliance, operational efficiency, and economic viability of the project	New revenue stream, innovation in water reuse, sustainability leadership	Regulatory burden, infrastructure investment costs	Great	Project Owner	Regular meetings, internal coordination
PtX Company (End User)	Recipient of reclaimed water for hydrogen production	Reliable water supply meeting electrolysis quality standards	Secure water source, cost-effective solution	Dependence on WWTP quality, potential supply disruptions	Great	Project Manager	Contract agreements, quality monitoring
SILHORKO-EUROWATER	Water treatment technology specialist	Providing technical expertise and system solutions for RO treatment	Business growth, technology showcase	Technical risks if water quality is not met	Great	Project Manager	Technical workshops, quality assurance
Rambøll	Engineering consultancy	Feasibility studies, technical assessments, and infrastructure design	Project experience, potential future contracts	Complex regulatory landscape, potential cost overruns	Great	Project Manager	Contractual scope definition, milestone tracking
NIRAS & COWI	Consulting companies	Supporting feasibility studies, regulatory compliance, and environmental assessments	Strengthened consulting portfolio, industry knowledge	Regulatory complexity, extended timelines	Great	Project Manager	Clear deliverables, phased collaboration

Regulatory & Governmental Bodies

Stakeholder	Role	Interest	Advantages	Disadvantages	Influence	Responsible	Handling
Bornholm Kommune	Local authority	Permitting, environmental impact assessment, and urban planning	Sustainable development, environmental protection	Bureaucratic delays, public scrutiny	Great	Project Manager	Early engagement, permit tracking
Miljøstyrelsen (Danish Environmental Protection Agency)	Regulator for wastewater treatment	Ensuring environmental compliance and sustainable wastewater management	Stronger regulatory framework, environmental protection	Need for extensive reporting and compliance	Great	Project Owner	Compliance meetings, reporting
Danish Competition and	Economic regulator	Ensuring compliance with economic regulations and	Market efficiency,	Regulatory constraints on pricing	Great	Project Owner	Regular updates,

Stakeholder	Role	Interest	Advantages	Disadvantages	Influence	Responsible	Handling
Consumer Authority		revenue caps for water supply	consumer protection				economic assessments
Energistyrelsen (Danish Energy Agency)	Oversees energy sector regulations	Compliance with renewable energy directives and PtX project approvals	Alignment with EU regulations, green energy promotion	Bureaucratic complexity, evolving policies	Medium	Project Owner	Policy tracking, consultation meetings
DANVA	Industry association for water and wastewater companies	Supporting best practices, benchmarking, and policy influence	Industry networking, knowledge sharing	Limited direct decision-making power	Medium	Project Manager	Collaboration forums, industry benchmarking

Infrastructure & Construction Stakeholders

Stakeholder	Role	Interest	Advantages	Disadvantages	Influence	Responsible	Handling
Construction Companies	Responsible for building pipelines, storage, and treatment facilities	Timely project completion, adherence to safety and environmental regulations	Job creation, long-term contracts	Project delays, cost overruns	Great	Project Manager	Contractual agreements, timeline monitoring
Roadwork & Infrastructure Contractors	Handling excavation, road modifications, and pipeline installations	Minimize disruptions, ensure public safety	Infrastructure development, potential for future contracts	Public inconvenience, traffic disruptions	Medium	Project Manager	Coordination meetings, impact assessments
DIN Forsyning	Multi-utility company supplying water for PtX in Esbjerg & Varde	Providing benchmark data and lessons learned	Industry knowledge, collaboration opportunities	Not directly involved in the project	Medium	Project Manager	Information exchange, benchmarking analysis

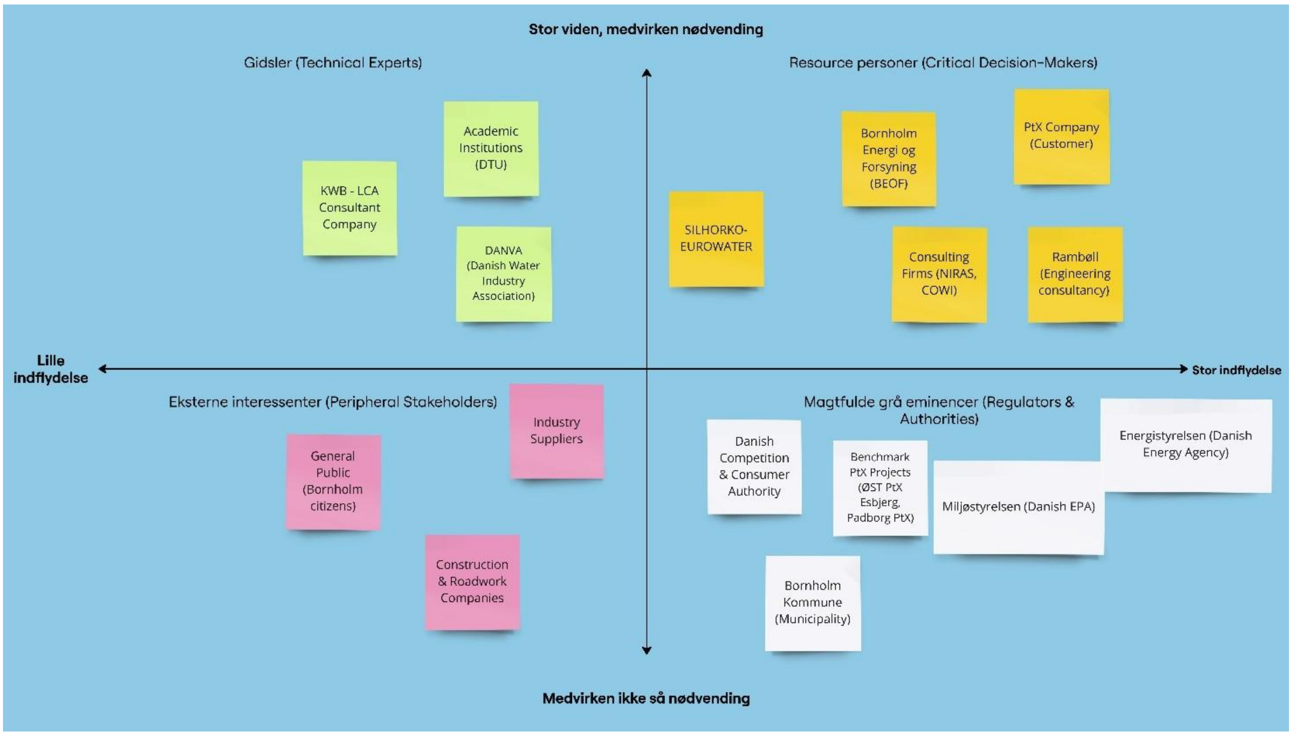
Industry & Benchmarking Stakeholders

Stakeholder	Role	Interest	Advantages	Disadvantages	Influence	Responsible	Handling
ØST PtX Esbjerg & Padborg PtX Projects	Existing PtX projects for comparison	Sharing lessons learned, best practices, and benchmarking data	Knowledge transfer, industry collaboration	Project differences limit direct applicability	Medium	Project Manager	Case study evaluations, networking

Public & Community Stakeholders

Stakeholder	Role	Interest	Advantages	Disadvantages	Influence	Responsible	Handling
Local Communities &	Concerned about land use, environmental	Transparency, minimal environmental disruption,	Environmental improvements, sustainability	Potential resistance to construction	Medium	Project Owner	Public consultations,

Stakeholder	Role	Interest	Advantages	Disadvantages	Influence	Responsible	Handling
Environmental Groups	impact, and sustainability	community benefits					transparency initiatives
Academia & Research Institutions (DTU, Universities, etc.)	Research and innovation in sustainable energy & water reuse	Opportunities for pilot studies, knowledge-sharing	Research funding, collaboration opportunities	Limited direct project involvement	Medium	Project Manager	Research partnerships, knowledge exchange



Annex 2 - Rules when establishing a PtX plant

Type of Permit	Legal Basis	Application Area	Authority
Municipal Plan (Supplement)	Planning Act	The municipal plan must, among other things, include guidelines for the location of technical facilities, including PtX facilities, cf. Planning Act § 11 a, para. 1, no. 5, and requirements for local planning for technical facilities, cf. Planning Act § 11 b, para. 1, no. 8.	Municipality
Local Plan	Planning Act	Where there is a clear starting point, a local plan for the PtX facility should be prepared, cf. Planning Act § 13, para. 2, regarding local planning for large construction and facility projects that could significantly impact the surrounding environment.	Municipality
Coastal Zone	Planning Act §§ 5 a and 5 b (on planning in the coastal zone), § 11 a, para. 1, no. 21, § 9 (regarding statements to the municipality), § 16, para. 4 (requirements for local plans) and § 29, para. 2 (notification to the minister).	The coastal zone covers coastal areas within approximately 3 km from the coast in rural and summer house areas. The coastal zone is not a prohibition zone, but specific requirements are set for planning in these areas.	Municipality - Requirements for municipal and local plans
Raw Material Plans in Relation to Planning	Guidelines and framework for planning must not conflict with regional raw material plans, cf. § 11, para. 4, no. 7. The same applies to local plans, cf. § 13, para. 1, no. 7.	Municipal plans and local plans must not conflict with regional raw material plans, cf. Raw Material Plan § 5 a.	Municipality - Requirements for municipal and local plans
Rural Zone Permit	Planning Act § 35, para. 1	Facilities established in rural zones require a rural zone permit unless there is a local plan with compensatory effect, cf. § 15, para. 4.	Municipality
Building Permit	Building Act and Building Regulations (BR 18)	PtX facilities are generally covered by the Building Act if their construction significantly impacts the surrounding environment.	Municipality
Exemption from the Agricultural Act	Agricultural Act §§ 6-7 and 28	May be relevant with entry and registration of use or lease agreements (restrictions) on setting up PtX facilities unless agricultural obligations are lifted.	Agricultural Agency
Possible Permits under the Road Act	Road Act	May be relevant if it is necessary to establish new access roads, driveways, or other similar elements in connection with the PtX facility.	Municipality
Exemption from § 3 Areas	Nature Conservation Act § 3	Prohibition against certain changes in the condition of several natural areas, including specific lakes and watercourses, but exemptions may be granted in special cases, cf. § 65, para. 3.	Municipality
Exemption from Dune Protection Line	Nature Conservation Act § 8	Dune areas are protected zones where most changes to existing conditions require an exemption. The purpose is to protect the dunes as vital parts of the coastal nature and landscape, including measures to prevent erosion.	Coastal Authority

Exemption from Coastal Protection Line	Nature Conservation Act § 15	Coastal protection zones are protected areas where most changes to existing conditions require an exemption. The purpose is to protect Danish coastal areas from erosion and maintain their natural state.	Coastal Authority
Exemption from Lake and River Protection Lines	Nature Conservation Act § 65, para. 1, cf. § 16, para. 1	Relevant only if PtX facilities are planned within or near areas covered by lake and river protection lines.	Municipality
Exemption from Forest Protection Guidelines	Nature Conservation Act § 65, para. 1, cf. § 17, para. 1	Relevant only if PtX facilities are planned within or near areas covered by forest protection guidelines.	Municipality
Exemption from Ancient Monument Protection Lines	Nature Conservation Act § 65, para. 2, cf. § 18	Relevant only if the PtX facility is planned within or near an area covered by ancient monument protection lines.	Municipality
Exemption from Church Building Guidelines	Nature Conservation Act § 65, para. 2, cf. § 19, para. 1	Relevant only if the PtX facility is planned within or near an area covered by church building guidelines.	Municipality
Exemption from Preservation	Nature Conservation Act § 50	Relevant only if the PtX facility is planned within or near an area covered by preservation regulations.	Preservation Board
Exemption from Peace Obligation	Exemption from Forest Act § 11	Relevant only if the area is under peace obligation and it has been lifted.	Environmental Agency
Exemption from Protection of Cultural Heritage Sites	Museums Act Chapters 8 and 8 a	Museums Act Chapters 8 and 8 a include rules on the protection of cultural and natural values in connection with physical planning and in relation to the designation and preservation of protected areas of cultural heritage sites.	Municipality
Exemption from Species Protection Order	Nature Conservation Act § 29a and Species Protection Order § 19, para. 1; §§ 14-19	Relevant only if the project realization involves particularly rare or sensitive species.	Environmental Protection Agency
Soil Contamination Act (JFL)	Soil Contamination Act §§ 8 and 50	In certain cases, a permit under § 8 must be issued before construction or earthworks are carried out on land, which is or may be contaminated. Processing of the permit shall include, among other things, if construction work is carried out in an area that is classified as risky for contamination. Additionally, there is a mandatory requirement for notification under § 50 in such cases.	Municipality grants permits under JFL § 8 and must comply with notification obligations under the Soil Relocation Order.
Environmental Permit for Reuse of Excavated Soil	Environmental Protection Act § 33	Reuse of excavated soil from a PtX plant requires a permit under § 33, particularly when the soil may impact the environment.	Municipality
Screening and Environmental Report (Plans or Programs)	Environmental Assessment Act §§ 8-10	Municipality and local plans require screening for environmental impacts, depending on the screening result.	Municipality
Screening and Environmental Impact Assessment (EIA) for Project	Environmental Assessment Act §§ 21 and 25	Requirement for environmental impact assessment for projects in categories 1 and 2 under the law; otherwise, a screening is needed.	Municipality or Environmental Protection Agency
Environmental Permit	Environmental Protection Act § 33, para. 1, and Executive Orders no. 2080 of 2020 and 1152 of 2021 concerning environmental approval	Permits required for the establishment and operation of listed enterprises (environmentally harmful activities).	Municipality or Environmental Protection Agency, depending on the type of PtX activity
Risk Assessment	Risk Management Order no. 374 of 2016, Act on	Risk assessment is a summary of general regulations related to environmental	Municipality or the Environmental

	Environmental Protection, Environmental Safety, and Occupational Safety Laws	protection, environmental safety, and occupational health laws. Approval is given by the relevant authority.	Protection Agency, depending on the risk assessment result.
Fire Safety Permit	Fire Protection Act with relevant technical regulations	Permit for operations involving flammable liquids, gases, and combustible solid materials.	Emergency Management Agency and Police
Connection Permit	Environmental Protection Act § 28, para. 3	Permit for connecting to the municipal wastewater treatment system.	Municipality
Water Abstraction Permit	Water Supply Act Chapter 4	If groundwater or surface water is to be used for production and no public water supply is available, a water abstraction permit is required.	Municipality
Notification to the Danish Safety Technology Authority (SIK)	Gas Safety Act with associated regulations	Any gas plant installation must be reported to SIK before being put into operation. SIK must approve electrical installations for electrical plants.	Danish Safety Technology Authority (SIK)
Connection to the Transmission Grid	Various EU Regulations and Electricity Supply Legislation	Connection to the transmission network for electrolysis and synthesis plants.	Energinet

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eurobalt.org/WaterRecyclingToolbox
interreg-baltic.eu/project/waterman

WaterMan promotes a Baltic Sea Region-specific approach to water recycling, which makes use of the alternation of too much and too little water that has become typical for humid areas in the EU to strengthen the resilience of local water supply. Building on this approach, the project supports municipalities and water companies in adapting their water supply strategies.

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