

Report AquaSPICE

*Case study at BASF Antwerp
Part II: Reuse of streams at the steam
cracker site of BASF*





The Improved containers on site at BASF Antwerp

Case study at BASF Antwerp: test period February – June 2023

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1. Abstract

During the second part of the AquaSPICE trials at BASF, the IMPROVED containers were deployed at two separate locations at the steam cracker site. In the first location a dilution steam blowdown, where steam has been in direct contact with the product, was treated aiming to produce boiler feed water using Reverse osmosis (RO), ion exchange (IEX) and granular activated carbon (GAC). Additionally, a novel electrodeionization (EDI) technology was tested to polish furnace/boiler blowdown and produce boiler feedwater. Similarly to the Dow Terneuzen case, boiler feed water could not be produced from the dilution steam blowdown due to small molecule uncharged organics such as EtOH and MeOH passing all physicochemical treatments and causing high TOC in the produced water. The furnace/boiler blowdown treatment on the other hand proved very promising using the EDI and had a high-quality water and did not show any signs of fouling.

In the second location both reverse osmosis and novel closed circuit reverse osmosis (CCRO) were tested to produce boiler feed water from the NTBA (“Niet te behandelen afvalwater” - uncontaminated wastewater) tank. The CCRO was implemented in the IMPROVED containers in specific agreement by the patent holder DuPont. However, this system was retrofitted and cannot be guaranteed that all specifications are according to the patent and should be considered a mimic CCRO.

The NTBA tank collects water from 1) run-off from the spraying of air-cooled condensers in the hot months, 2) rain water and 3) brackish blowdowns coming originally from the docks used for cooling of equipment. The brackish blowdowns needed to be reduced as much as possible, otherwise the permeate quality was insufficient and the membrane suffered from fouling. While the brackish streams were still coming into the NTBA in full flow, the CCRO proved to be much more stable on this water compared to the conventional RO. The CCRO provided very good quality water with $<100 \mu\text{S}/\text{cm}$ conductivity and 110 ppb TOC. Finally, the EDI was placed after the CCRO in order to polish the CCRO water. The EDI effluent had to be partially recirculated to the influent to meet the minimal flowrate demand. When the EDI was coupled with the CCRO, the produced water quality was excellent ($<0.07 \mu\text{S}/\text{cm}$ and <40 ppb TOC).

2. Introduction

Access to fresh water is critical for the chemical industry, where it is essential for numerous processes. Currently, the reliable provision of fresh water is under threat due to the depletion and deteriorating quality of ground and surface water sources, including increasing salinity. Adopting sustainable practices, such as recycling industrial process water and utilizing alternative water sources, offers a viable path forward. At BASF's Antwerp site, the steam cracker plays a central role in converting naphtha into a range of key chemical building blocks. In this process, naphtha is vaporized with water vapor and superheated in furnaces at around 840°C, breaking down long hydrocarbon chains into valuable components such as ethylene, propylene, butadiene, pyrolysis gasoline, and hydrogen.

These intermediates are not primarily used in conventional plastic production, but serve as feedstocks for high-value downstream products. For example, ethylene and propylene are critical for producing ethylene oxide and propylene oxide, which are further processed into poly-alcohols for polyurethane insulation materials and into surfactants for care chemicals. Other key value chains include acrylic acid and polyacrylic acid, used in a variety of applications, as well as nitrobenzene and aniline, precursors for MDI, which also feeds into the polyurethane sector. The only significant link to traditional plastics at the Antwerp site lies in the polystyrene value chain. This underlines the strategic importance of the site in supporting diverse and essential industries beyond plastics.

The site operates continuously to meet global demand, processing approximately two million tonnes of naphtha annually. This substantial production capacity highlights its integral role in BASF's global operations and in providing materials that underpin sectors such as insulation, personal care, and specialty chemicals.

This study explores innovative technologies such as electrodeionization (EDI) and Closed Circuit Reverse Osmosis (CCRO) deployed at two locations within the BASF Antwerp steam cracker site, as part of the AquaSPICE project, aimed at enhancing water sustainability. These efforts are supported by the IMPROVED water treatment containerized pilots, developed under the Interreg Flanders-Netherlands-funded IMPROVED project. Housed in two 40-foot sea containers, the pilots incorporate nine modular water treatment skids that can be configured for different process needs. They are capable of treating two separate water streams simultaneously at a nominal flow rate of 250 l/h each. The available treatment technologies include Reverse Osmosis (RO), Ultrafiltration (UF), Ion Exchange (IEX), Granular Activated Carbon (GAC), Electrodeionization (EDI), Electrodialysis with reversal (EDR), Advanced Oxidation Processes (AOP), Membrane Aerated Bioreactor (MABR), and a coagulation and flocculation system with a lamella settler.

2.1 Problem Statement of the BASF Antwerp Case

BASF holds the title of the world's leading manufacturer of basic chemicals. Its facility in Antwerp ranks as the second largest BASF site and relies on Biesbosch surface water for producing demineralized and process water. This particular water source requires demineralization prior to its use in steam-water cycles for generating energy.

In the steam cracking process depicted in the diagram, hydrocarbon feedstock is converted into valuable cracked products, such as ethylene, propylene and hydrogen. To optimize product yields and minimize coking rates, dilution steam (6-7 barg) is mixed into the hydrocarbon feed. After the products exit the furnace, the dilution steam is condensed to separate it from the hydrocarbons, recovered, and reevaporated in the dilution steam generators. To avoid accumulation of salts and other impurities, a fraction of the dilution steam flow is removed as blowdown.

The cracking process requires high temperatures (up to 850°C). These temperatures are achieved via combustion of fuel gas in several furnaces. To maximize the thermal efficiency of these furnaces, the heat of the hot flue gasses is recovered by producing high pressure (120 barg) steam. The steam generation system

of each of the furnaces also produces a certain amount of blowdown. To maximize energy recovery of these hot blowdowns (365°C) they are mixed into the DSGs. The high purity of these blowdowns compared to the process water/dilution steam system makes them ideal as makeup water for this loop, avoiding additional use of fresh BFW.

This interconnected system ensures efficient cracking, steam generation, and waste management.

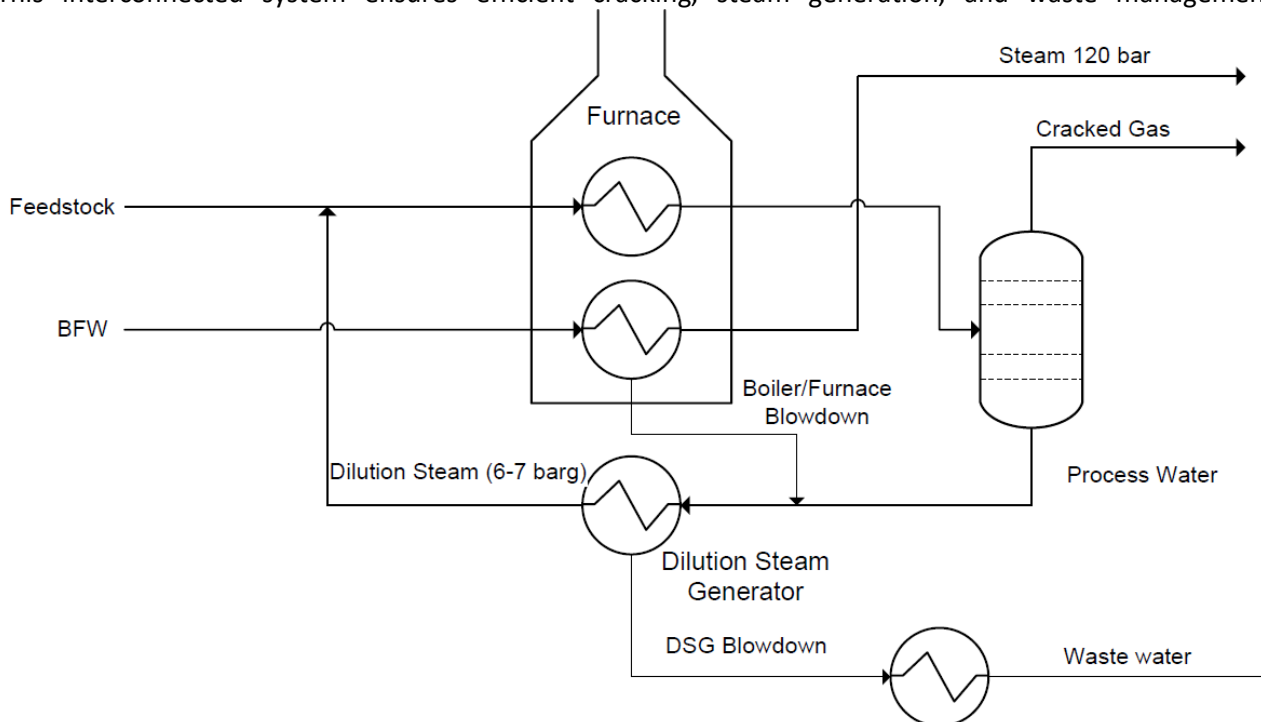


Figure 1 Process diagram of the relevant streams at the steam cracker site

Location 1

1. The first stream of interest is the dilution steam generator blowdown. Since the dilution steam has been in direct contact with the feedstock, his stream is high in organic load (150 ppm TOC), but not as much in terms of ionic load 277 $\mu\text{S}/\text{cm}$.
2. The secondary stream of interest is boiler/furnace blowdown. The boiler is fed with boiler feed water that is being evaporated into steam. The water at the bottom of the boiler is then concentrated in ions and needs to be blown down to protect the boiler from corrosion and scaling. This stream needs to be polished before reuse since it has a conductivity of around 7-15 $\mu\text{S}/\text{cm}$ and TOC of <100 ppb. As Figure 1 demonstrates, currently this stream is perfectly reused as dilution steam make up in terms of water and heat, but BASF has many other boiler blowdowns that are not reused. This makes it an interesting case study. The tests with the EDI from location 1 were extended by trucking several batches of 25 m³ of water to further test the EDI on boiler blowdown water at location 2.

Location 2

At the steam cracker site of BASF the demin water is used to spray air cooled condensers in the hot summer days when the coolers run out of cooling capacity. The water that is sprayed on the condensers then drips on the ground and is collected inside of a concrete tank called NTBA - Figure 2.

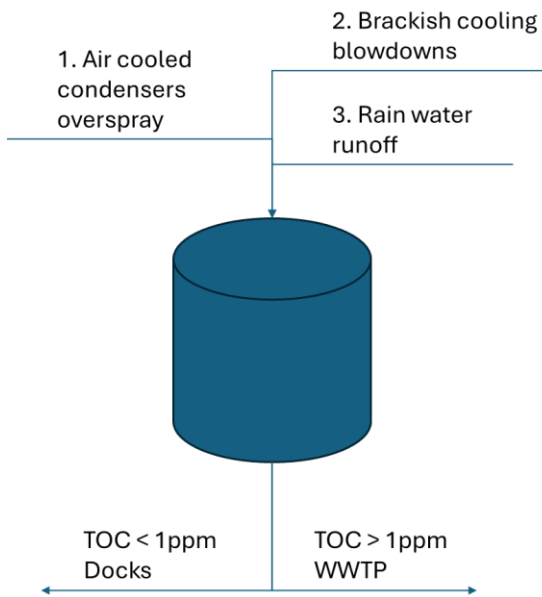


Figure 2 NTBA tank and its constituent streams

The major contributors to this tank are the air condenser spray water runoff and the rain runoff in the rainy months. These are both very clean in terms of organics and ionic load. The brackish blowdowns originate from the docks and are used for cooling. The brackish blowdowns are quite small in volume, less than 1 m³/hr. Currently, the water in the NTBA is being monitored for organics and is sent to the docks unless the TOC is over 1ppm, in which case it is sent to the wastewater treatment plant. The brackish cooling water blowdown that is collected in the NTBA is the only stream with high conductivity and is therefore wasteful to discharge the NTBA water in the docks instead of reusing it. Towards the end of the tests the CCRO was shortly coupled with the EDI in order to test if boiler feed water can be produced.

With the AquaSPICE project, the BASF Antwerp plant strives to investigate and increase knowledge of cost-effective treatments for water reuse.

2.2 Goal

At the BASF steam cracker site the tests were done in two locations.

At location 1, the tests were focused on treating the dilution steam blowdown (Figure 1) that is highly polluted with organics using physicochemical treatments such as reverse osmosis, ion exchange and granular activated carbon Figure 3. The goal is to treat this water ideally to boiler feed water (<0.1 μS/cm and <100 ppb TOC) or process water (<700 μS/cm and < 5ppm TOC). Additionally, the boiler/furnace blowdown stream (Figure 1) was treated with electrodialysis (EDI) in order to upgrade it to boiler feed water Figure 4.

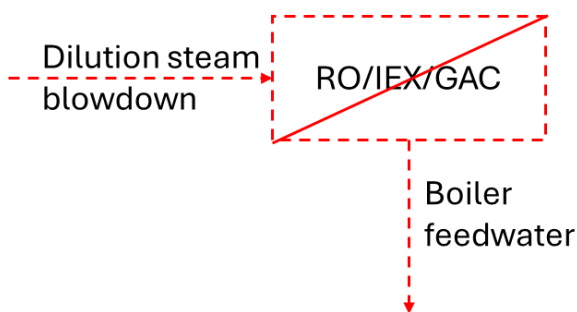


Figure 3 Recovery of the dilution steam blowdown formed at the steam cracker as boiler feed water.

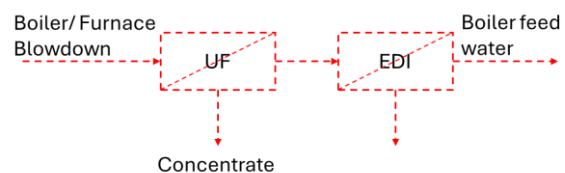


Figure 4 Recovery of the boiler/furnace blowdown as boiler feed water using EDI.

At location 2, the objective is to investigate if the water from the NTBA tank can be recovered as boiler feed water or as spray water for the air cooled condensers - Figure 5. The NTBA water was treated with both conventional RO as well as CCRO, making a comparison between the two technologies. CCRO is a novel, patented RO configuration that is advertised to be less prone to scaling and biofouling on the RO membranes [1].

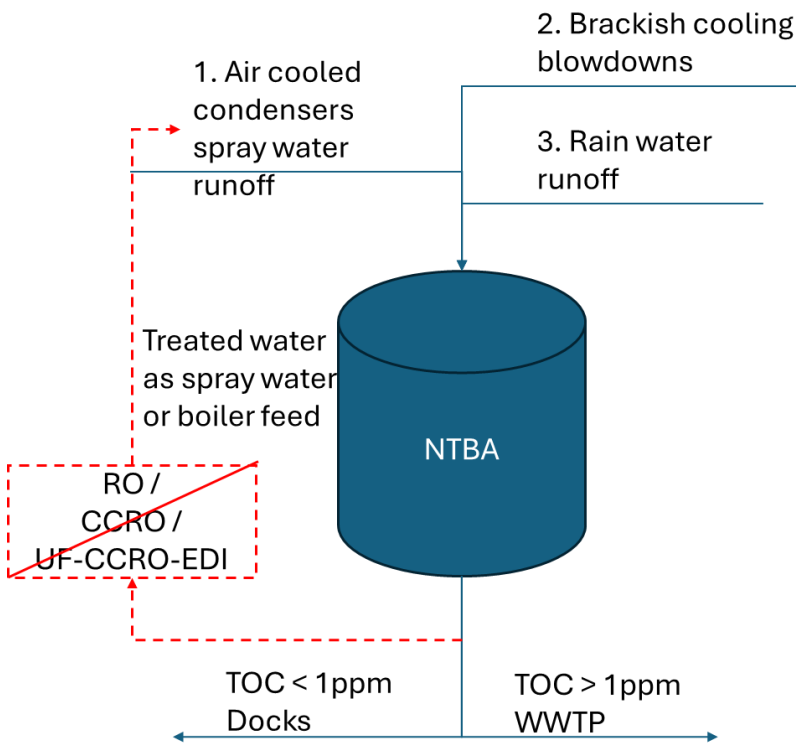


Figure 5 Recovery of the NTBA tank water as boiler feed water or spray water for the air cooled condensers. Red represents the new target technological arrangement

3. Technologies of interest – theoretical background

3.1 Ion exchange

IEX is an electrochemically driven process. Ions are removed from the solution, because they are exchanged with ions already present on the IEX resin. In this specific case, regenerated cation resin (weak acid cation (WAC) and strong acid cation (SAC)) has H^+ , while regenerated anion resin has OH^- (strong base anion (SBA) or a free base (weak base anion (WBA)) connected to its functional groups. The degasser (DG) removes CO_2 after cations are removed, therefore lowering the bicarbonate load to the anion resin. The mixed bed (MB) contains both SAC and SBA resin and polishes the water to $< 1 \mu S/cm$ electrical conductivity (EC). The mixed beds can also be operated separately as a condensate polishing unit (CPU). As the IEX module removes ions, the resin slowly gets saturated, creating the need for a regeneration. By measuring pressure, EC, pH, TOC, sodium (Na) and silica (Si) before and after selected columns, the quality of the process can be monitored.

3.2 Reverse osmosis

In RO, a pressure gradient leads to separation through a semipermeable membrane. The RO membranes typically do not have visible pores and are considered dense membranes. The suspended solids are mechanically rejected by the membrane, while salts and water are dissolved into the active layer and the rejection is dictated by difference in diffusion coefficients of the water and solutes. Other factors such as

membrane and solute charge also have a significant role in the determination of the rejection, but this is out of the scope of this report.

Salts, suspended solids, viruses, and dissolved components are retained in the concentrate, while water and some limited dissolved components move through the membrane in the permeate. RO membranes are typically not cleaned by backwashing but are mostly cleaned-in-place (CIP), or can be flushed with air to remove fouling and prevent clogging of the feed spacer.

Closed circuit reverse osmosis (CCRO)

The CCRO alternates between two modes of operation: closed-circuit desalination with high circulation rates and the flush cycle. In closed-circuit mode, the RO recirculates all of the concentrate stream blended with raw feed and produces no brine (Figure 6). The pressure increases subsequently as the osmotic pressure increases. Once a setpoint is reached, the system transitions to plug-flow, the concentrate valve opens and the system is flushed. The continuous changing hydraulic and osmotic pressure conditions are unfavorable for microorganisms, and thereby reducing fouling. The purging of the brine, before crystals can form, avoids scaling. In addition, the water recovery of CCRO is higher than conventional RO, thereby decreasing the waste stream. But the permeate quality will fluctuate during the concentration cycle, requiring a permeate buffer tank [1] [2] [3] [4].

The CCRO was implemented by modifying the conventional RO in the containers in accordance with the patent holder DuPont who allowed the modification exceptionally for UGent. The concentrate stream was directed to the feed of the pump instead of the buffer tank and the programming was adjusted to accommodate the cyclic nature of CCRO. The water is recycled in the system for a set number of minutes and then the system will be flushed for a set time. The ratio of the filter and flush cycle dictates the recovery of the system. The volume flushed from the system was kept such that it matched or exceeded the dead volume of the system.

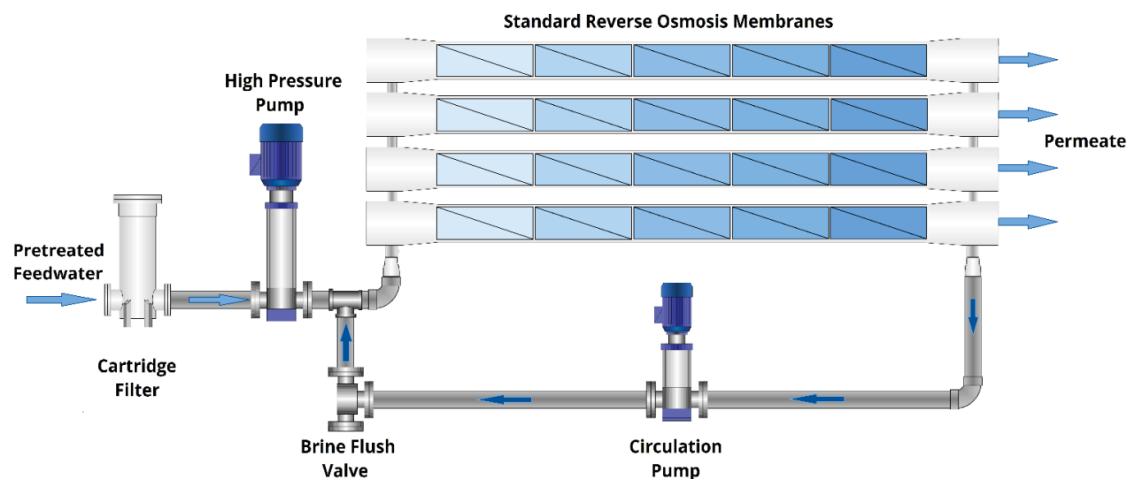


Figure 6 Schematic overview of the working principle of CCRO during closed circuit mode; after each filtration cycle the brine flush valve will open for certain amount of time [5]

3.3 Electrodeionization (EDI)

Electrodeionization (EDI), also known as Continuous Electrodeionization (CEDI), is an advanced water treatment technology that merges the principles of electrodialysis with ion-exchange processes to achieve high levels of water purity. Unlike conventional electrodialysis, which uses alternating layers of cation and anion exchange membranes, EDI incorporates mixed bed ion exchange resins within the water channels. This

addition serves to lower the electrical resistance across the stack and improves the quality of the treated water by enhancing ion removal capabilities.

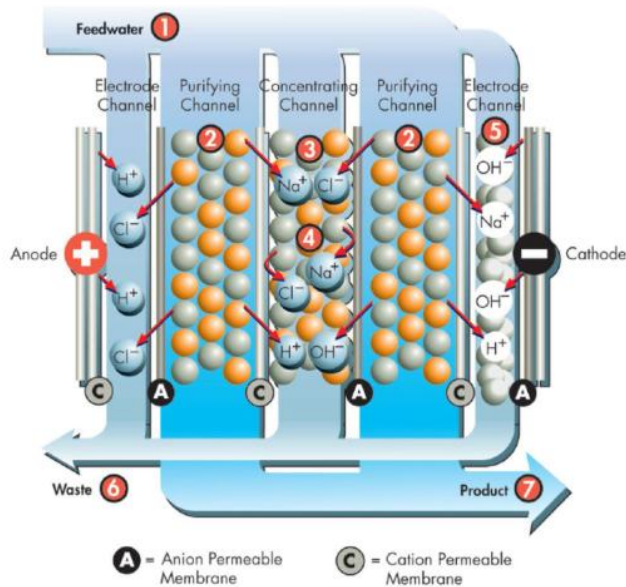


Figure 7 Schematic representation of the EDI technology. Source <https://www.chunkerowaterplant.com> [6]

In the operation of EDI, the mixed bed resins are crucial not only for ion exchange but also for their continuous regeneration, which is a distinctive feature of this technology. As water passes through the resin-filled channels under an electric field, water molecules are split at the ion exchange membranes into hydrogen (H^+) and hydroxide (OH^-) ions. These ions then regenerate the resins by replacing the captured cations and anions, respectively. This process of in-situ regeneration allows the system to operate continuously without the need for periodic resin replacement or chemical regeneration, thus ensuring consistent production of high-purity water.

Electrodeionization (EDI) systems typically exhibit high water recovery rates, generally ranging from 90% to 95%. This makes EDI an efficient process for the reuse and treatment of water, especially in industries requiring ultra-pure water. The quality of feed water entering an EDI system is critical for optimal performance and operational life of the system. The feed water should be pretreated to remove particulates, organic compounds, and chlorine, and should have a low level of total dissolved solids (TDS), usually less than 5 ppm. The conductivity of the feed water should also be minimized, typically below $40 \mu S/cm$, to reduce the electrical load and enhance the overall efficiency of the ion removal process in the EDI system. The specific limits for the module used in the trials are given in the chapter Materials and Methods.

3.4 Ultrafiltration

Ultrafiltration is a membrane-based separation process widely used in various industries, including water treatment, pharmaceuticals, and food processing. Fundamentally, ultrafiltration operates on the principle of size exclusion, where a semi-permeable membrane selectively allows smaller molecules and solvents to pass through while retaining larger solutes such as proteins, colloids, and suspended solids. The membranes used in ultrafiltration typically have pore sizes ranging from 1 to 100 nanometers, which are engineered to target specific contaminants based on their molecular weight. The driving force for the separation process is pressure, applied to facilitate the movement of the feed solution through the membrane.

The efficiency of ultrafiltration is influenced by several theoretical factors, including flux rate, rejection rate, and fouling propensity. Flux rate refers to the volume of liquid that can pass through the membrane per unit area and time, and it is a critical parameter for assessing the performance of the system. Higher fluxes allow

for smaller membrane area to be utilized and therefore lower capex, but can lead to problems with fouling which may require more frequent membrane cleaning, shorter membrane lifetime and more equipment downtime. Rejection rate, on the other hand, measures the membrane's ability to retain specific solutes, ensuring the quality of the permeate. Fouling, the accumulation of unwanted materials on the membrane surface, poses a significant challenge as it can reduce permeability and necessitate regular cleaning or membrane replacement.

4. Materials and Methods

4.1 Ion exchange

The deionization happens from top to bottom in vertical columns with 10 cm internal diameter, while the regeneration happens in the opposite direction. The hydraulic arrangement of the columns is normally WAC-SAC-Degasser-WBA-SBA-MB1 (Table 1). Mixed bed 2 (MB2) is a separate unit that can be connected to another technology. A general overview of the IEX layout is provided in Figure 8.

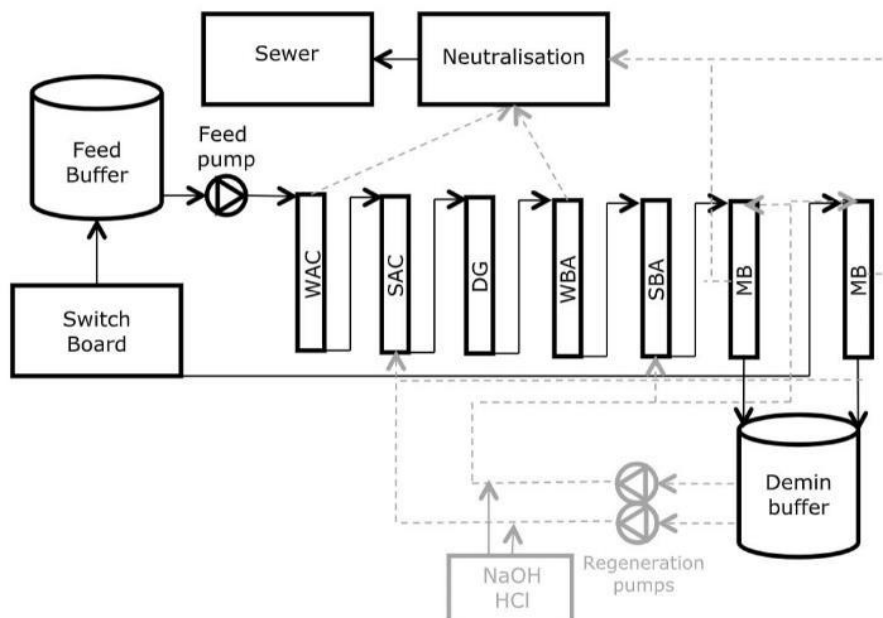


Figure 8 Schematic overview of the IEX module. The gray lines/equipment are used during regeneration.

During the trials at the steam cracker all columns were used except for the mixed beds.

Table 1 Arrangement and resin type inside the IEX setup

Column	Bed height, fresh (cm)	Resin	Column height (cm)
WAC	79 (6.2L)	Bypassed	85
SAC	136 (10.6 L)	Bypassed	145
<i>Degasser</i>			
WBA	35 (2.7 L)	Bypassed	145
SAC	136(10.6 L)	Dowex 650C (Na)	145
MB1	140 (10.9 L)	Bypassed	145
MB2	139 (10.9 L)	Bypassed	145

4.2 Reverse osmosis

In Figure 9 the scheme of the RO set-up is shown. The used RO membrane was a Dupont FilmTec BW30 PRO-4040, with an active membrane area of and 7.9 m². The pressure housing was a Codeline 40E100. The pH, flow, pressure, conductivity, temperature were continuously measured online with 10-seconds sampling intervals.

A general overview of the RO layout is provided in Figure 9.

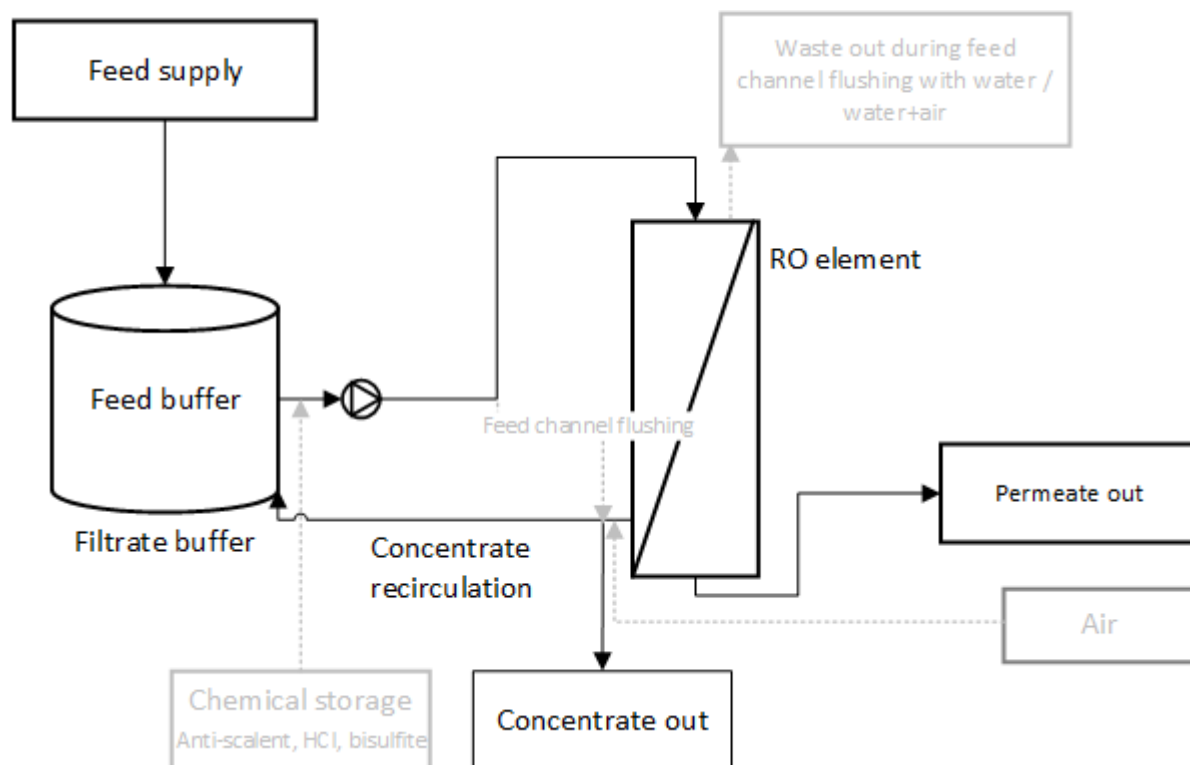


Figure 9 Schematic overview of the conventional RO module. The lines in gray are used only during cleaning in place or injection of air.

The RO was modified to CCRO by rerouting the concentrate recirculation to the suction of the high RO pump and by installing a brine discharge valve before the backpressure regulator that is located at the concentrate outlet of the pressure vessel.

4.3 Electrodeionization

The EDI skid was purchased from Pure Water Group (PWG) and the module supplied was IonPure LXM04X. The maximum allowed feed water values given by the manufacturer can be seen in Table 1 Table 2 EDI maximum allowed values in the feedwater:

Table 2 EDI maximum allowed values in the feedwater

Parameter	Limit / Range
Conductivity equivalent (incl. CO ₂)	40 μS/cm (see note)
Feed water source	RO permeate (see note)
Temperature	5 – 45°C (optimum: 15 – 35°C)
Total chlorine (as Cl ₂)	< 0.02 ppm
Iron (Fe)	< 0.01 ppm
Manganese (Mn)	< 0.01 ppm
Sulfide (S ²⁻)	< 0.01 ppm

Parameter	Limit / Range
pH	4 – 11
Total hardness (as CaCO ₃)	< 1 mg/L (optimum: < 0.2 mg/L)
TOC	< 0.5 ppm
Silica (SiO ₂)	< 1 ppm (optimum: < 0.2 mg/L)

The allowable conductivity, including dissolved carbon dioxide, must not exceed 40 µS/cm. If CO₂ levels exceed 5 ppm, degassing may be required; above 10 ppm, degassing is mandatory.

The system requires a feed water flow rate between 250 and 750 liters per hour. The operating pressure at nominal flow conditions is 1.7 to 2.5 bar.

4.4 Ultrafiltration

The ultrafiltration is a process where suspended solids are filtered over a membrane with small pores. This process is commonly used as a pretreatment process for reverse osmosis. The membranes used in UF can be backwashed periodically and are resistant to low levels of free chlorine allowing cleaning in place with bleach.

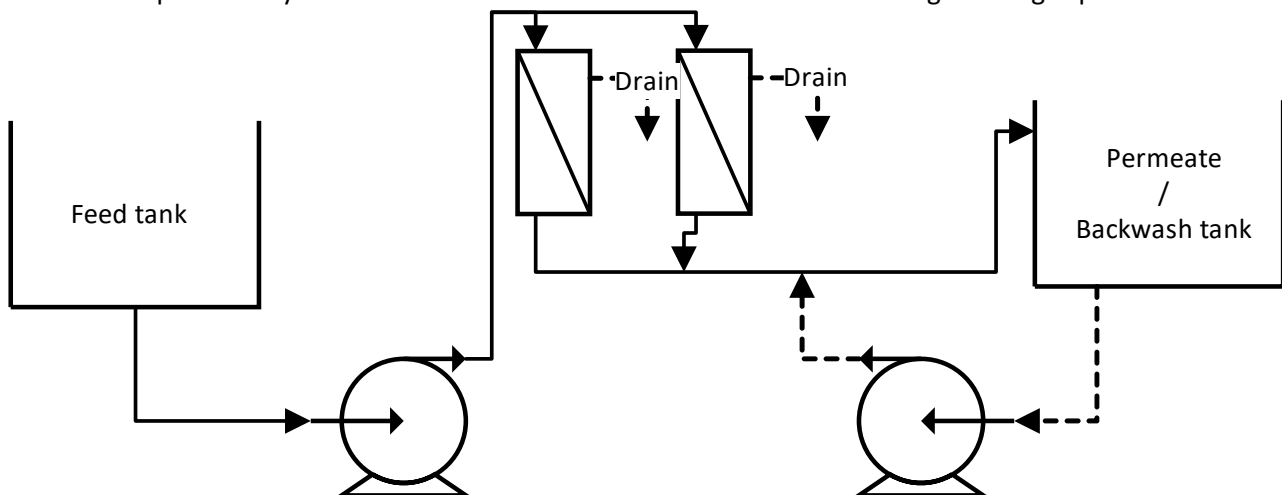


Figure 10 Simplified schematics of the UF skid

The UF in the IMPROVED containers is based on two identical hollow fiber modules from INGE model Dizzer P 4040-6.0 operated in parallel. The nominal membrane pore size is 20 nm. One of the modules can be isolated from the system by closing down manual valves in case the required permeate flowrate can be achieved with one module at higher flux. The system automatically alternates between filtration, drain, backwash and forward flush modes. In filtration the permeate tank is filled first before outputting water to the next technology. During drain cycle the modules are drained of water and the filtered suspended solids. During backwash the water is rapidly pushed in the opposite direction and the filtered cake material is dislodged from the membrane surface. Finally, the feed space of the modules is flushed before going back into filtration mode. The permeate tank was not dosed with chemicals – no chemically enhanced backwash, only normal backwash was used.

5. Results and Discussion

Location 1

The tests in Location 1 were performed from 7 until 23 Aug 2023. Two streams were tested in parallel – the process blowdown coming from the steam cracker and the boiler blowdown.

Dilution steam blowdown coming from the steam cracker

This stream comes from steam that has been in direct contact with the product and is therefore saturated with organics, many of which oxygenated. Similar stream was treated at the Dow site in previous report. In the current trials the stream was tested with a combination of activated carbon, ion exchange (WAC-SAC-WBA-SBA), and reverse osmosis – Table 3:

Table 3 Test schedule for the process blowdown treatment

	07/08/23	09/08/23	10/08/23	11/08/23	12/8/23	13/08/23	15/08/23	19/08/23	23/08/23
GAC-IEX-RO									
RO-GAC									
RO									

The quality of the incoming dilution steam blowdown can be seen in Table 4:

Table 4 Quality of the dilution steam blowdown coming from the steam cracker

PH	Cond.	NH4	TOC	NO3	NO2	Br	Cl	F	PO4	SO4
	µS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
10.1	277.5	9.7	150.3	< 0.10	2.31	< 0.10	1.41	12.1	< 10	0.25
Cr	Ca	Fe	K	Cu	Mg	Na	Ni	SiO2	Zn	
µg/L	mg/L	µg/L	mg/L	µg/L	mg/L	mg/L	µg/L	µg/L	µg/L	
< 0.8	< 0.01	30.9	0.0415	< 1.0	< 0.002	28570	1.3	358	< 1.0	

Similarly to the Dow trials, the aim was to produce boiler feed water or process water, but unfortunately it was impossible to achieve these goals with the technologies that were applied - Table 5:

Table 5 Average TOC and conductivity of the produced water with different technological train using process blowdown as feed

Train	TOC, ppm	Conductivity, µS/cm
GAC-IEX-RO	15.6	5.5
RO-GAC	17.0	5.1
RO	32.7	79.9

The results in Table 5 are averaged for 3 samples in GAC-IEX-RO, 1 sample from RO-GAC and 5 samples for RO only. None of the applied technologies could achieve boiler feed water or process water quality. The conductivity of the produced water was not an issue; however, the TOC could not be reduced to below 0.1 ppm in order to be reused as boiler feed water. The minimum TOC was achieved with the GAC-IEX-RO train where the IEX was operated with WAC, SAC, WBA and SBA columns at 15.6 ppm which is too high for any type of reuse. The theory, similar to the Dow case was that small uncharged organics can pass via all of the water treatment technologies. Such examples are methanol and ethanol, which can only be practically removed by a biological treatment. Analysis of some of the treatment trains for organics can be seen below - Table 6:

Table 6 Components above detection limit analyzed in some of the treatment technologies and the feed, averaged for 5 samples

Techn	Acetaldeh	Acetone	Acetonitri	Aniline	Butanol-	Butanone	Ethanol	Methan	Propanol-
ology	yde (mg/L)	(mg/L)	le (mg/L)	(mg/L)	N (mg/L)	-2 (mg/L)	(mg/L)	ol (mg/L)	N (mg/L)
Feed	1.027	0.277	0.115	0.077	0.111	0.034	4.520	21.684	0.219
GAC	0.067	0.25	0.102	0.040	0.021	0.029	3.492	13.932	0.962
RO-P	0.194	0.219	0.172	0.024	0.022	0.017	4.029	10.786	0.443

Some of the treatment trains show higher values than the feed, but this is probably due to matrix effects affecting the integration of the absolute value. Overall Ethanol and Methanol are indeed the components with the largest concentration in the feed and the treatment options hardly reduce it. Overall, the treatment of this stream proved to be unsuccessful due to the lack of proper biological step that can reduce the small uncharged organics.

Boiler/furnace blowdown from the steam cracker treated with UF-EDI

The UF was placed before the EDI in order to protect it from iron particles coming from the boiler and the heat exchanger used to cool down the water before entering the IMPROVED water treatment pilots. The iron is a heavy metal that can stick to the ion exchange resins inside the EDI and can foul them. Moreover, the particles could cause blockage of the resins, hence the need for UF pretreatment.

The EDI was operated connected to the boiler blowdown stream after cooling via heat exchanger from the 3rd of August until the 22nd of August. Afterwards the pilots moved to location 2 of the steam cracker, but water was trucked 3 times with a 25 m³ tank. When the water was directly connected to the stream, the feed water flowrate was 400 l/h, but to prolong the tests it was set between 220 and 270 l/h when it was connected to the trucked water - Figure 11. The recovery was always set to 90 % meaning the feed water was 444 l/l and 44 l/h were discharged during the tests at location 1 - Figure 12.

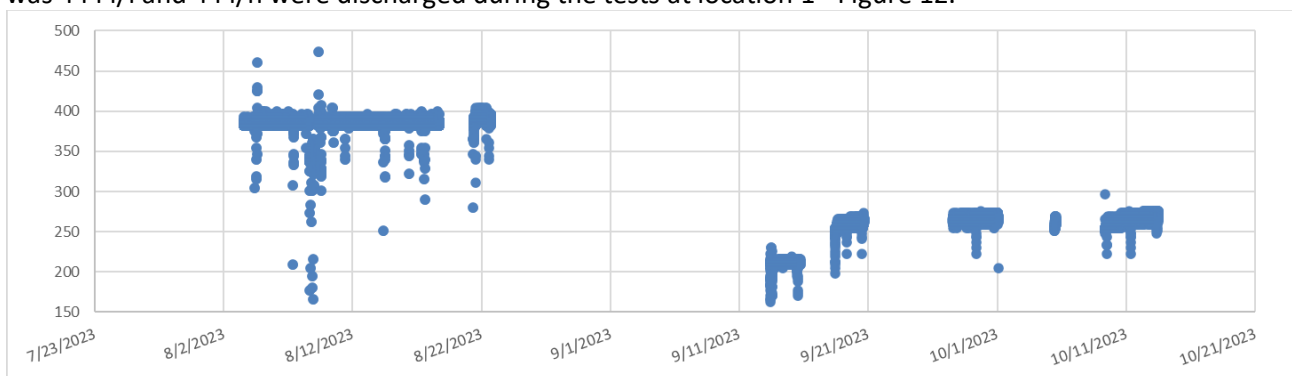


Figure 11 EDI product flowrate, l/h

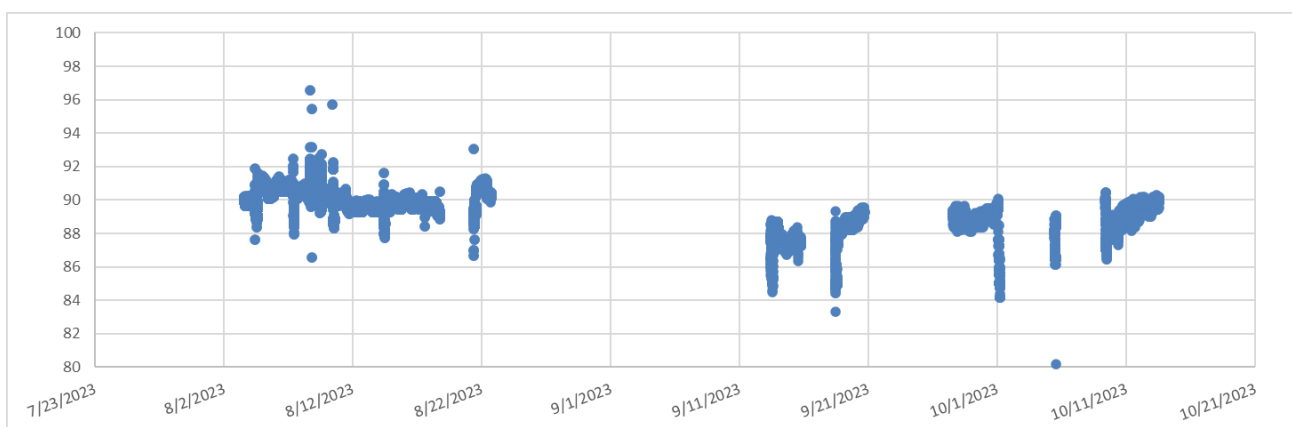


Figure 12 Recovery of the EDI, %

The temperature fluctuated between 30 and 45 °C - Figure 35. Overall higher temperature helps the EDI to perform better by improving the kinetics of transport inside the ion exchange membranes and the resins. However, it should be kept below the maximum allowed temperature of the module to avoid overheating. The higher temperature also makes the stack less susceptible to iron fouling according to the stack producer.

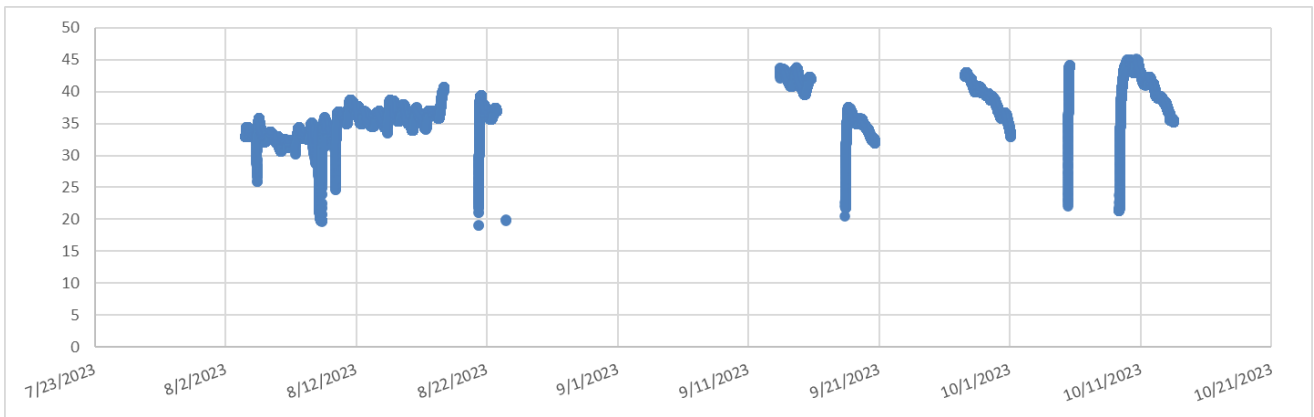


Figure 13 Temperature of the EDI, °C

The conductivity of the EDI feed for the period can be seen in Figure 36:

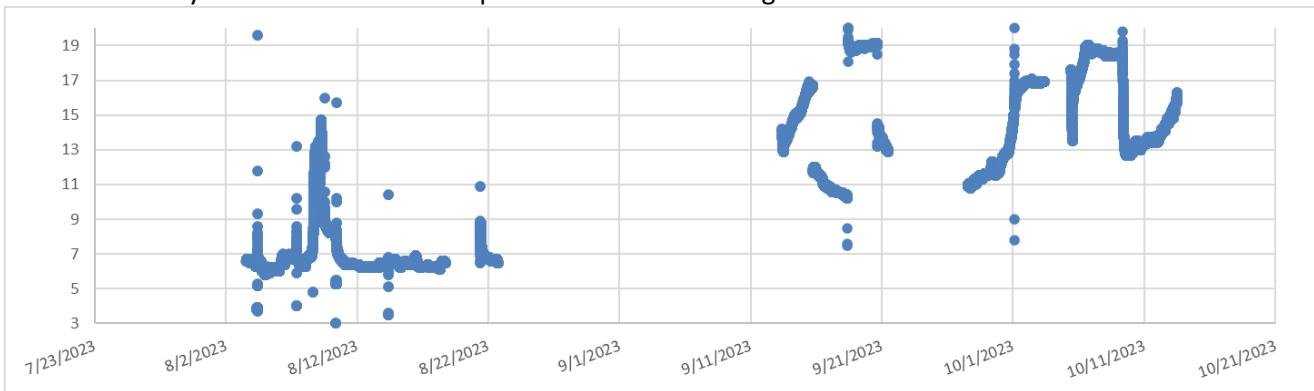


Figure 14 EDI feed conductivity of the water, $\mu\text{S}/\text{cm}$

The conductivity of the feed water was between 6 and 15 $\mu\text{S}/\text{cm}$ when connected to the heat exchanger and between 10 and 19 when connected to the trucked water. The slightly higher conductivity in the trucked water is probably due to contamination from the truck.

The concentrate conductivity of the EDI, which is important for reuse and further treatment options can be seen in Figure 15. Typically the concentrate conductivity of the EDI was between 25 and 90 $\mu\text{S}/\text{cm}$.

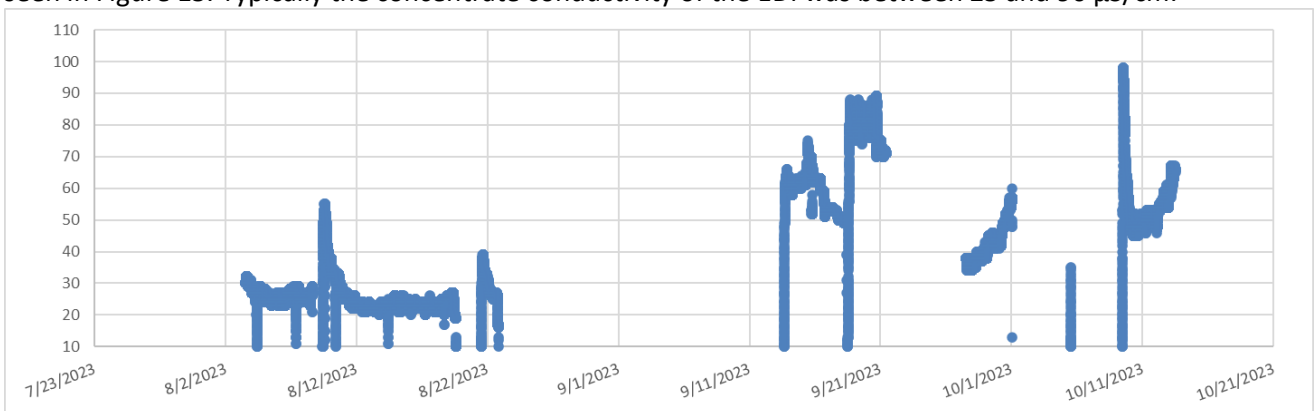


Figure 15 Concentrate conductivity of the EDI, $\mu\text{S}/\text{cm}$

The conductivity of the produced water was always below 0.09 $\mu\text{S}/\text{cm}$ when connected to the heat exchanger and below 0.11 $\mu\text{S}/\text{cm}$ when connected to the trucked water. Overall, the limit of BASF for boiler feed water is 0.1 $\mu\text{S}/\text{cm}$, so this water seems feasible for direct reuse, considering that the slightly higher conductivity in the trucked water is due to the slight feed water contamination and the startup effects of the EDI. In all

instances in the trucked water, the conductivity was starting slightly higher and going down as the EDI stabilizes in performance.

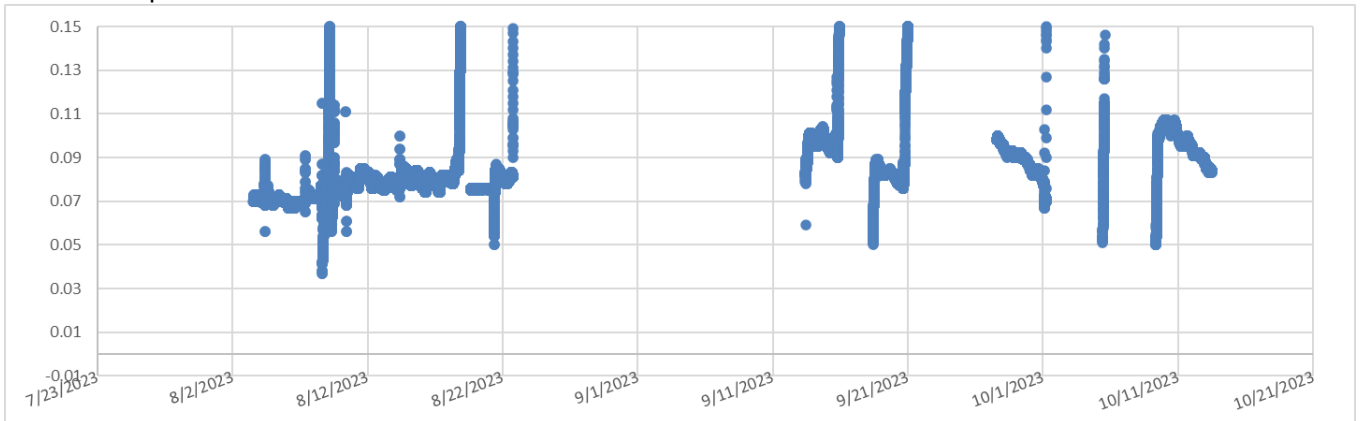


Figure 16 Conductivity of the EDI product, $\mu\text{S}/\text{cm}$

It is important to note that the peaks in the product conductivity in Figure 16 are due to system shutdowns. During a shutdown there is no current applied to the system and the ions can slowly migrate from the concentrate to the feed compartment, increasing the conductivity. We can also notice that after a startup the conductivity is somewhat higher, then stabilizes to a lower value.

The TOC after the EDI was measured daily - Figure 40:

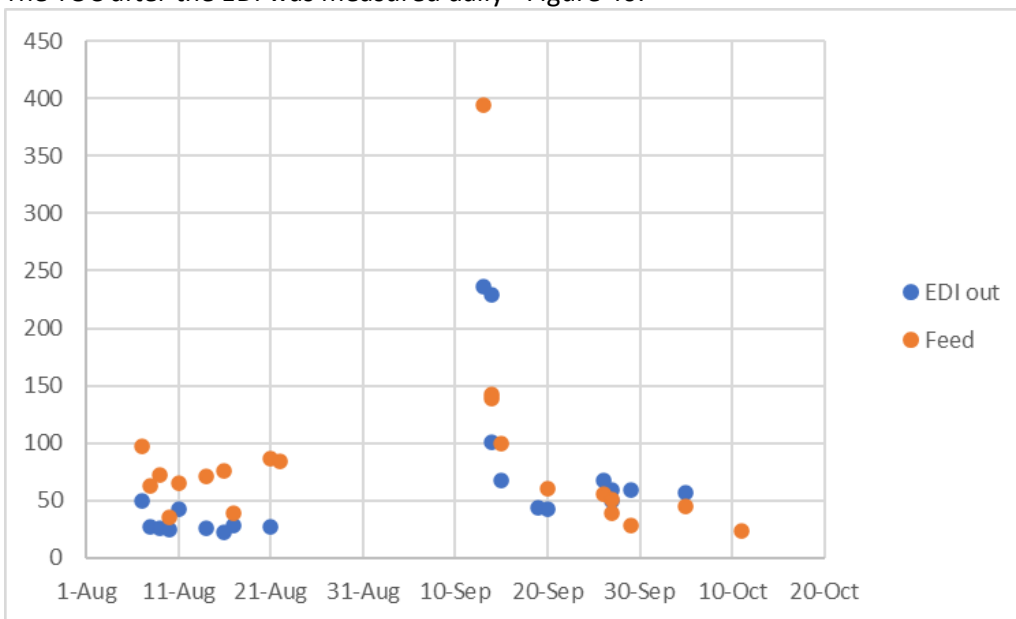


Figure 17 TOC before and after the EDI, ppb

The TOC after the EDI was always below 50 ppb in the directly connected to the heat exchanger. For the trucked water it was a slightly different story as especially in the first trucked water the TOC of the feed water was 400 ppb. This spike in the feed TOC was attributed to contamination in the feed lines from the truck to the pilots. In the following batches the TOC was below 70 ppb. In some instances, the TOC of the feed was slightly higher than the permeate. This could be due to TOC desorbing from the resins from the previously higher peak, or just an inaccuracy in the measurement.

As expected the EDI doesn't remove much TOC as the TOC needs to pass the dense membrane to go into the concentrate stream. This creates a large steric hindrance for larger TOC molecules and the mechanism of removal of TOC is such that only charged molecules can be removed.

If we disregard the initial peak of TOC in the first batch (due to feed line contamination), the TOC in the permeate was also below 100 ppb which is the limit for boiler feed water of BASF.

The desalination energy is the electrical energy used by the EDI to produce 1 m³ of product. As seen in Figure 41, the desalination energy is 110-150 W-h/m³ for the online water and between 150 and 300 W-h/m³ for the trucked water. Overall, these numbers are very good and the EDI seems like an excellent, chemical-free alternative to mixed bed resins to polish this stream.

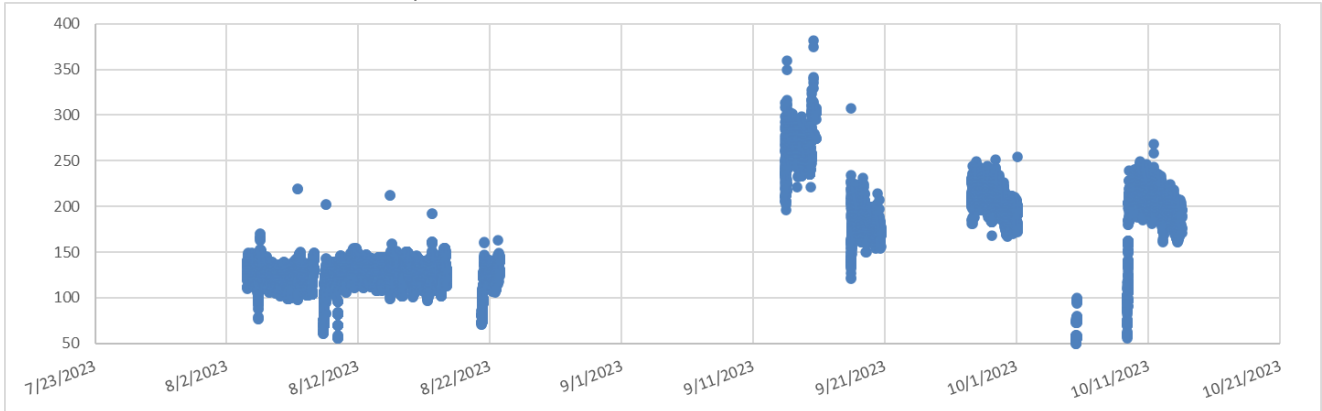


Figure 18 Desalination energy of the EDI, W-h/m³

The stack resistance may indicate fouling of the resins and the membranes. Since the temperature of the water varied a lot, it was normalized via the following equation provided by the stack manufacturer

$$R_{norm} = T \times ((0.02 \times R) + 0.5)$$

Where R_{norm} is the normalized resistance, T is the temperature in °C and R is the raw resistance of the stack obtained by dividing the voltage over the current. The resulting normalized resistance can be seen in Figure 19.

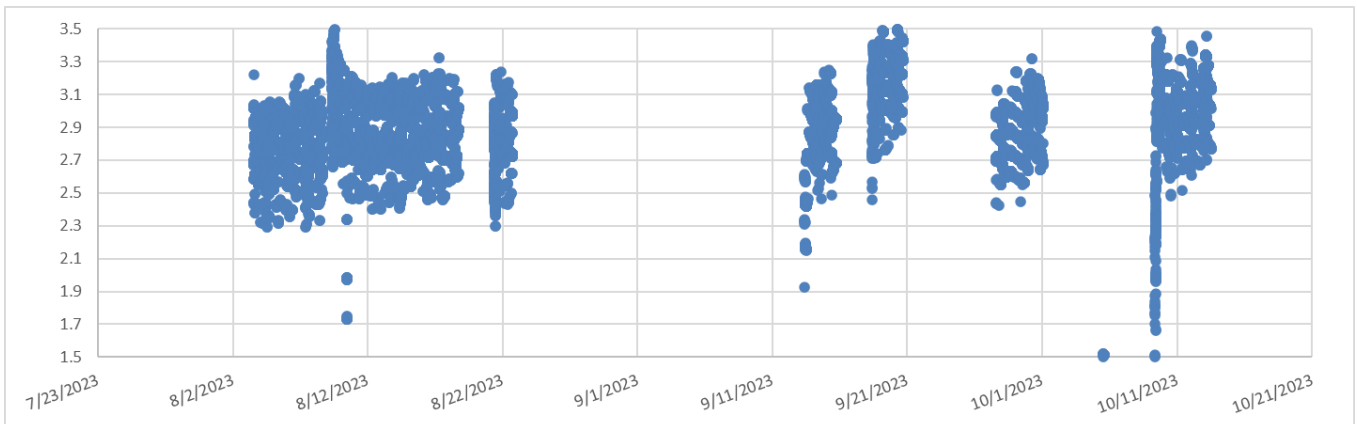


Figure 19 EDI normalized stack resistance, Ohm

Here the absolute value of the resistance is not that important, rather we are looking if there is an increasing trend in resistance, that suggests fouling of the stack. We see that no appreciable increase in resistance that can be observed in the stack during the testing period. Also, no increase in the pressure drop of the stack was observed. Overall, the stack showed no signs of blockage or fouling.

Location 2

The tests on Location 2 were performed from Sep 8th until Nov 2nd 2023 - Table 7 .

Table 7 Overview of the trials on the second location of the steam cracker site

	08/09/23	14/09/23	21/09/23	28/09/23	05/10/23	12/10/23	19/10/23	26/10/23	02/11/23
RO									
CCRO									
UF-CCRO-EDI									

The trials were focused on the treatment of the NTBA tank water using RO and CCRO. Towards the end of the trial period the EDI was coupled with the CCRO to evaluate the quality of the produced water.

Since the composition of the NTBA tank is highly variable in time, it is not fair to describe it with averages and standard deviation values. Hence, the complete data is provided in Table 8:

Table 8 Composition of the NTBA tank

Date	pH	Cond.	TOC	NH3	F	Cl	Br	PO4	SO4	NO2	NO3	SiO2	Fe
		µS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	µg/L	µg/L
06/09/23	7.78	3200	2.30	0.37	0.22	894.1	3.28	0.0	159.3	0.55	3.9	4197.0	90512.0
08/09/23	7.24	3500	2.67	0.12	0.24	1083.4	4.19	0.2	157.4	0.62	3.3	14.0	248.0
11/09/23	7.70	3280	1.98	0.36	0.24	989.8	3.85	0.0	145.9	0.21	3.7	2709.0	558.0
13/09/23	7.46	4940	3.93	0.00	0.36	1537.4	6.06	0.0	230.2	0.22	5.1	551.0	1232.0
15/09/23	7.99	7430	3.88	0.00	0.43	2425.2	8.79	0.0	357.7	0.74	5.5	20.0	305.5
18/09/23	7.76	5280	3.07	0.32	0.00	1745.1	6.14	0.0	236.5	1.07	2.5	2202.0	333.0
20/09/23	7.78	6060	2.76	0.36	0.00	1934.5	6.75	0.0	261.7	1.20	9.3	1452.0	60.0
22/09/23		3320	3.03	0.26	0.02	984.4	3.51	0.0	132.6	1.32	4.5	4451.0	379.0
25/09/23		5870	3.24	0.45	0.19	2214.5	7.92	1.8	309.1	0.47	5.4	5933.0	488.6
27/09/23	7.90	6360	3.02	0.52	0.14	2061.1	7.28	0.0	279.6	0.35	4.7	6243.0	210.0
29/09/23	7.70	3070	3.35	0.10	0.35	1012.7	0.00	0.0	147.0	0.00	6.0	6193.0	504.0
02/10/23		913	3.02	0.00	0.26	346.5	1.39	0.0	48.7	0.00	4.7	6839.0	392.0
04/10/23		1360	2.53	0.00	0.21	212.8	0.89	0.0	30.5	0.00	3.6	5676.0	152.0
06/10/23		795	0.25	0.00	0.18	206.8	0.81	0.3	28.5	0.36	3.9	5633.0	234.0
09/10/23	6.35	832	0.05	0.10	0.10	235.3	0.88	0.4	32.1	0.00	3.2	3653.0	405.0
11/10/23	7.49	812	1.74	0.21	0.18	198.3	0.79	0.5	28.0	0.06	5.1	4899.0	164.0
13/10/23	7.52	881	2.67	0.00	0.24	233.8	0.94	0.5	33.3	0.00	6.5	3195.0	366.0
16/10/23		672	3.05	0.00	0.24	178.4	0.82	0.0	28.7	0.00	6.7	5192.0	214.0
18/10/23	7.68	786	1.93	0.23	0.23	201.7	0.80	0.4	28.8	0.73	7.9	5125.0	298.0
20/10/23	7.50	783	2.15	0.00	0.24	173.4	0.82	0.0	29.6	0.00	7.4	5431.0	321.4
23/10/23	7.50	693	2.38	0.00	0.27	180.8	0.77	0.0	30.2	0.10	7.5	5637.0	374.0
25/10/23	7.90	742	2.78	0.00	0.25	161.8	0.70	0.0	26.7	0.11	5.5	5493.0	938.6
27/10/23	6.49	658	2.64	0.00	0.21	143.5	0.00	0.0	23.2	0.00	6.8	5365.0	161.2
30/10/23	7.35	679	2.63	0.00	0.20	169.0	0.00	0.0	24.9	0.25	5.8	4815.0	302.4

RO and CCRO on the NTBA tank

Since one of the largest constituents of the NTBA tank is the rain water runoff, historical data for the trial period is added in Figure 20 and Figure 21:

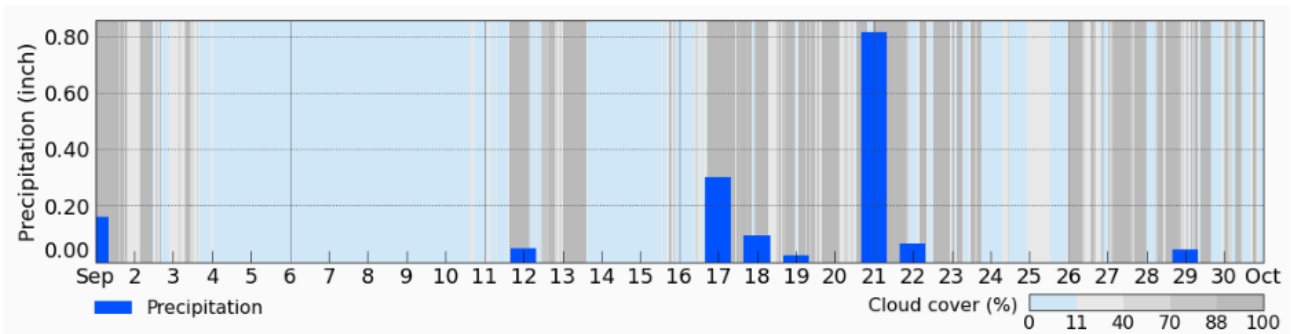


Figure 20 Historical precipitation data for Antwerp September 2023, source meteoblue.com

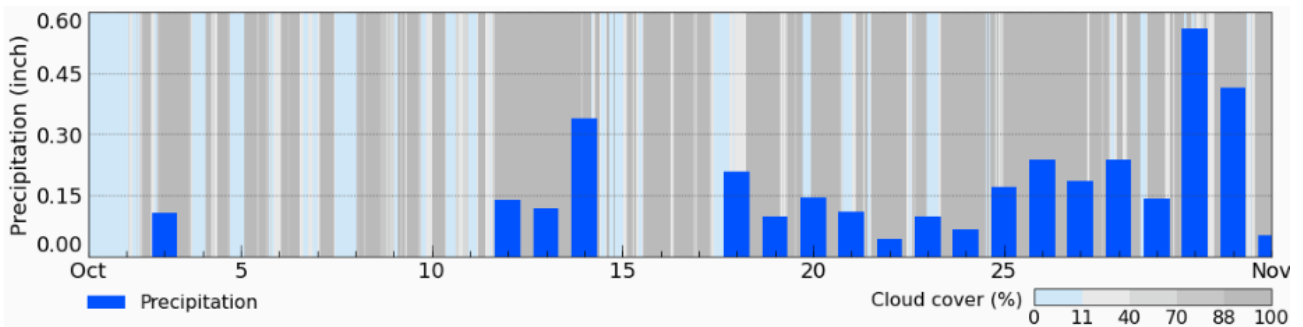


Figure 21 Historical precipitation data for Antwerp October 2023, source meteoblue.com

What we see from the weather data is that there was a large rainfall spike on Sep 21st and the second part of October was very rainy, leading to a larger contribution of the rainfall to the feed of the NTBA tank.

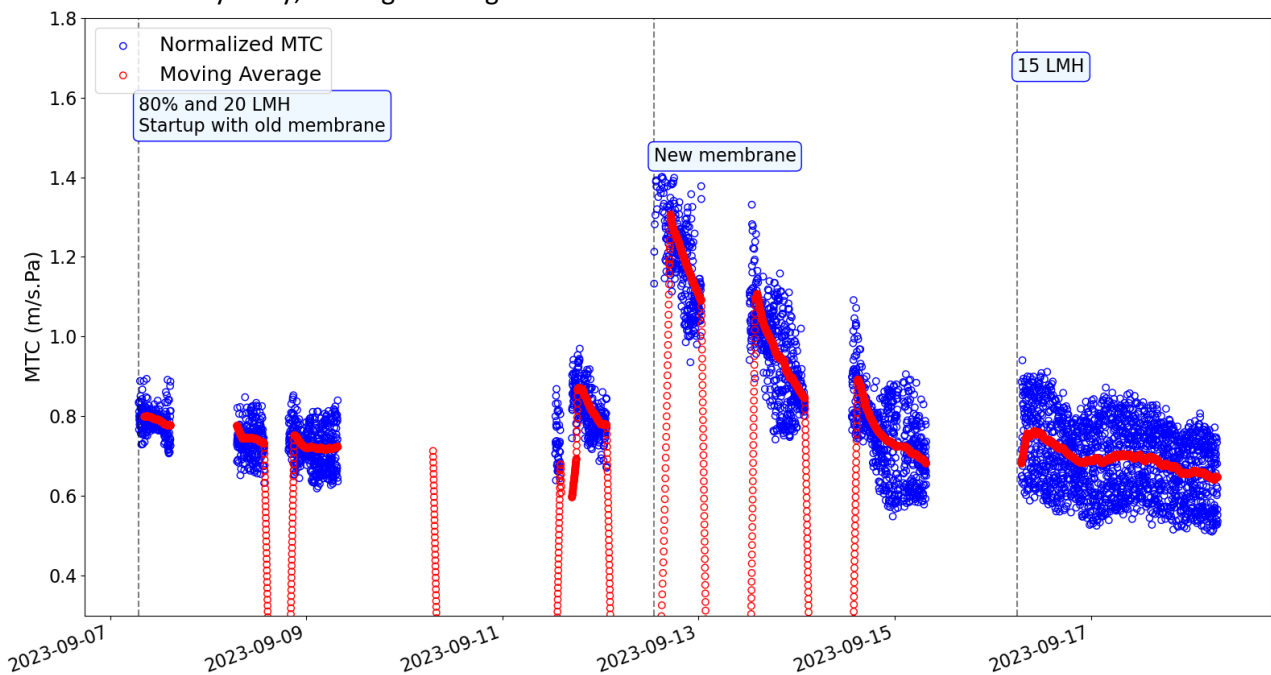


Figure 22 membrane mass transfer coefficient of the membrane in conventional RO configuration operated on the NTBA tank water

Initially the test were started with conventional RO configuration at 80 % recovery and 20 Lmh flux. The water from the NTBA tank was fed to the RO without any pretreatment, except for the 50 micron cartridge filters as the UF was busy with pretreatment of the EDI. The membrane used initially was an old membrane from the Location 1 experiments, which was later replaced with a new membrane. The operation was intermittent due to the startup, but what we can also see is a rapid fouling of the membrane in Figure 22 indicated by the rapid decline of the membrane mass transfer coefficient (MTC). After reducing the flux to 15 Lmh, the MTC is more stable, but the MTC continues to decline rapidly.

The membrane was cleaned in place with NaOH and HCl cleaning in place (CIP) and the RO skid was switched to CCRO configuration for the rest of the tests - Figure 23.

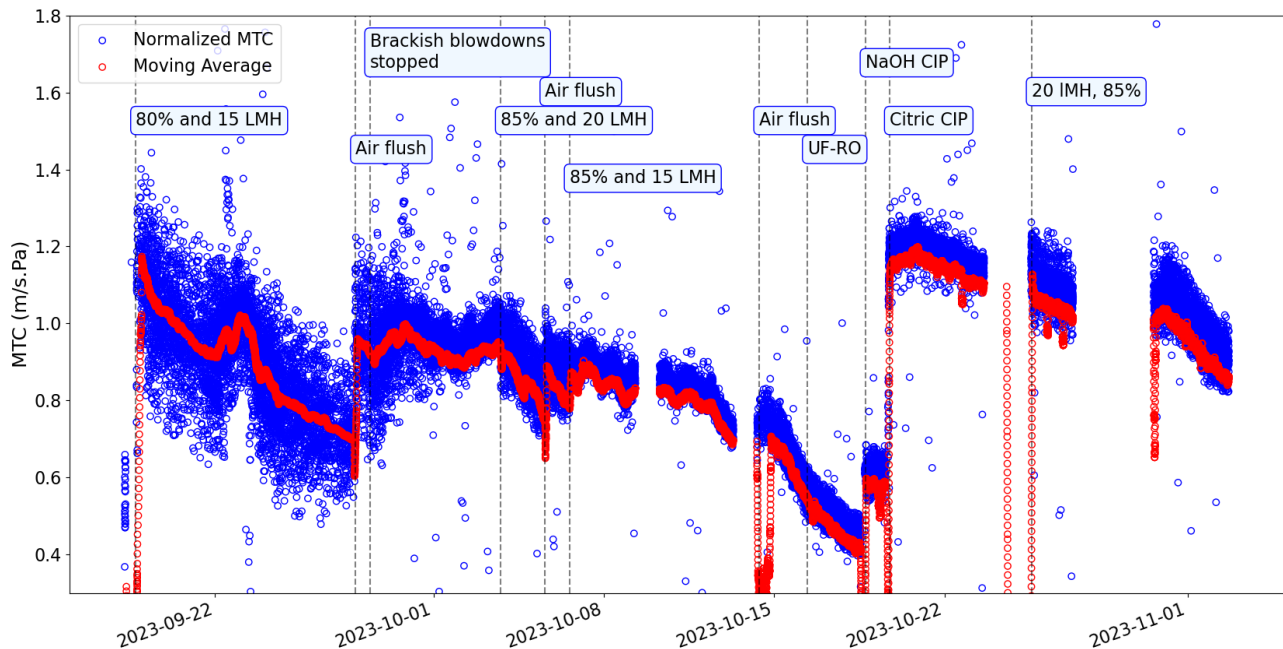


Figure 23 Mass transfer coefficient of the membrane in CCRO mode on the NTBA tank water

As seen, the rapid decline of the MTC continued with the CCRO but to a much lesser effect. The membrane MTC declined from 1.2 to 0.7 in 9 days from Sep 18 until Sep 27. For comparison, in RO mode the MTC declined from 1.3 to 0.7 m/s/Pa in less than 2 days, but the flux was also slightly higher at 20 Lmh. This is still a very rapid decline for the CCRO. An air flush was done on the membrane where 1.5 bar of compressed air is mixed with the water in forward flush, allowing the bubbles to scour the spacer and the membrane. The flushing lead to a dramatic increase in the MTC from 0.7 to 0.95. A sample of the air-scour water was taken, but was not analyzed due to miscommunication with the laboratory - Figure 24:



Figure 24 A sample of the water during and air flush scouring

Since the rain runoff and the spray water runoff of the air-cooled condensers are quite clean, the fouling of the membrane was attributed to the brackish blowdowns. As previously stated, these are brackish streams coming from the docs used for cooling of equipment. BASF was asked to reduce these streams as much as possible in order to evaluate if the fouling of the membrane would be improved.

After the brackish blowdowns were reduced as much as possible, the fouling of the membrane became much more stable in time and on 6th of October the recovery was increased to 85 %. Two more air flushes were done on the 5th and 14th of October, each with less effect on the MTC, hence the fouling was becoming more stable. On the 16th of October UF was placed before the CCRO, without any effect on the MTC. A CIP with NaOH was done on the 18th of October with little effect, followed by a CIP with citric acid that restored the membrane almost to the initial MTC of 1.17 m/(s.Pa). The CIP with citric acid water was tested and showed predominantly Zn and Fe - Table 9:

Table 9 sample of the water from the CIP with citric acid on 19th October

	Zn	Fe	Cr	Cu	Ca
Ppm	253.2	182.5	0.6	0.4	0.2

Silica was not analyzed in this sample due to a miscommunication with the lab. The presence of Zn and Fe in the CIP water suggest that the majority of these metals are coming from the wash off of the galvanized metal structures at the steam cracker site. The air cooled condensers are also consisting of galvanized steel, and are sprayed with highest quality demin which should reduce the corrosion. Demin can still dissolve the Zn to some degree as demin water can be quite aggressive, there is no alternative as water with hardness would scale on the surface of the condensers.

On 25th of October the flux was increased to 20 Lmh, which had a negative effect on the MTC rate, and therefore this flux was too high for stable operation. This very last period of the MTC also coincides with two very rainy days in October 30 and 31. In this period the UF was placed before the CCRO, so suspended solids brought by the rain would be rejected by the UF. However, the UF will not stop dissolved Zn and Fe coming from the metal structures at the steam cracker site. After the tests, a membrane autopsy was done as seen on Figure 25:



Figure 25 Membrane autopsy after the CCRO tests

Although the membrane and the spacer are severely fouled, the fouling would easily be removed with light rubbing, which would explain the effectiveness of the air flushes. Moreover, this severe fouling was never observed as an effect on the normalized pressure drop, likely because of its weak mechanical attachment to the membrane. A sample was scraped from the membrane surface and sent for plasma destruction followed by ICP-OES analysis. The autopsy proved once again that the predominant fouling metals are Zn and Fe, but also some Ca, Si and Al - Table 10:

Table 10 Membrane autopsy after the CCRO tests. The numbers should be interpreted as relative and not absolute

	Zn	Fe	Ca	Si	Al	Mg
g/kg	17.1	9.99	5.26	4.93	2.21	0.96

The Ca and Al in the membrane autopsy were not present in the CIP with citric acid on 19th of October. This suggests that the fouling changed, possibly due to the heavy rains at the end of the experimental period. While no antiscalants were used in the tests, the presence of silica is concerning and may require the use of antiscalants in a full-scale installation. On the other hand, the membrane permeability was completely recovered with the previous CIP with citric acid, so the silica is likely colloidal of nature.

Although the air flush water was quite murky and no UF pretreatment was used during the first half of the tests, the membrane feed channel pressure drop remained stable during the whole testing period - Figure 26:

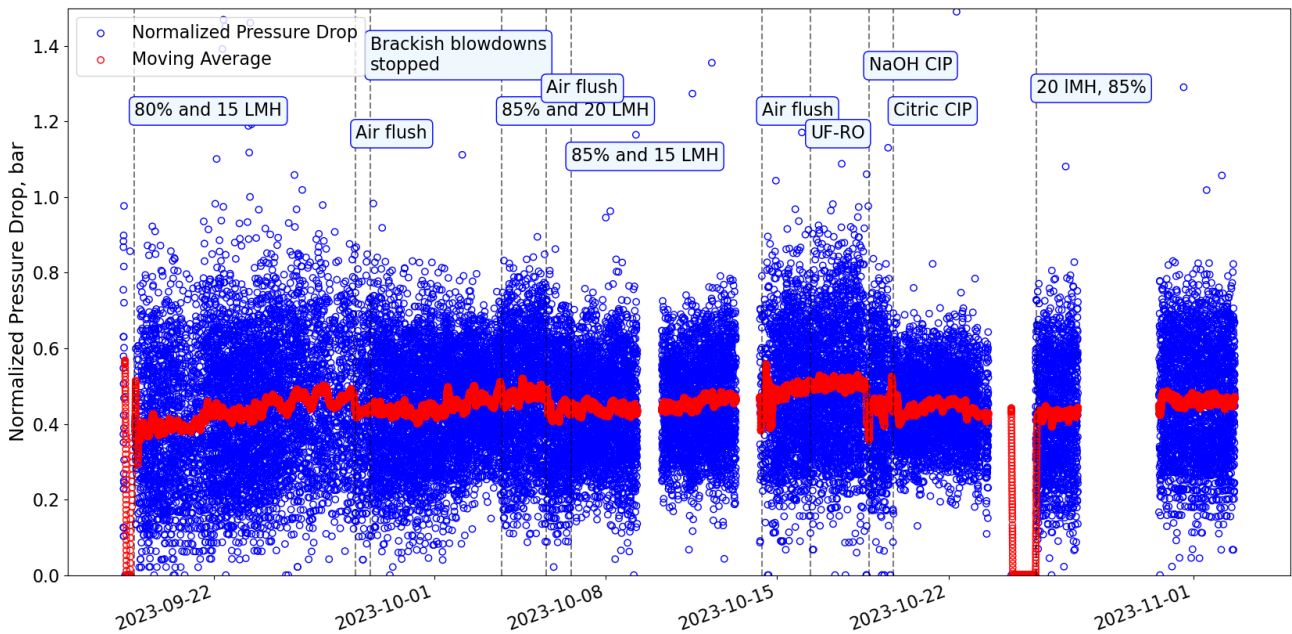


Figure 26 Normalized pressure drop, indicating no significant feed spacer fouling

Before the brackish blowdowns were stopped, the feed and concentrate conductivities were very high - Figure 27. This is of course detrimental to the energy of the RO as it needs to overcome the osmotic pressure.

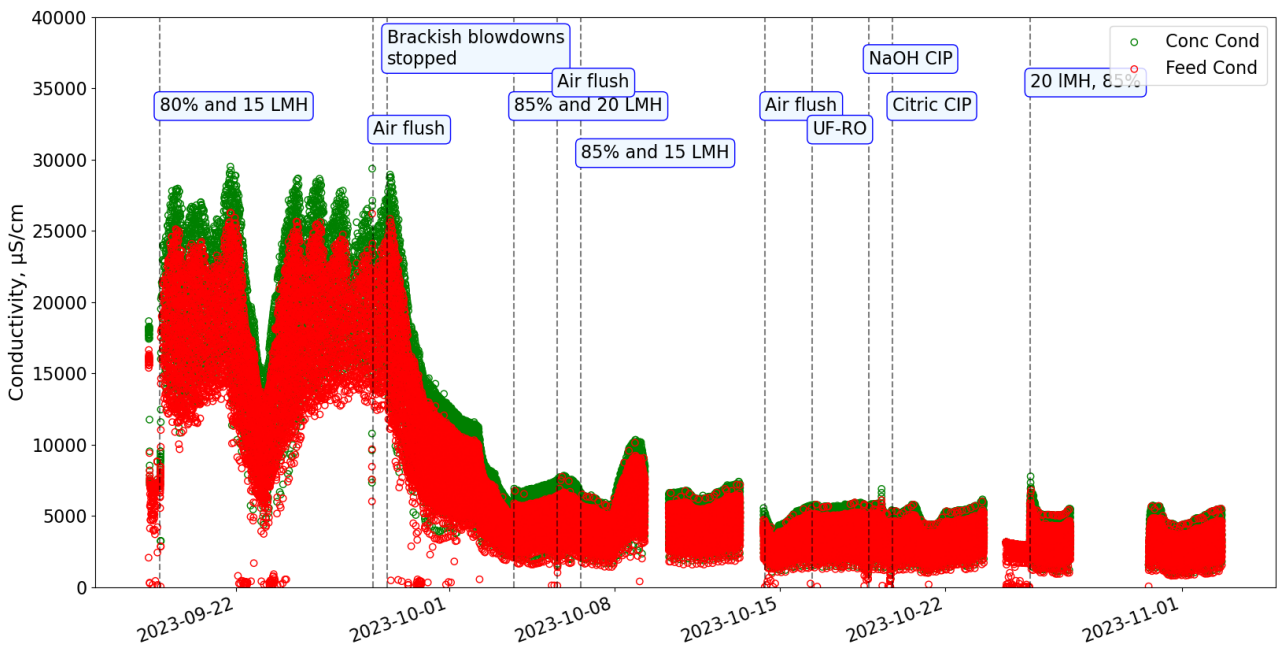


Figure 27 Feed and concentrate conductivities of the CCRO

The high feed and concentrate conductivities in the periods with high flowrate of the brackish blowdowns also lead to a very high permeate conductivity in excess of 400 $\mu\text{S}/\text{cm}$. After tapering off the brackish blowdown streams, the permeate conductivity was lower than 100 $\mu\text{S}/\text{cm}$ and typically around 40-60 $\mu\text{S}/\text{cm}$ - Figure 28.

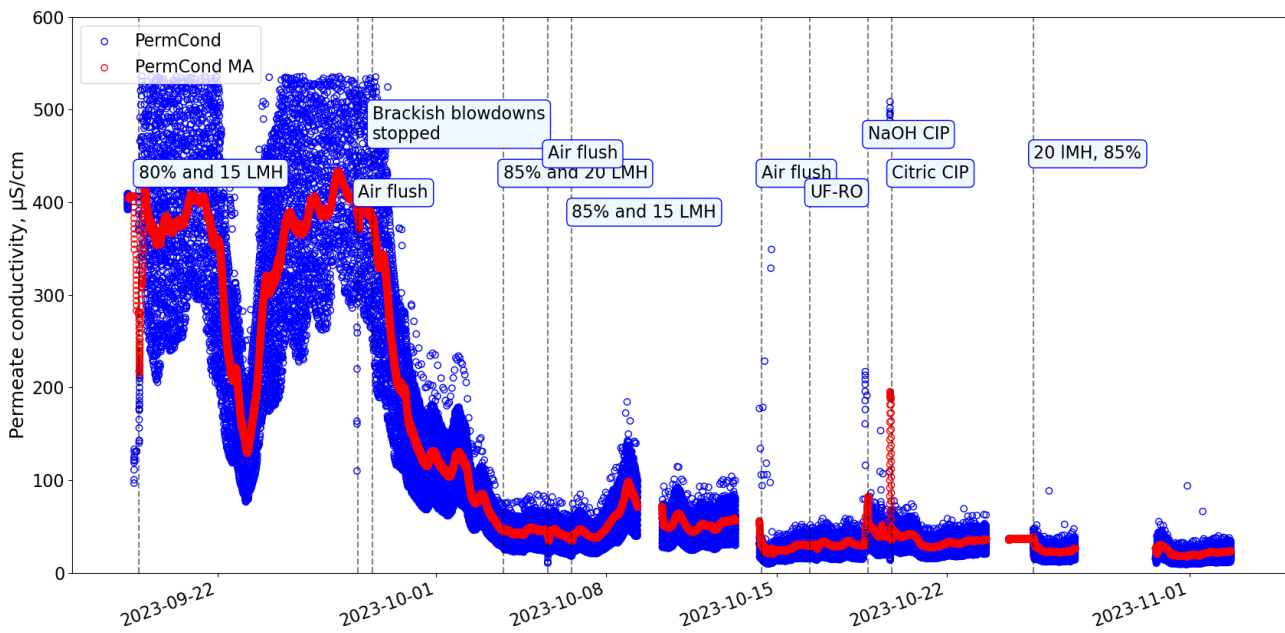


Figure 28 Permeate conductivity of the CCRO

During the periods with high brackish blowdowns the normalized salt passage was 1.7-2.0 %, but after the brackish blowdowns were tapered off, the normalized salt passage dropped to below 1% which is the expected value for this membrane - Figure 29.

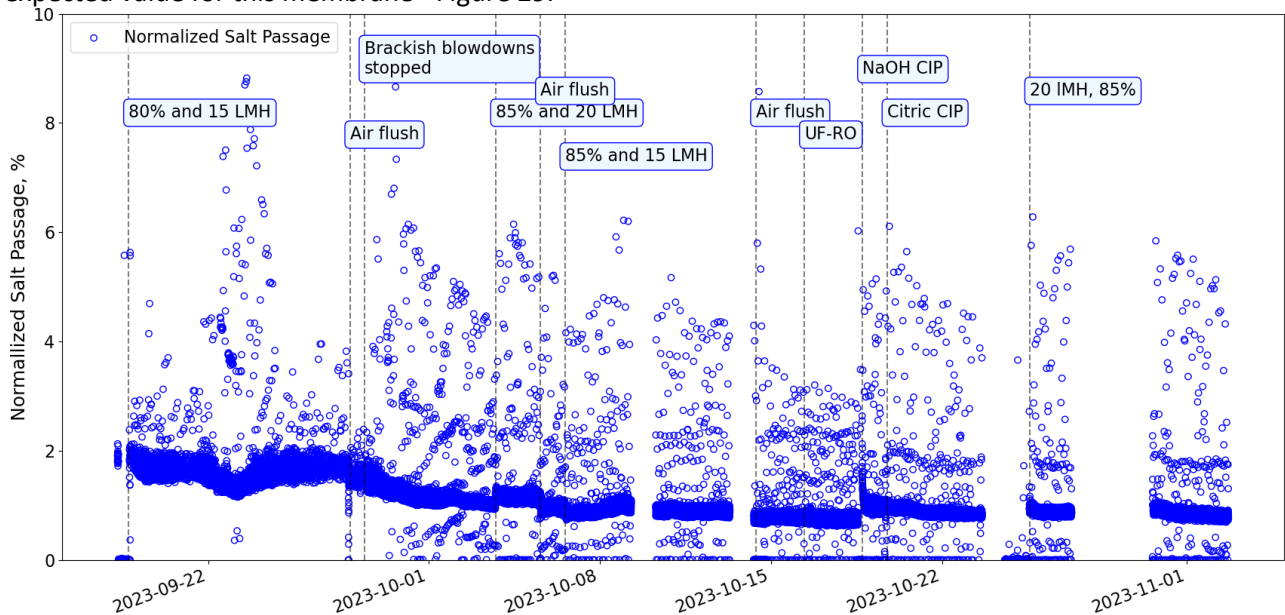


Figure 29 Normalized salt passage of the CCRO

The temperature throughout the tests remained rather stable and fluctuated around 15 to 22 °C - Figure 30.

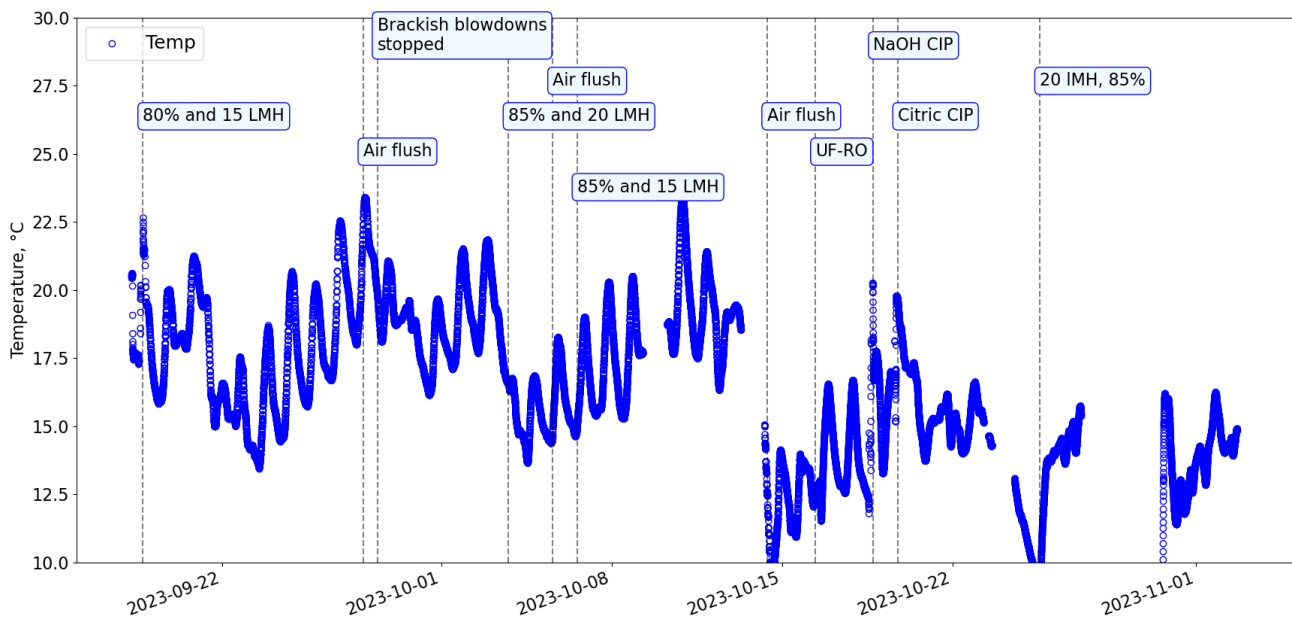


Figure 30 Temperature of the CCRO feed water

The total organic carbon (TOC) after the RO and the CCRO was quite low, typically below 50 ppb – Figure 31:

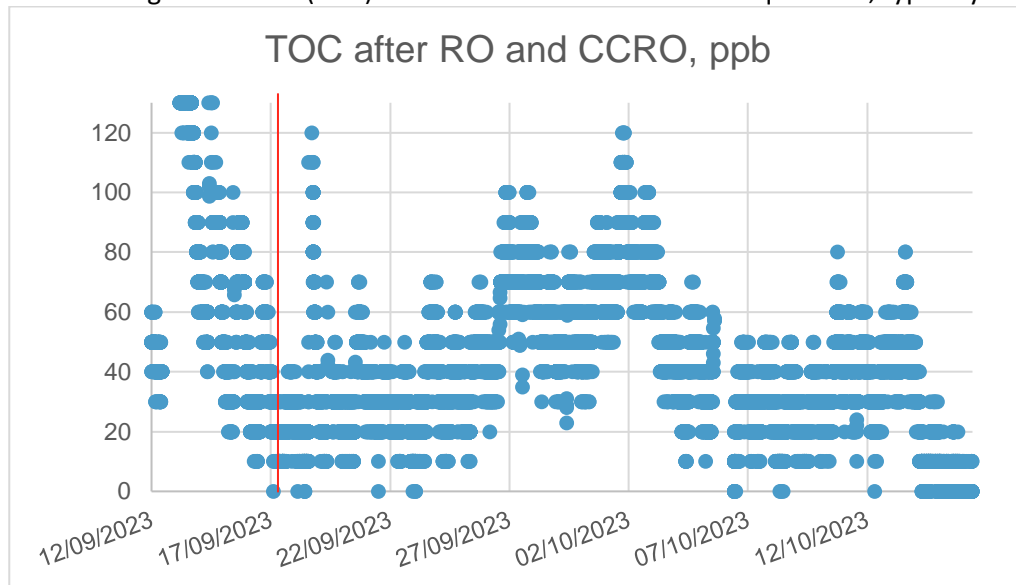


Figure 31 TOC after RO (until Sep 18th) and CCRO, ppb. Switch denoted by the red line

The TOC is somewhat higher with the RO (switched to CCRO on Sep 18), however, this is probably a startup effect since it takes some time until the buffer tank from which the RO permeate is sampled stabilizes in quality. It is important to note that the TOC is the difference between total carbon (TC) and inorganic carbon (IC). The IC is quite high after the RO due to the dissolved CO₂, typically above 2000 ppb.

Hence when the TOC is low, it becomes a small difference of two large numbers (total and inorganic carbon) leading to inaccuracies, explaining the negative TOC values seen in Figure 31. Typically, these cases requires an inorganic carbon remover setting on the TOC analyzer, but this module was malfunctioning on the online analyzer and could not be used. On 16th of October, the TOC after the RO was stopped since it showed mostly negative numbers.

UF-CCRO-EDI on the NTBA tank

On Oct 16, the EDI was connected to the effluent of the RO in order to assess the technology. This however could not be done directly because the conductivity of the water produced by the RO was somewhat high at 25-50 $\mu\text{S}/\text{cm}$, while the EDI module manufacturers recommend no more than 40 μS as a lumped indicator of water quality. Moreover, the flowrate of the CCRO permeate was 119 to 158 l/h depending on the flux setting, while the minimal flowrate recommended for the EDI module is 220 l/h. To avoid these issues the EDI was operated with partial recirculation of the permeate - Figure 32:

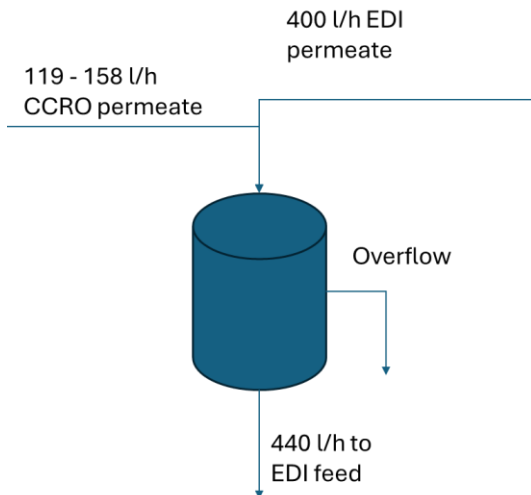


Figure 32 A schematic of the buffer tank used for partial recirculation of the EDI permeate allowing the EDI to work at the nominal flowrate of 440 L/h

The EDI was operated at 90 % recovery meaning that 44 L/h were discharged as concentrate and 400 L/h were returned to the buffer tank. The tank was fed with 119 to 158 L/h depending on the flux of the RO (15 LMH until 25th of October followed by 20 LMH, see previous section). The EDI flowrates are manually adjusted so these numbers are only an aim and can differ slightly over time. The exact product flowrate can be seen in Figure 33:

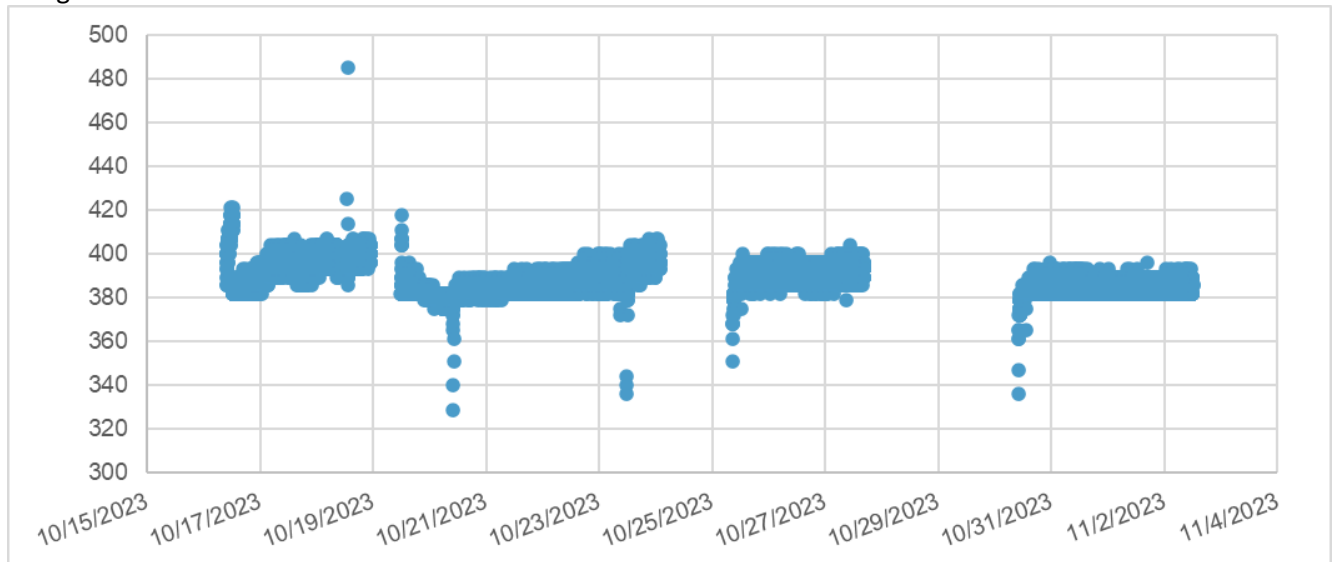


Figure 33 EDI product flowrate, l/h

Throughout the tests, the recovery was tightly controlled to be 90 % and was never changed - Figure 34. It should be noticed that in practice, the concentrate of the EDI is typically sent back to the RO, hence the recovery of the EDI does not affect the system recovery, and only provides additional hydraulic load and decreases the energy efficiency of the RO step.

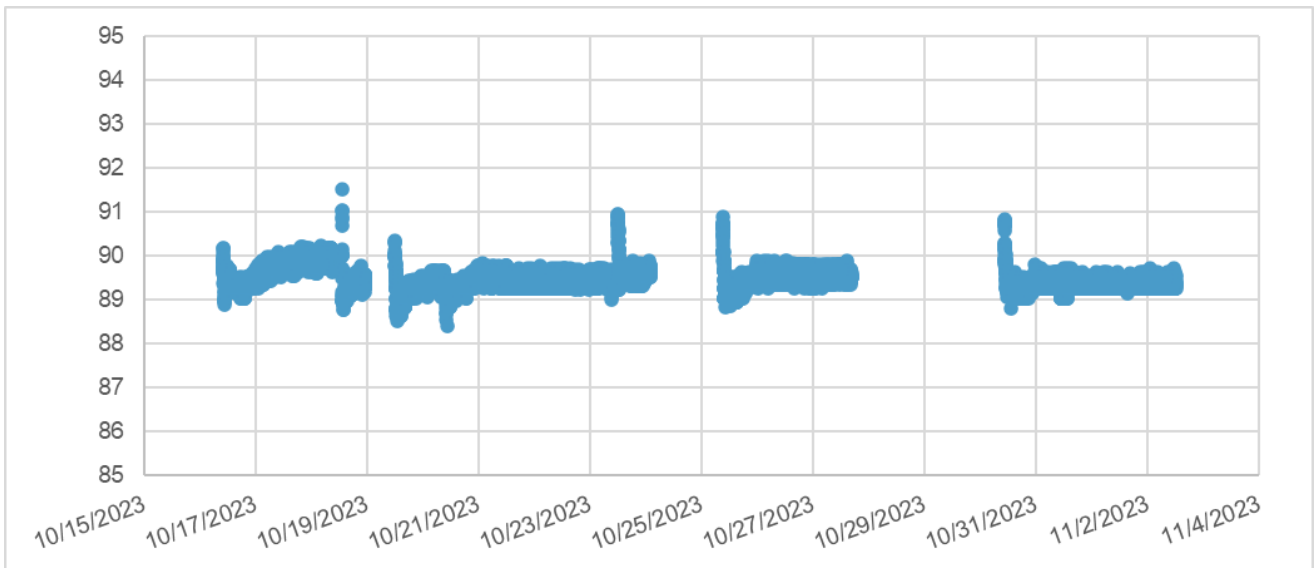


Figure 34 Recovery of the EDI, %

The temperature fluctuated between 23 and 29 °C - Figure 35.

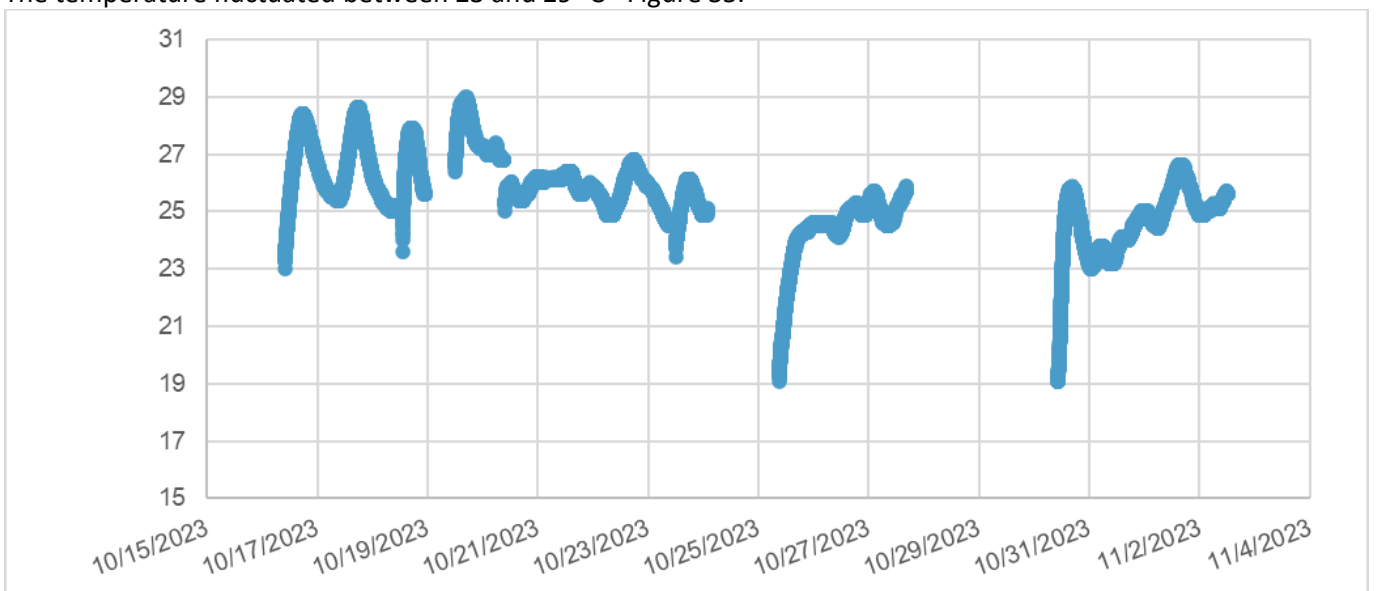


Figure 35 Temperature of the EDI

The conductivity of the EDI feed for the period can be seen in Figure 36:

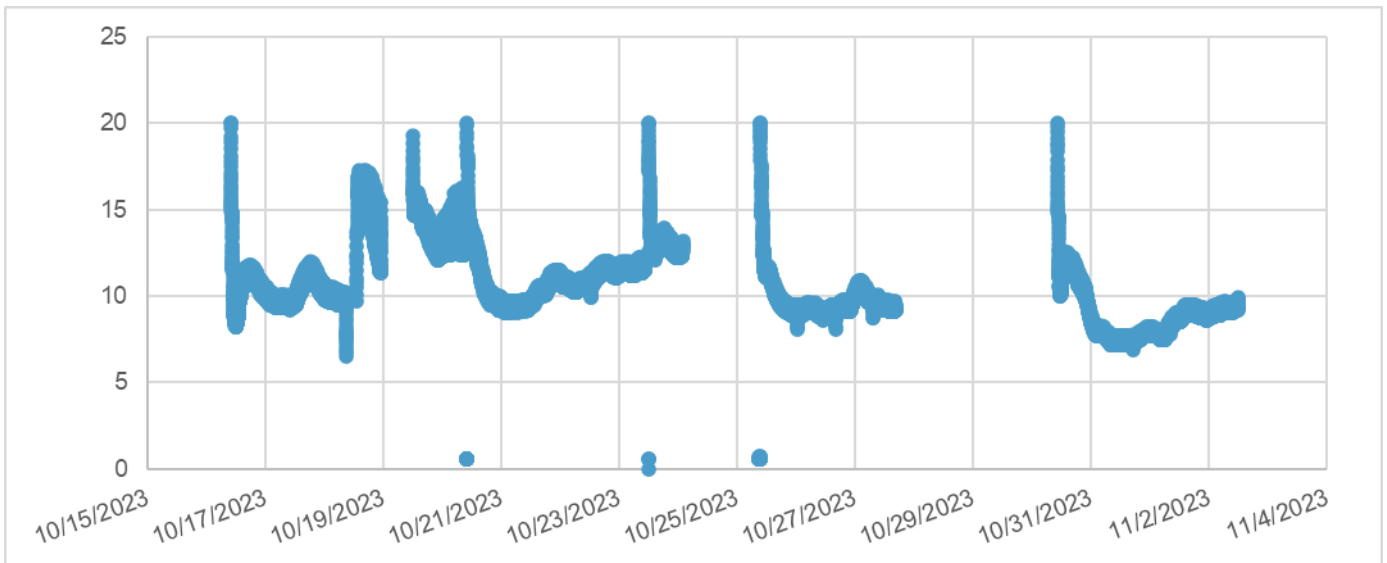


Figure 36 EDI feed conductivity of the water coming from the buffer tank

The peaks in the feed conductivity are due to start/stop events due to alarms coming from the steam cracker site. In the case of an alarm, the system needed to be stopped due to its location in an ATEX zone. On average the feed water to the EDI was 6-13 µS/cm.

The concentrate conductivity of the EDI can be seen in Figure 37:

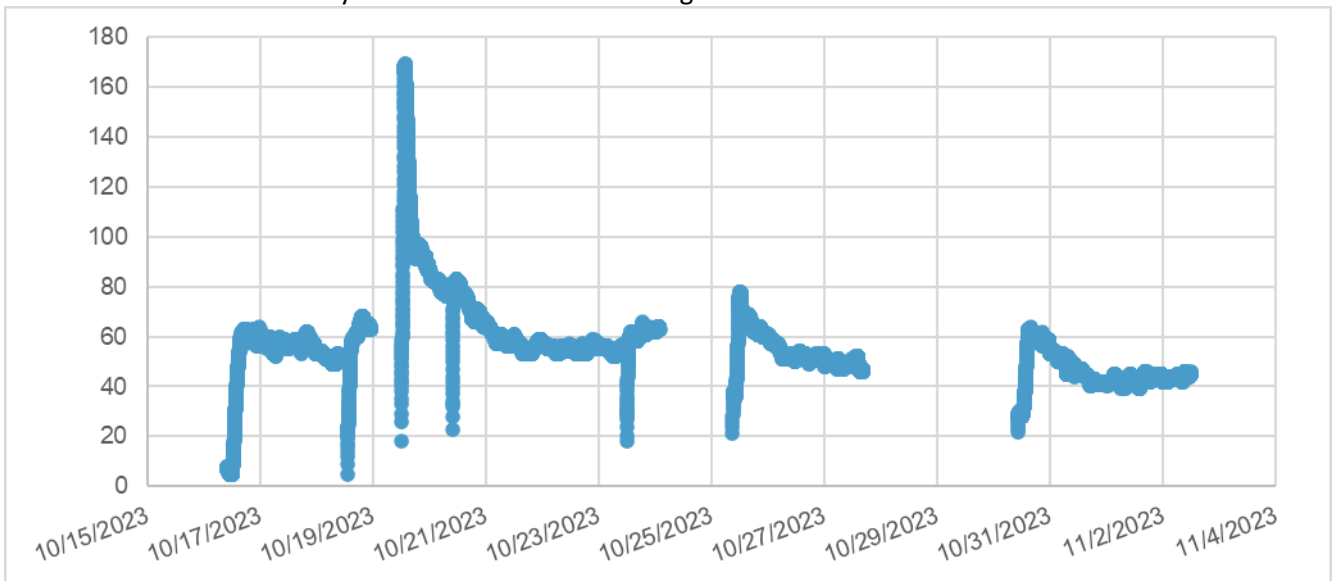


Figure 38 Concentrate conductivity of the EDI, µS/cm

The conductivity of the water produced by the EDI was always below 0.1 µS/cm and mostly fluctuated between 0.06 and 0.07 µS/cm - Figure 39. This is an excellent conductivity, based on which the water can be reused both as boiler feed water and as spray water for the air cooled condensers.

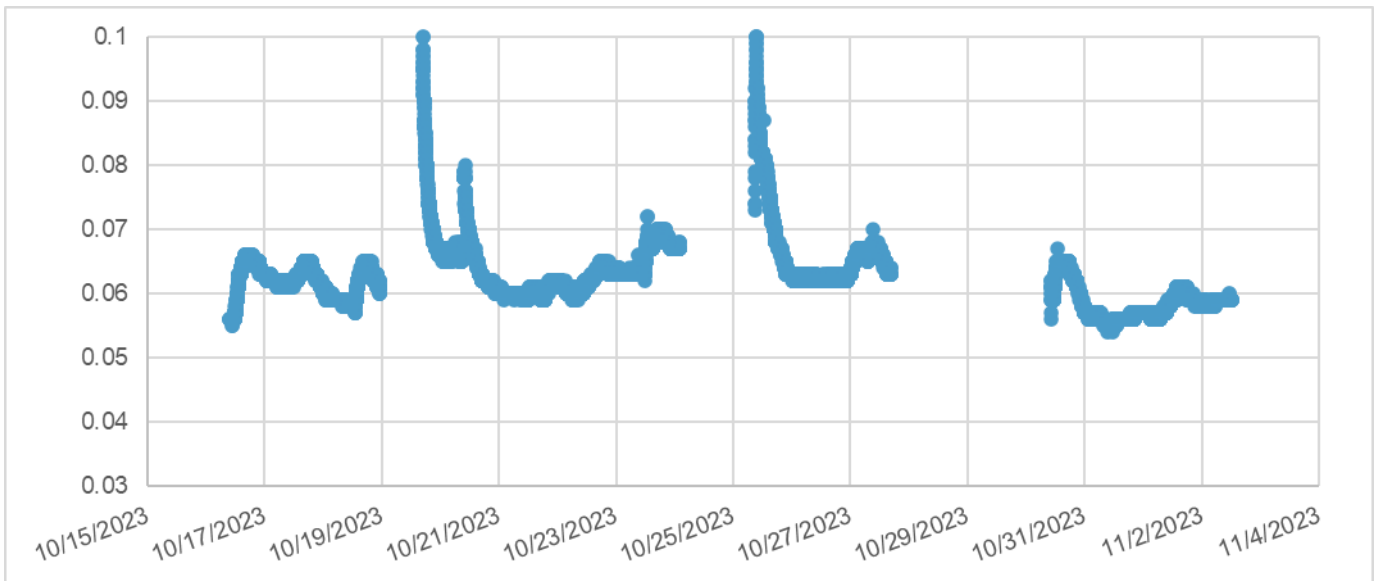


Figure 39 Conductivity of the EDI product, $\mu\text{S/cm S/cm}$

The TOC after the EDI was measured daily - Figure 40:

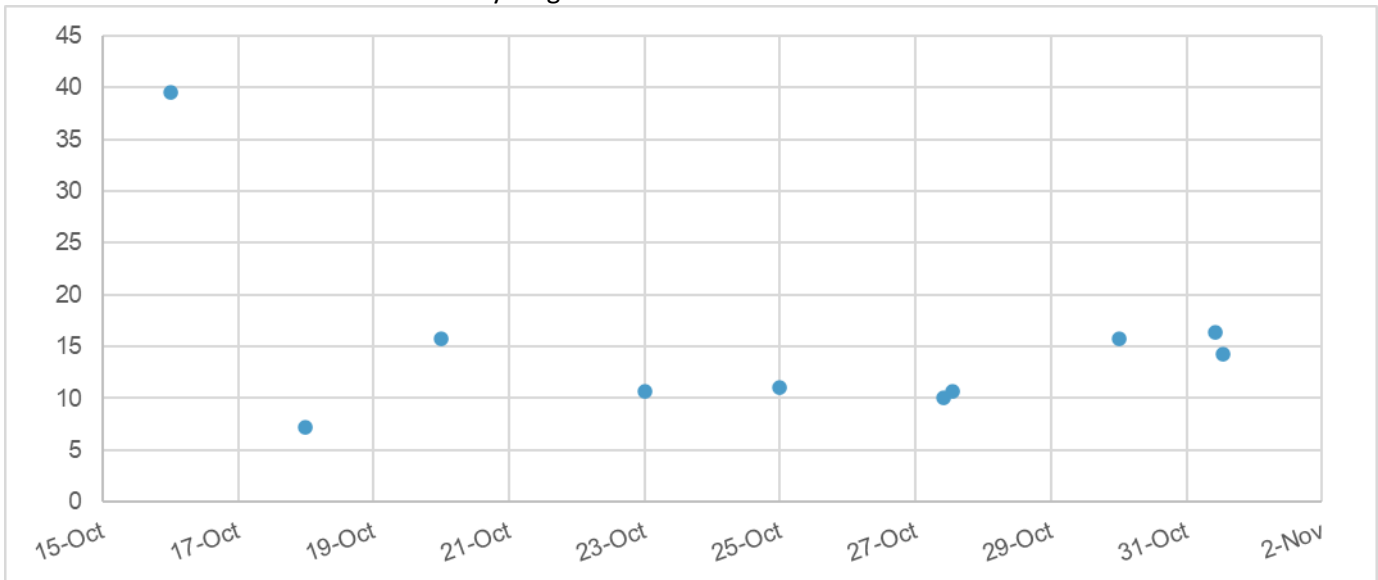


Figure 40 TOC after the EDI, ppb

The TOC after equilibration was always below 20 ppb, which is an excellent result and more than satisfactory for use as boiler feed water. The samples were taken as grab samples and analyzed at the Sievers TOC analyzers at the containers.

The desalination energy is the electrical energy used by the EDI to produce 1 m^3 of product. As seen in Figure 41, the desalination energy is 60-80 W-h/m^3 , which is excellent. To put this into perspective, the typical energy used by brackish water RO in low salinity applications is 0.6-1.2 kW-h/m^3 [7]

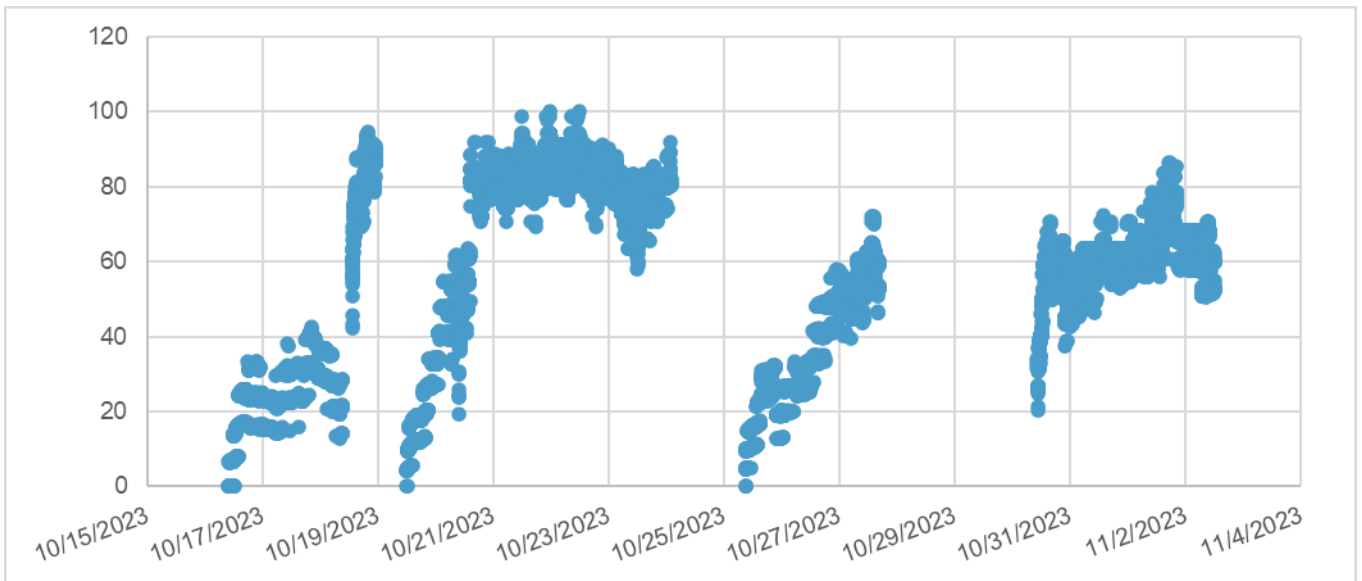


Figure 41 Desalination energy of the EDI

Initially the desalination energy is much lower at around 20-40 W-h/m³, however this is a transient phenomenon until the resins inside the membrane stack are equilibrated. It can be noticed that after Oct 25th, the desalination energy is decreased from 80 to 60 W-h/m³. On Oct 25th the CCRO flux was increased from 15 to 20 Lmh, thus the fraction of the RO permeate in the EDI feed buffer was increased. The higher CCRO flux also leads to a better RO permeate quality (Figure 28), possibly giving an explanation for the lower desalination energy. In a real world application the EDI water would likely be treated with double pass RO, leading to an even lower desalination energy.

The stack resistance was also observed, since an increasing stack resistance may indicate fouling of the resins and the membranes – Figure 42:

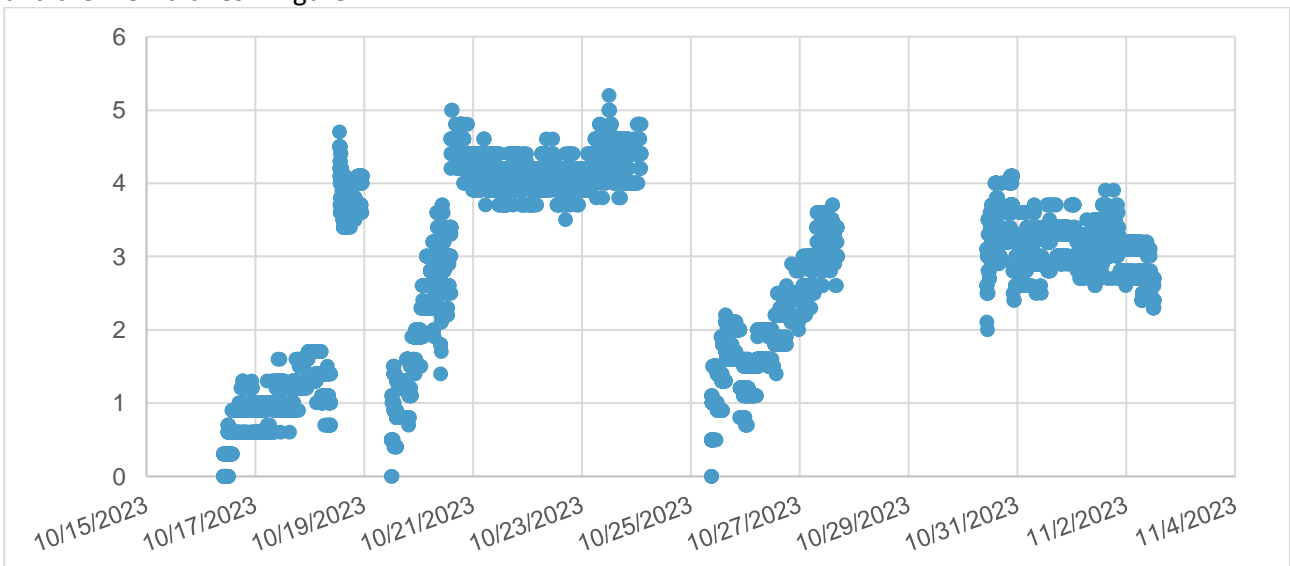


Figure 42 EDI stack resistance, Ohm

We see that there are two levels of equilibration of the stack, before and after Oct 25th. On Oct 25th the flux of the RO was increased from 15 to 20 Lmh, hence the ratio of RO water to EDI permeate recirculated in the feed buffer was changed. No trends of increasing stack resistance can be observed for the period.

6. Conclusions

The AquaSPICE piloting at BASF Antwerp focused on the feasibility for recovery and performance of advanced water treatment technologies for the reuse of different streams at the steam cracker site. Two distinct locations within the steam cracker complex were tested.

At Location 1, the focus was on reclaiming dilution steam blowdown and boiler/furnace blowdown. Despite comprehensive treatment with granular activated carbon, ion exchange, and reverse osmosis, the dilution steam blowdown could not be sufficiently purified for reuse. The main limiting factor was the persistent presence of small, uncharged organic molecules such as methanol and ethanol, which are poorly removed by conventional physicochemical methods and would likely require biological treatment to meet reuse standards.

Conversely, treatment of boiler blowdown using ultrafiltration and electrodeionization (EDI) proved to be very successful. The EDI system consistently produced water of excellent quality, with conductivity below 0.1 $\mu\text{S}/\text{cm}$ and TOC below 100 ppb—meeting BASF's boiler feedwater standards. The stack showed no evidence of fouling or resistance increase throughout the trials, and energy consumption was low, reinforcing EDI as a viable, chemical-free alternative to conventional mixed-bed polishing.

At Location 2, reverse osmosis (RO) and closed circuit reverse osmosis (CCRO) were applied to water from the NTBA tank, which includes rainwater runoff, air cooler spray water runoff, and limited volumes of brackish blowdown. The initial trials with conventional RO revealed rapid membrane fouling, primarily due to the presence of metals such as zinc and iron, traced to galvanized structures at the site. Transitioning to CCRO provided greater operational stability and improved membrane performance. The system stability further improved after BASF minimized the volume of brackish blowdowns that were flowing into the NTBA tank.

When coupled with EDI, the CCRO-treated water from the NTBA achieved excellent purity—conductivity consistently below 0.1 $\mu\text{S}/\text{cm}$ and TOC under 20 ppb. This confirmed the potential for high-quality water reuse, including for boiler feed or cooling spray applications. Notably, the energy demand of EDI remained very low, between 60–80 Wh/m^3 , underscoring the system's efficiency and suitability for continuous operation.

Overall, the pilot testing validated EDI and CCRO as robust and scalable technologies for industrial water reuse. While certain streams such as dilution steam blowdown remain difficult to treat without biological processes, the results provide a compelling case for expanding closed-loop water reuse in energy-intensive industrial processes, contributing meaningfully to BASF's sustainability and circular water strategies.

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List of abbreviations

BGAC	Biological granular activated carbon
CapEx	Capital Expenditure
CCRO	Closed-circuit reverse osmosis
CIP	Cleaning in place
COD	Chemical oxygen demand
DO	Dissolved oxygen
EDR	Electrodialysis reversal
EDI	Electrodeionization
GAC	Granular activated carbon
IC	Inorganic carbon, ion chromatography
IEX	Ion exchange
IMPROVED	Integrale Mobiele PROceswater Voorziening voor een Economische Delta
MABR	Membrane aerated bioreactor
MB	Mixed bed resin
MTC	Mass transfer coefficient
NDP	Net Driving Pressure
NPD	Normalized Pressure Drop
NSP	Normalized salt passage
NTBA	Niet Te Behandelen Afvalwater (uncontaminated wastewater that requires no treatment prio to discharge)
OpEx	Operational Expenditure
PFRO	Pulse-flow reverse osmosis
RO	Reverse osmosis
SAC	Strong Acid Cation
TC	Total Carbon
TOC	Total organic carbon

Appendices

Appendix 1. Equations used in the RO normalization

$$SP = EC_p \times T_{cf_EC} \times Q_{cf}$$

$$EC_p = 100 \times \frac{EC_{permeate}}{(EC_{feed} \times (\log \frac{1}{1 - Recovery})) / Recovery}$$

$$T_{cf} = \exp^{(U_{par} \times ((\frac{1}{T_{feed} + 273.15}) - (\frac{1}{T_{ref} + 273.15})))}$$

Where U_{par} is the Dow membrane U-value, equal to 3200, EC_p is the recovery corrected permeate conductivity, T_{ref} is the reference temperature equal to 25 °C and T_{cf} is the conductivity corrected temperature.

$$NPD = dP \times Q_{cf} \times T_{cf}$$

$$dP = P_{feed} - P_{concentrate}$$

$$Q_{cf} = (\frac{Q_{vc}}{\frac{Q_{permeate} + Q_{concentrate}}{2}})^m$$

$$Q_{vc} = \frac{Q_{feedn} + Q_{concentraten}}{2}$$

$$T_{cf} = (\frac{\eta_{ref}}{\eta_{feed}})^n$$

Where NPD is normalized pressure drop [kPa], Q_{feedn} normalized design feed flow of the RO system [$m^3 \cdot h^{-1}$], $Q_{concentraten}$ normalized design concentrate flow [$m^3 \cdot h^{-1}$], T_{cf} is the viscosity corrected temperature, Q_{vc} is the viscosity corrected flow, η_{ref} and η_{feed} are reference and feed viscosity respectively, m and n are Dow membrane values, equal to 1.6 and 0.4, respectively.

$$MTC = \frac{Q_{permeate} \times T_{cf} \times 10^{-5}}{36 \times Q_{permeate}}$$

$$NDP = ((\frac{P_{feed} + P_{concentrate}}{2} - P_{permeate}) \times 100) - (\frac{OP_{feed} + OP_{concentrate}}{2} - OP_{permeate})$$

$$T_{cf_OP} = \frac{T_{feed} + 273.15}{T_{ref} + 273.15}$$

$$OP_{feed} = EC_{feed} \times EC_{OP_feed} \times T_{cf_OP}$$

$$OP_{concentrate} = EC_{concentrate} \times EC_{OP_concentrate} \times T_{cf_OP}$$

$$OP_{permeate} = EC_{permeate} \times EC_{permeate} \times T_{cf_OP}$$



Where MTC is the mass transfer coefficient [$\text{m}\cdot\text{S}^{-1}\cdot\text{Pa}^{-1}$], NDP net driving pressure [kPa], OP osmotic pressure calculated for feed, permeate and concentrate [kPa] and T_{cf_OP} is the osmotic pressure corrected temperature.