



Research article

Comparison of cooling tower blowdown and enhanced make up water treatment to minimize cooling water footprint

Sarah I. Müller^a, Gergana Chapanova^b, Thomas Diekow^b, Christian Kaiser^b, Lies Hamelink^c, Ivaylo P. Hitsov^d, Lisa Wyseure^c, David H. Moed^c, Laurence Palmowski^a, Thomas Wintgens^{a,*}

^a Institute of Environmental Engineering (ISA) RWTH Aachen University, Mies-van-der-Rohe-Str. 1, 52072, Aachen, Germany

^b Dow Olefinverbund GmbH, Olefinstraße 1, 04564, Böhlen, Germany

^c Evides Industriewater B.V., PO box 3063 NH, Rotterdam, Netherlands

^d CAPTURE (Centre for Advanced Process Technology for Urban REsource recovery), Frieda Saeyssstraat 1, 9052, Gent, Belgium



ARTICLE INFO

Keywords:

Industrial water
Cooling tower blowdown treatment
Cooling tower water footprint
Water reuse
Cooling tower make up treatment
Cooling tower

ABSTRACT

When water supply restrictions increasingly escalate to water supply risks, developing strategies to minimize the water footprint of wet cooling systems becomes crucial. This study compares two water engineering approaches to minimize the water footprint of a recirculating evaporative cooling tower (CT): (1) reusing cooling tower blowdown and (2) producing demineralized water to increase the cycles of concentration (CoC) of the CT.

Our techno-economic analysis across various scenarios and CT settings reveals that reusing blowdown (option 1) is the most feasible approach for an industrial cooling system currently operating at CoCs of > 3, discharging blowdown with a conductivity of 2 mS/cm and a total organic carbon (TOC) concentration of approximately 20 mg/L. Compared to enhanced make up treatment, blowdown reuse allows higher water savings (13 %) and involves lower implementation and operation costs.

Pilot scale trials validated the feasibility of both approaches. Blowdown and enhanced make up treatment included biologically activated carbon filtration, ultrafiltration and reverse osmosis, producing high-quality permeate, suitable for (re)use as CT make up or within other processes. The blowdown treatment reached a product quality of 80 µS/cm conductivity and 70 µg/L TOC, make up treatment 20 µS/cm in conductivity and 60 µg/L TOC, respectively.

The study's findings underscore the viability of blowdown reuse as a cost-effective and efficient strategy to minimize the water footprint of cooling systems under increasing water scarcity conditions.

1. Introduction

Water scarcity has become a visible threat in many countries. Seasonal record low water levels in rivers/lakes and constantly decreasing groundwater levels indicate that action needs to be taken (Toreti et al., 2022; Wunsch et al., 2022). Using 45 % of all abstracted water, the industry is Europe's largest water user (FAO, 2022; UNESCO, 2023). More than 80 % of abstracted freshwater in the industry was reportedly used for cooling purposes in 2019 (Eurostat, 2023). Thus, it is crucial to emphasize the optimization and general water use minimization of cooling processes in the industrial sector, especially in areas of (seasonal) water scarcity. Maximizing heat integration and reuse (total site

heat integration, see, e.g., Dhole and Linnhoff (1993); Wang et al. (2021)) can concurrently reduce cooling and, thus, water requirements. Additional strategies involving water engineering measures are available and necessary to minimize the water footprint of the cooling process. Further, using reclaimed water for application in cooling towers has and should be gaining popularity in reducing overall freshwater abstraction in industries (Cherchi et al., 2019; Hansen et al., 2016).

Typical large water-using cooling systems (> 100 MW_{th} capacity) utilized for industrial applications can be classified into two main categories: (1) once-through and (2) evaporative (open) recirculating cooling where (1) requires large water volumes (approx. 86 m³/h/MW_{th}) to feed heat exchangers and directly discharges the heated water

* Corresponding author.

E-mail addresses: mueller@isa.rwth-aachen.de (S.I. Müller), GChapanova@dow.com (G. Chapanova), TDiekow@dow.com (T. Diekow), CKKAISER@dow.com (C. Kaiser), lies.hamelink@outlook.com (L. Hamelink), Ivaylo.Hitsov@UGent.be (I.P. Hitsov), lisa.wyseure@evides.nl (L. Wyseure), D.Moed@evides.nl (D.H. Moed), palmowski@isa.rwth-aachen.de (L. Palmowski), Wintgens@isa.rwth-aachen.de (T. Wintgens).

<https://doi.org/10.1016/j.jenvman.2024.121949>

Received 16 April 2024; Received in revised form 12 July 2024; Accepted 23 July 2024

Available online 30 July 2024

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back to receiving water bodies. Thus, applying these systems only in areas with sufficient water resources (e.g., close to the sea/large rivers) is compulsory. While (1) does not actually consume (evaporate) the used water, receiving water bodies are thermally “polluted”. The latter (2) uses water that is recycled within the system as a medium for heat transfer, incorporating the mechanism of evaporation by ambient air for cooling. It results in a specific cooling water demand of approx. $2 \text{ m}^3/\text{h}/\text{MW}_{\text{th}}$ (Cherchi et al., 2019; European Commission, 2016; 22449-1, 2020). In regions with water supply restrictions, where water-cooled systems are necessary, it is recommended to use an evaporative recirculating system, which shows an approximately 50 times lower water demand per MW_{th} (European Commission, 2016). As regions with water scarcity are predicted to be extended far beyond the current status (UNEP, 2017), systems running on once-through cooling might be forced to change cooling practices to the less freshwater-demanding recirculating cooling system.

1.1. Water use in evaporative recirculating cooling towers

Before the required water for cooling is fed to the recirculating cooling tower, it typically undergoes treatment for hardness removal, depending on initial and required quality. After this treatment, treated water, called cooling tower make up, is sent to the cooling tower. The make up is conditioned chemically to prevent severe system failures potentially caused by corrosion, scaling, and biofouling (Gartiser and Ulrich, 2002; Pinel, 2021). As a cooling method, evaporation inherently results in water losses from the system. The discharge of cooling tower blowdown is essential for controlling the accumulation of minerals and organic matter in the recirculating water (Gartiser and Ulrich, 2002; Guyer, 2014; Hill, 1990).

The blowdown percentage is recommended at 10 % of the make up (EPA, 2017). In reality, this value can, however, be greater than 50 % and therefore holds the potential for reducing freshwater needs in case blowdown is (partly) reclaimed and reused (Altman et al., 2012; Gartiser and Ulrich, 2002). Another approach, recently proposed by Pinel (2021), considers new methods for cooling water conditioning requiring enhanced make up treatment. It enables the blowdown percentage of make up to be reduced much further than 10 %, potentially reducing freshwater demand.

The water lost by evaporation (Q_{EVAP}) and drift (Q_{D}), potential system leaks (Q_{L}), as well as water discharged as blowdown (Q_{CTBD}), need to be replaced with cooling tower make up water (Q_{CTMU}), thus equation (1) applies:

$$Q_{\text{CTMU}} = Q_{\text{EVAP}} + Q_{\text{D}} + Q_{\text{L}} + Q_{\text{CTBD}} \quad (1)$$

Cycles of Concentration (CoC) in cooling water systems often describe their water use efficiency. It is defined as the ratio of Total Dissolved Solids (TDS) in the blowdown, TDS_{CTBD} (= TDS in recirculating cooling water in CT), to TDS in make up (TDS_{CTMU}). This definition inhibits potential inaccuracies, when TDS is altered by added conditioning agents (acids, biocides or similar). Assuming Q_{D} and Q_{L} as neglectable and using a mass balance of the TDS, the CoC can be calculated using known Q_{CTMU} and Q_{CTBD} (Aquaprox, 2009; Guyer, 2014) as shown in equation (2):

$$\text{CoC} = \frac{TDS_{\text{CTBD}}}{TDS_{\text{CTMU}}} = \frac{Q_{\text{CTMU}}}{Q_{\text{CTBD}}} \quad (2)$$

Consequently, increasing the CoC of a given cooling system, e.g., by improving make up water quality lowering, i.e., TDS_{CTMU} , will decrease both Q_{CTMU} and Q_{CTBD} (smaller water footprint). However, the operating efficiency of the cooling tower needs to be maintained and cooling tower equipment protected, leading to a limitation of feasible CoC increase. As water evaporates from the cooling towers, minerals and organic matter are concentrated in the recirculated water. Accumulation of minerals and organic matter in the water and their deposition on surfaces can

adversely affect equipment and cooling system operation. Corrosion, scaling, and biofouling can occur and thus need to be prevented. In full-scale cooling towers, the electrical conductivity of blowdown, instead of its correlated, time-consuming TDS measurements (Taylor et al., 2018), is generally used as an indicator of water quality to control the required flows of blowdown and make up. Blowdown electrical conductivity seldom exceeds $4500 \mu\text{S}/\text{cm}$ in freshwater-fed systems (Koeman-Stein et al., 2016; Pinel, 2021).

Furthermore, the make up/recirculating cooling water undergoes regular conditioning with biocides, scale inhibitors, dispersants, and corrosion inhibitors, as Gartiser and Ulrich (2002) outlined. This conditioning is essential for preventing scaling, corrosion, and fouling. However, it also raises environmental concerns, given the potential formation of disinfection by-products and other environmental issues associated with these conditioning agents (Grote et al., 2022). Therefore, discharging Q_{CTBD} from the system removes water with accumulated minerals and emits conditioning chemicals. Higher Q_{CTBD} necessitates the reintroduction of more chemicals into the CT system. Added conditioning agents (acids, biocides or similar) can alter the TDS in the recirculating water. Thus, equation (2), utilization of TDS or conductivity ratios includes minor inaccuracies to determine the actual CoC. A water/solids balance check is recommended.

1.2. Water saving strategies

Various (retrofitting) strategies exist to lower the industrial water footprint related to cooling. Owing to both energy and water conservation, required cooling capacity should always be minimized through improved heat integration (see, e.g., Chew et al. (2013)) and waste heat recovery (e.g., Wallerand et al. (2018)). Further, the cooling system's architecture, type, and operations should be reassessed, i.e., hybrid systems (involving partial waterless operation) and drift eliminators (European Commission, 2016). The CoC should be optimized/maximized considering system limitations and local restrictions. (Pinel, 2021; Walker et al., 2012). In terms of water engineering, to minimize the overall freshwater intake for cooling, the following two approaches can be taken to retrofit existing open recirculating cooling systems, which will be considered within this work (see Fig. 1: displayed relevant variables are further introduced in section 3.3.1):

Option 1: Improving make up quality (through enhanced make up treatment) for maximum achievable CoC (compare Pinel (2021)).

Option 2: Treatment of blowdown for Water Reuse (as make up or in other processes) (compare Wagner et al. (2022); Jain et al. (2021); Wagner et al. (2020)).

Thus, to find optimal water engineering measures for maximized water saving and timely implementation in existing open evaporative cooling towers, the goals of this investigation were to (i) apply different water engineering strategies and (ii) determine the most feasible option for water footprint minimization for the selected case study.

1.3. Applied water treatment technologies

Pilot plants were utilized due to their ability to simulate full-scale operations under controlled conditions, allowing for detailed observation and refinement of treatment processes. The test campaigns aimed to assess the performance based on chosen key performance indicators (KPI): TOC, nutrients and salts rejection, fouling/blocking tendency by permeability/pressure drops within treatment systems, water and cost efficiency. Detailed information on KPI calculation can be found in the Supplementary Material (SM).

A treatment configuration of Biologically activated carbon filtration (BACF) and ultrafiltration (UF), followed by Reverse Osmosis (RO) was used to assess both options evaluated within this work.

BACF and UF are applied as enhanced pretreatment to remove organics/nutrients (i.e. TOC) and potential foulants from raw water. UF was removed from the treatment train for at least one week of operation

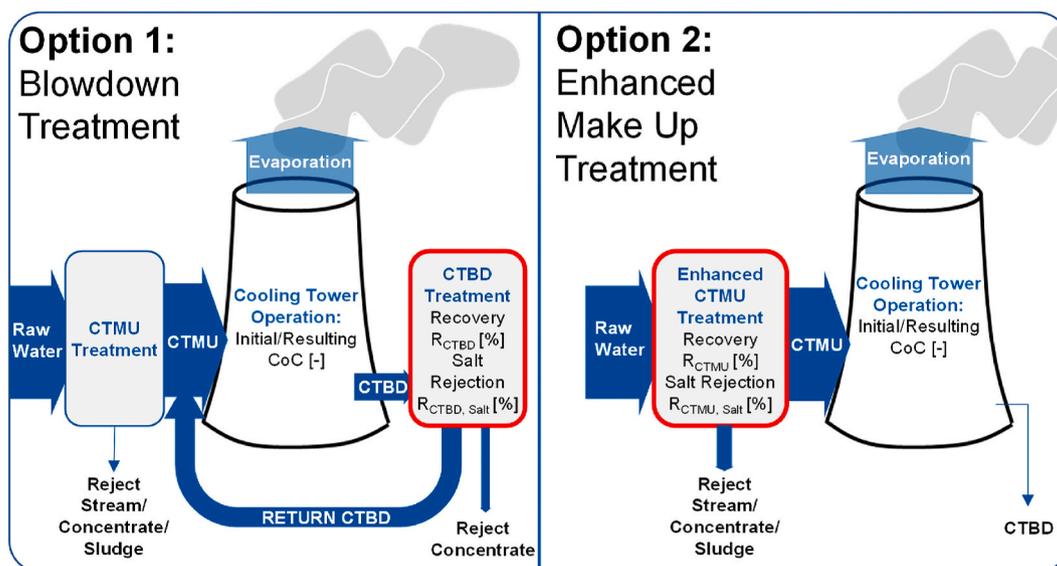


Fig. 1. Illustration of analyzed water flows and variables relevant to assessed water minimization strategies; CTBD is Cooling Tower Blowdown, CTMU is Cooling Tower Make Up, CoC is Cycles of Concentration.

to challenge its necessity. Reasons to choose these pretreatments over others (e.g., coagulation/flocculation, softening) were several: (1) both treatments require only minor amounts of chemicals, particularly when compared to conventional coagulation/flocculation processes; (2) the use of the macroporous granular activated carbon (GAC) medium in the BACF was shown to result in enhanced protected bioactivity in comparison to other filtration media, including anthracite and sand - BACF has the ability to adsorb and remove/retain swiftly biodegradables (i.e., responsible for fouling on subsequent treatment steps) as well as slowly biodegradable components (e.g., the corrosion inhibitor benzotriazole) (Wagner et al., 2020; Liu et al., 2011; Urfer et al., 1997; Li and DiGiano, 1983; AWWA, 1981); (3) longevity and efficiency of the subsequent membrane treatment/desalination step is enhanced (ElHadidy, 2016; Hallé et al., 2009), (4) robustness and reliability have been proven in several large-scale applications.

Reverse Osmosis (RO) desalination was chosen as bulk demineralization step, due to its proven robustness and reliability as physical barrier for salts and organics (e.g., Nthunya et al., 2022; Liu et al., 2022). Due to high quality requirements for the treated water to be reused (either in CT or elsewhere), nanofiltration was decided inferior to RO in the regarded case. Treatment by ion exchange resins for bulk demineralization would lead to significant chemical usage, while further not being a complete barrier for relevant organic fractions, such as biopolymers or low molecular weight neutrals (Laforce et al., 2022; De Meyer, 2020). Further, Electrodialysis (ED) is not considered as a desalination option as it cannot sufficiently reject remaining uncharged species in (pretreated) raw water or blowdown. Further, ED is more capital-intensive than RO (Patel et al., 2021).

Comprehensive analyses, including water quality assessments (section 2.2), water usage evaluations, and cost analyses, were conducted to determine the overall viability and performance of the treatment configurations. The objective was to trial treatment sequences that minimize water use with minimum costs and environmental impact.

2. Material and methods

2.1. Pilot plant experiments

The pilot plant experiments for blowdown and make up treatment were performed in Böhlen, Germany, at the Dow chemical industrial site from June to August 2022. There, Dow operates and supplies a cracking

refinery and other chemical plants, producing commodity chemicals such as ethylene, propylene, aniline, and others (Dow, 2023). The mobile infrastructure of the IMPROVED containers was used to perform the pilot plant experiments. The containers are mobile water treatment units developed as part of an Interreg-funded project (Interreg, 2016). A detailed process flow diagram (filtration mode) of the tested treatment configurations is shown in Fig. 2.

Table 1 summarizes the primary operating conditions and characteristics of the applied treatment technologies for both options trialed.

Blowdown was taken directly from the collection basin of a fan-induced draft, counter-flow cooling tower located at the Dow Olefinverbund GmbH premises in Böhlen, Germany. It consists of 4–6 times concentrated decarbonized surface water, being irregularly oxidized to control biological growth (shock dosage with in-situ generated monochloramine). Raw water for the enhanced make up treatment was taken from a local reservoir (selected water quality parameters can be found in Table 3).

The applied settings for RO Feed adjustment, i.e., antiscalant dosage and pH adjustment, were estimated with the MM5 software provided by Genesys International. Table 1 shows the operating conditions and characteristics of the applied treatment technologies/pilot plants. The applied system recovery rate of 84 % (Enhanced make up treatment (Option 2)) was the maximum achievable recovery rate of the applied RO system (minimum concentrate rejection of 34 L/h was necessary for continuous operation).

2.2. Sample analysis

The pH values in grab samples were measured using a hand-held Hanna (HI99192) pH meter. Conductivity and Dissolved Oxygen (DO) were measured using an Orion Star A329 Multiparameter meter. The DO sensor relies on optical measurement. Turbidity was measured using a Hanna (HI98703) portable meter. TOC was analyzed by taking grab samples with a Sievers M5310 C TOC analyzer. Na, Ca, Mg, and Phosphate were analyzed in the laboratory according to DIN EN 11885 (E22) and sulfate according to DIN EN ISO 10304-1. Total Inorganic Nitrogen (TIN) was calculated based on laboratory measurements of nitrite (DIN EN 26777 (D10)), nitrate (DIN EN ISO 10304-1 (D20)), and ammonium (DIN 38406-E5-1). Chloride (dissolved) was analyzed according to DIN EN ISO 10304-1 D20.

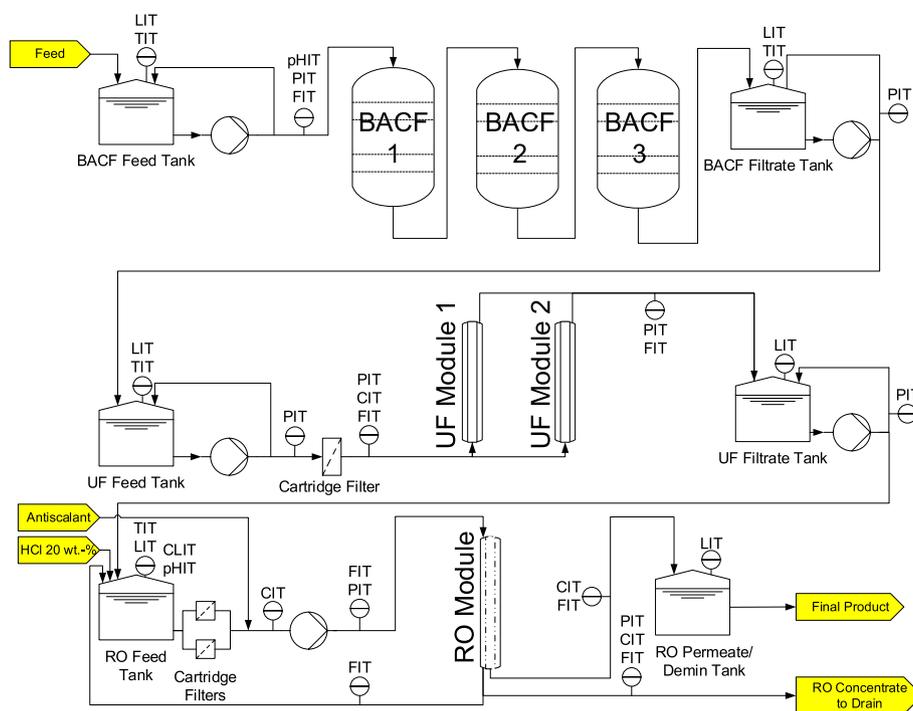


Fig. 2. Process Flow Diagram of trialed process configuration in IMPROVED containers (filtration mode) provided by Ghent University; Sensors (Indicator Transmitters (IT)) on temperature (TIT), level (LIT), pH (pHIT), pressure (PIT), flow (FIT), conductivity (CIT) and chlorine (CLIT) are indicated; BACF is Biologically Activated Carbon Filtration, UF is Ultrafiltration, RO is Reverse Osmosis.

3. Results and discussion

3.1. Produced water qualities

Selected main water quality parameters of produced water after each treatment step, also giving the initial raw blowdown/lake water quality, are shown in Table 2 (option 1) and Table 3 (option 2). These parameters were selected due to their relevance in representing operational treatment performance on nutrients (Turbidity, Organics, Phosphate and Nitrogen) and salt content (Na, Ca, Mg, Cl and Sulfate). As can be seen from Tables 2 and 3, high-quality water is achieved after RO treatment for both raw waters, enabling reuse and higher CoC, respectively.

Tables 2 and 3 only display water qualities of treatment scenarios, including UF as pretreatment. The water qualities of operations of both treatment trains without UF can be found in the Supplementary Material (SM).

3.2. Process stability

In the following, the three treatment technologies applied for blowdown (option 1) and enhanced make up treatment (option 2) are assessed regarding treatment stability and performance to evaluate their feasibility for application at the respective industrial site.

3.2.1. Cooling tower blowdown treatment (option 1)

3.2.1.1. Pretreatment: Biologically activated carbon filtration and ultrafiltration. Before initiating the blowdown trials, the BACF was employed for surface water pretreatment, exhibiting DO removal and nutrients (see Table 1: Operated Bed Volumes before starting trials). Thus, it is assumed that the activated carbon filter was biologically activated at the onset to feed blowdown. During the first 4 days of operation, a significant removal of nutrients (TOC 39 (± 9) % (n = 4); Total Inorganic Nitrogen (TIN) 16 (± 4) % (n = 3), Phosphate 9 (± 6) % (n = 3)) was achieved (also compare Figure SM 1). An increase in normalized water

permeability (NWP) of the BACF, coupled with a decrease in nutrient removal and dissolved oxygen (DO) uptake in the second week, is likely attributable to a decline in biological activity within the filter. This decline can be related to shock dosages of in-situ generated monochloramine (biocides dosage in recirculating cooling system). While higher permeability is preferable, leading to lower energy requirements and higher water recoveries, nutrient uptake and biological transformation/growth (leading to lower permeability) should not be ruled out completely. Thus, after 16 days, sodium bisulfite (SBS) was dosed in the feed tank of the BACF (0.1 g/L) to neutralize chlorine. Initially, permeability kept increasing for 2 days. The subsequent decrease in permeability can be attributed to an increased regrowth of biology ("protected" from chlorine through SBS dosing). Initial removal rates of nutrients as seen during start-up (first week of blowdown treatment operation) could not be (re)achieved within the 13 days of operating with SBS. Full-scale technology will require further balancing/optimization of biological growth control.

UF Normalized Water Permeability (NWP) shows significant daily fluctuations (directly related to temperature; see Figure SM 2 and Figure SM 6). Thus, the normalization approach requires more in-depth consideration not covered in this work. After 1 week of operation, the NWP of the system shows a steep decrease in permeability. However, after a CIP performed after 2.5 weeks, permeability is fully restored, indicating that the pretreated water-specific UF fouling is reversible and the system can be operated long-term.

TOC rejection decreases from > 10 % during the first 4 days of operation to 5 % on average. This observed behavior could be linked to alterations in the characteristics of TOC present in the BACF effluent. Specifically, during the initial days, a higher proportion of biopolymeric (larger molecular) TOC structures could have been retained in the ultrafiltration (UF) process.

To summarize, a reliable operation of the system and rejection of 23 % TOC (n = 20) (BACF) and 7 % (n = 16) (UF) on average could be achieved, highlighting the feasibility of the proposed technologies as pretreatment. A water recovery of 99.9 % (5 backwashes à 50 L for an

Table 1
Operating conditions and characteristics of applied blowdown (option 1) and make up (option 2) treatment technologies.

BACF	UF	RO
<ul style="list-style-type: none"> - 3 cylindrical columns of each 50 L volume operated in series - Biologically activated NORIT GAC 830 W (3 x ~ 43 L) - Volume Flow: 500 L/h - Filtration velocity: 15 m/h - Empty Bed Contact Time: ~5 min per column - Backwashing: as required (if pressure drop > 1 bar) - Operated Bed Volumes (BV) when starting treatment: ~ 4700 BV with (pretreated) surface water for option 1 ~ 3800 BV with (pretreated) surface water for option 2 - Average operating temperature: 18 °C for option 1 12 °C for option 2 	<ul style="list-style-type: none"> - 2 modules of 4'' inge dizzer® P Multibore® 0.9 membrane run in parallel (dead-end mode, filtration inside to outside, reused from previous trials) - Membrane Area: 2x 6 m² - Permeate Flux: ~35 L/(m²h) - Filtration Time: 30 min - Backwash Time: 15 s (not chemically enhanced) - Forward Flush Time: 30 s - Cartridge filter 50 µm - Cleaning in Place (CIP) procedure: 1 h acid circulation wash (0.1 M HCl), flushing with demineralized water, backwash for ~ 15 s, 1 h alkaline circulation wash (0.1 M NaOH), flushing with demineralized water, backwash for ~ 15 s - Average operating temperature: 18 °C for option 1 13 °C for option 2 	<ul style="list-style-type: none"> - 1 module DuPont FilmTec™ LCLE-4040: partial recirculation of concentrate - Membrane Area: 8.7 m² - Module Feed Flow: 1030 L/h - Permeate Flux: 20 L/(m²h) - Cartridge filter 50 µm - CIP procedure: Circulation in forward flush mode with acid (0.1 M HCl, 1 h), System flush with demineralized water for approx. 5 min for three times, Circulation in forward flush mode with base (0.1 M NaOH, 1 h), System flush with demineralized water for approx. 15 min - System recovery: 75 % for option 1 84 % for option 2 - Average operating temperature: 19 °C for option 1 13 °C for option 2 - Feed adjustments: Antiscalant (Genesys LF): 4 mg/L; 20 w.-% HCl for pH 6.1 (~ 0.14 g/L_{Feed}) for option 1 Antiscalant (Genesys LF): 1.5 mg/L; no pH adjustment for option 2

operation period of 28 days) was achieved for the BACF, while UF was operated with a water recovery of 96 %. Water recovery of UF could be increased to > 98 % through the reuse of UF backwash water (similarly by UF, see, e.g., drinking water treatment plant in Roetgen (Gemeinde Roetgen et al., 2017)) or further optimization of operating parameters (e.g., longer filtration cycles).

3.2.1.2. Desalination: Reverse osmosis. The RO operation was initiated with a new DuPont FilmTec™ LCLE-4040 membrane. As the produced concentrate is partially recirculated to the system's feed tank, the applied module represents both the front and end module, considering a full-scale system scale-up including several RO stages. Both scaling and fouling are expected to affect one module.

Similar to UF normalization, fluctuations of normalized operational RO KPIs due to temperature are still visible, which could not be removed by further tuning of normalization (see Fig. 3 and Figure SM 7).

During start-up, all KPIs settled around an average value within two days of operation, showing fluctuations attributed to high variability in temperature ($\Delta T > 15$ °C) with nearly stable, slightly increasing, respectively decreasing trend (Fig. 3). Normalized Pressure Drop (NPD), related to fouling phenomena/membrane integrity, increases by ~ 1 %/day, while the Mass Transfer Coefficient (MTC), indicating temperature normalized membrane permeability, shows a ~1 %/day decreasing trend. Salt Passage, normalized for temperature and permeate flow (NSP), remained stable at approx. 0.9 % after two days of operation. A CIP restored initial operational KPIs, leading to comparable behavior of KPIs till the end of week 3.

Except for the first day (70 % recovery), the RO system was operated

with a recovery of 75 % for the four-week trial period with and without UF. TOC in RO permeate was measured below 100 µg/L for more than 80 % of the analyzed samples (average TOC in Permeate: 69 µg/L; average TOC rejection: 99.4 %).

After 3 weeks of operation, the UF was removed from the treatment combination to see the effects on the RO. Within 2 days, MTC dropped significantly (approx. 13 %). No changes were visible on the cartridge filter compared to previous days. A CIP was performed after day 2 operating without UF, restoring initial conditions. However, a similar strong decline of MTC (approx. 7 %/day) could be observed after the CIP, which indicates no long-term feasibility of the treatment train without UF with chosen operational settings (i.e., 75 % recovery of RO system).

The produced water quality of permeate is shown in Table 2. Regarding TOC, permeate could be reused as boiler feed water (requirement of TOC < 0.2 mg/L). However, the remaining salts require further treatment, e.g., by ion exchange or additional RO treatment, if boiler feed water is the desired point of reuse (DIN, 2003).

Summarizing, the RO with UF as a pretreatment was operated stably for 3 weeks, demonstrating the reversibility of fouling by a CIP performed after one week of operation, making it a suitable technology to be applied. Without UF, RO MTC showed no stable behavior (approx. 7 % decrease per day); thus, pretreatment of blowdown by BACF and UF is recommended.

Table 2
Initial and treated water quality parameters of blowdown treatment (option 1).

Parameter	Raw Blowdown	BACF Filtrate	UF Filtrate	RO Permeate
pH [-]	7.7 (±0.1) (n = 16)	7.2 (±0.1) (n = 8)	7.4 (±0.2) (n = 8)	5.6 (±0.1) (n = 8)
Conductivity [µS/cm]	1934 (±43) (n = 16)	2080 (±57) (n = 15)	–	79 (±9) (n = 15)
Turbidity [NTU]	6.6 (±2.8) (n = 15)	2.9 (±0.2) (n = 18)	0.5 (±0.3) (n = 14)	0.2 (±0.06) (n = 15)
TOC [mg/L]	20.6 (±0.7) (n = 16)	15.8 (±2.3) (n = 18)	13.5 (±0.4) (n = 16)	0.07 (±0.06) (n = 18)
PO ₄ -P [mg/L]	1.6 (±0.1) (n = 8)	1.5 (±0.2) (n = 8)	1.4 (±0.3) (n = 8)	0.05 (±0.01) (n = 7)
TIN [mg/L]	16.0 (±0.5) (n = 8)	15.0 (±1.5) (n = 8)	13.7 (±2.2) (n = 8)	2.4 (±0.5) (n = 8)
Na [mg/L]	174.2 (±14.3) (n = 8)	179.2 (±20.8) (n = 8)	–	11.8 (±2.8) (n = 8)
Ca [mg/L]	173.4 (±11.1) (n = 8)	170.7 (±11) (n = 8)	–	0.2 (±0.08) (n = 8)
Mg [mg/L]	46.2 (±3.7) (n = 8)	46.7 (±4.4) (n = 8)	–	0.04 (±0.02) (n = 8)
Cl (dissolved) [mg/L]	282.4 (±5.6) (n = 8)	286 (±6) (n = 8)	–	10.3 (±1.4) (n = 8)
Sulfate [mg/L]	531 (±10.8) (n = 8)	534 (±12) (n = 8)	–	0.6 (±0.1) (n = 8)

Table 3
Initial and treated water quality parameters of enhanced make up treatment (option 2).

Parameter	Raw Make Up	BACF Filtrate	UF Filtrate	RO Permeate
pH [-]	7.47 (± 0.04) (online)	7.41 (± 0.10) (n = 3)	7.84 (± 0.45) (online)	6.34 (± 0.36) (n = 3)
Conductivity [$\mu\text{S}/\text{cm}$]	537.5 (± 2.95) (n = 6)	539.83 (± 1.83) (n = 6)	–	19.37 (± 12.76) (online)
Turbidity [NTU]	6.10 (± 2.14) (n = 5)	0.73 (± 0.14) (n = 5)	0.22 (± 0.10) (n = 5)	0.19 (± 0.03) (n = 5)
TOC [mg/L]	5.13 (± 0.14) (n = 8)	3.25 (± 0.17) (n = 7)	2.62 (± 0.21) (n = 7)	0.06 (± 0.08) (n = 6)
PO ₄ -P [mg/L]	0.07 (± 0.03) (n = 3)	0.058 (± 0.013) (n = 3)	0.1 (n = 1)	0.04 (± 0.01) (n = 3)
TIN [mg/L]	1.56 (± 0.56) (n = 3)	1.56 (± 0.56) (n = 3)	1.65 (n = 1)	0.41 (± 0.08) (n = 3)
Na [mg/L]	31.23 (± 6.44) (n = 3)	29.7 (± 4.63) (n = 3)	–	2.13 (± 0.45) (n = 3)
Ca [mg/L]	53.0 (± 3.34) (n = 3)	52.63 (± 3.09) (n = 3)	–	0.40 (± 0.35) (n = 3)
Mg [mg/L]	10.43 (± 0.88) (n = 3)	10.36 (± 0.92) (n = 3)	–	0.07 (± 0.06) (n = 3)
Cl (dissolved) [mg/L]	45.53 (± 2.40) (n = 3)	45.87 (± 2.42) (n = 3)	44 (n = 1)	1.84 (± 0.06) (n = 3)
Sulfate [mg/L]	100.07 (± 8.60) (n = 3)	99.4 (± 9.42) (n = 3)	95 (n = 1)	0.41 (± 0.35) (n = 3)

3.2.2. Enhanced cooling tower make up treatment (option 2)

3.2.2.1. Pretreatment: Biologically activated carbon filtration and ultra-filtration. Before make up trials were initiated, the BACF, meaning the new granular activated carbon NORIT GAC 830 W, was continuously fed with pretreated surface water (TOC = 3.3 ± 0.2 mg/L) (operating with the same operating conditions as shown in Table 1) for approx. 50 days for inoculation. TOC removal reached a plateau after 29 days with subsequent TOC rejections of 48 % (1.7 mg/L) for the remaining 32 days before make up trials. Thus, the activated carbon filter is assumed to show biological degradation, with adsorption sites mostly occupied. As shown in Figure SM 3, the growth of biology and the deposited suspended solids on the filter media steadily decreased their permeability. System failure after day 10 was due to external circumstances (power interruption), not due to the technologies applied. Backwashes to maintain a maximum pressure drop of 1 bar for the whole system were required approximately once per week.

After 14 days of technology operation producing make up, UF was added as an additional treatment step for the remaining 11 days of trial set-up. During the 11 days of operation, the trend of UF NWP remains stable, neither de- nor increasing (see Figures SM 4 and SM 9).

To summarize a reliable operation of the system and TOC rejections of 38 % (n = 20) (BACF) and 19 % (n = 7) (UF) on average could be achieved, highlighting the feasibility of the proposed technology as pretreatment. A 99.9 % (BACF) and 96 % (UF) water recovery was achieved.

3.2.2.2. Desalination: Reverse osmosis. Like UF normalization and blowdown results, fluctuations of normalized operational RO KPIs due to temperature are still visible (see Fig. 4 and Figure SM 8). For the make up trials, the same membrane type was used as for the blowdown trials. However, the membrane was not new but had previously been used in another set-up treating pretreated surface water for approx. 50 days. A

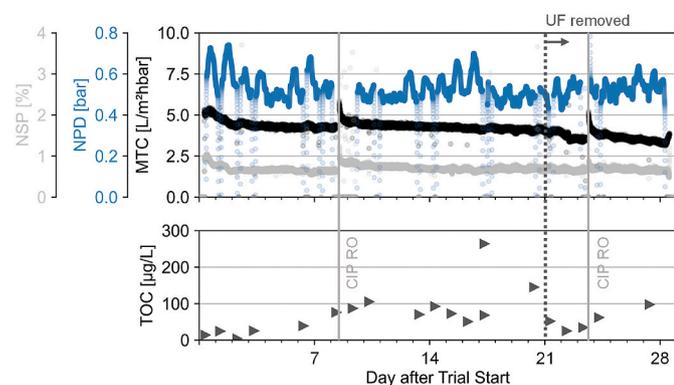


Fig. 3. Option 1 - Time series of RO operational KPIs (Normalized Salt Passage (NSP), Normalized Pressure Drop (NPD), Mass Transfer Coefficient (MTC); upper graph) and TOC in permeate (lower graph); CIP is Cleaning in Place.

CIP on the membrane was done before initiating the make up trials, restoring conditions comparable to the new membrane. System failure after day 10 was due to external circumstances (power interruption).

After start-up, operating without UF, NPD, and MTC continuously in-, respectively decreased (i.e., NPD ~ 5 %/day; MTC: ~ 4 %/day). This behavior illustrates the unstable operation of the BACF + RO system with the given operational settings in Table 1. NSP shows a small decreasing trend (i.e., ~ 2 %/day). On day 13, a CIP was performed, restoring initial conditions (compare Fig. 4). After operating for one day after the CIP, on day 14, the UF was added to the treatment train. Thus, with the additional pretreatment of the UF, the de-resp. increasing trend of the RO MTC and NPD could be adapted to 0.5 %/day and 0.3 %/day, respectively. Similarly, NSP shows a lower decreasing trend than operation without UF: ~ 1 %/day. Partly missing data on NPD in Fig. 4 right after the addition (day 14–17) of the UF is attributed to operational problems with the concentrate valve – which were solved after day 17.

The RO system was operated with a recovery of 84 % (maximum applicable recovery of the applied system). In optimized systems, this recovery rate could be increased. The module itself operated at a recovery of 17 % for the 25 days with and without UF. TOC in permeate was measured below 100 $\mu\text{g}/\text{L}$ for 79 % of the samples with and without UF (average rejection with and without UF: 98 %).

In summary, the RO was operated stably with the pretreatment of BACF and UF for 11 days with a set recovery of 84 %. Without UF, no stable operation was achieved. Thus, UF as a pretreatment before RO is recommended for make up treatment.

3.3. Comparison of options

3.3.1. Water saving

Material/water flow analysis modeling was performed considering scenarios of differing initial (2, 4, and 8) and resulting CoC in the operating CT, as well as water recovery rates (55–85 % (R_{CTBD}), and

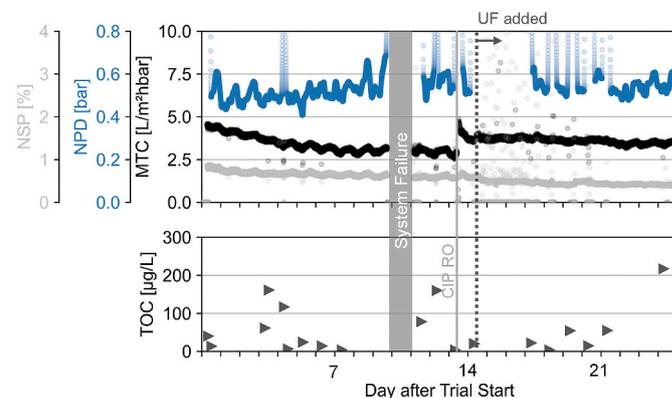


Fig. 4. Option 2 - Time series of RO operational KPIs (Normalized Salt Passage (NSP), Normalized Pressure Drop (NPD), Mass Transfer Coefficient (MTC); upper graph) and TOC in permeate (lower graph); CIP is Cleaning in Place.

75–95 % (R_{CTMU}) resp.) of analyzed treatment options. Water recovery (i.e., R_{CTMU} or R_{CTBD}) is the percentage of purified water to water fed into the complete treatment train, including all treatment steps. Flows and relevant (varied) parameters for make up/blowdown are illustrated in Fig. 1. Bypassing parts of raw water in option 2 was not considered as this does not imply a minimization case (it reduces the water footprint but does not minimize). Salt Rejection ($R_{CTBD, Salt}$ and $R_{CTMU, Salt}$) is based on pilot trials performed and depends on the most relevant ion rejections (e.g., Na^+ rejection for blowdown treatment was 93.8 %, while Mg^{2+} rejection was 99.9 %, see SM). The resulting CoC was calculated based on the maximum TDS accumulated in blowdown (i.e., 1.3 g_{TDS}/L for the considered industrial application). The make up treatment in option 1 implies hardness and organics removal (e.g., coagulation/flocculation) typically done for surface/groundwater-fed cooling towers. The water recovery rate of option 1, initial make up treatment (coagulation/flocculation, incl. sand filtration) was measured to be 99.9 %. Further details on calculations are given in the SM.

Using built model calculations, Fig. 5 illustrates results on potential water savings/losses: option 1 always shows potential for water savings (treated water is to be fed back to the CT as make up), while water-saving opportunities of option 2 are highly dependent on (i) the initial CoC that the cooling tower was operating on (baseline scenario), (ii) achieved CoC after CTMU treatment (Resulting CoC) and (iii) achievable water recovery (R_{CTMU}) of the applied make up water treatment system. With option 2, significant water losses may also occur (see initial CoC of 8 with R_{CTMU} of < 90 %). The resulting CoC for option 2 asymptotically approaches a limit value, thus highlighting that increasing CoC to > 100 only results in minor relative water savings. Fig. 5 also highlights the dependence of potential water savings on the baseline scenario (initial CoC).

Considering limitations in the quality of recirculating cooling water (CTBD) as a fixed parameter in the model calculations (here: TDS = 1.3 g/L), the CoC is based on the make up quality entering the system (compare equation (2)). If the initial CoC is high (assuming a fixed CTBD quality requirement), the make up quality is higher than that of a system operating at a lower CoC. Thus, according to this estimate, it can be said that a high initial CoC (≥ 4) corresponds with high make up quality, while a low initial CoC (< 4) indicates lower make up quality. Thus, the better the make up quality used for the baseline scenario, the lower the potential water savings. In particular, for option 2, the recovery rate is applied to the total water required (evaporated water, discharged blowdown, and other losses). At comparably low recovery rates of option 2, even water losses will occur (compared to the initial scenario). However, due to better raw water quality fed to the treatment system in

option 2, its recovery rate (R_{CTMU}) is generally expected to be higher than the recovery rate of option 1 (R_{CTBD}).

Further water chemistry changes due to the mixing of RO permeate and pretreated make up water were considered out of the scope of this work. Additionally, as the water quality of the treated blowdown typically exceeds the required make up quality (RO permeate), other processes within the industrial site requiring higher water quality (e.g., boilers) could and should be considered first for the reuse of treated water. The cost of higher-quality water is higher; thus, using treated desalinated blowdown can save costs for further water purification elsewhere while saving similar amounts of water. Primarily if potential end users are closely located, such as at large industrial sites, treated waste water reuse as demineralized water appears most economically attractive (Katsoyiannis et al., 2017; Kehrein et al., 2021).

3.3.2. Cost analysis

While maximizing water savings is necessary to avoid supply risks, affected industries are further required to choose the most economical option. Thus, assuming a required treatment train of BAC (20 min EBCT) + UF + RO for option 1 (Water Recovery of Treatment Train: 70 %) and BAC (20 min EBCT) + UF + RO for option 2 (Water Recovery of Treatment Train: 90 %), different scenarios were estimated for a recirculating cooling tower with an evaporation capacity of 1000 m^3/h (cooling capacity of approx. 500 MW_{th}). Estimates of advanced treatments for water footprint minimization are based on Class 4 estimate cost curves provided by Plumlee et al. (2014). The buying power of September 2011 dollars was adapted to 2022 dollars (factor 1.29) according to U.S. Bureau of Labor Statistics (2024) and subsequently converted to Euro by the purchasing power parities (2022 factor of 0.694 $\text{€}/\text{\$}$ (OECD (2024) data for Germany). Capital cost estimates include installation, yard piping, landscaping, legal and administrative costs, and contingency (30 % of equipment costs). Operations and maintenance costs include energy, replacement parts, chemical usage, and labor (if they represent a significant portion). More detailed information on the cost curve's development can be found in Plumlee et al. (2014). Estimated capital and operational expenditures using cost curves were used to calculate the Levelized Cost of Water (LCOW), based on supplied thermal cooling capacity C_p [MW_{th}], provided for 1 h [MWh_{th}], determined as:

$$LCOW \left[\frac{\text{€}}{MWh_{th}} \right] = \frac{\left(OPEX \left[\frac{\text{€}}{a} \right] + CAPEX \left[\text{€} \right] \cdot r \left[\frac{1}{a} \right] \right) \cdot \frac{1}{365 \cdot 24} \left[\frac{a}{h} \right]}{C_p \left[MW_{th} \right]} \quad (3)$$

with r (capital recovery factor), calculated as

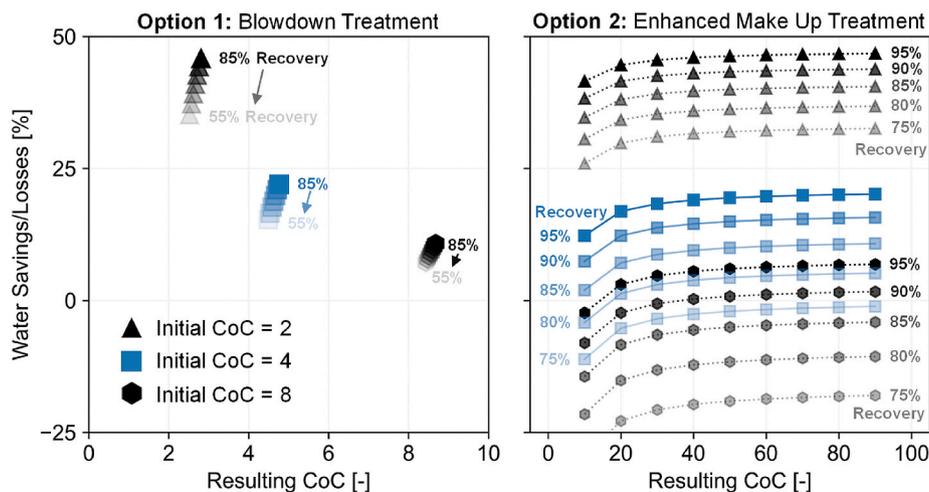


Fig. 5. Comparing water savings/losses [%] by application of option 1 (left graph) vs. option 2 (right graph) based on initial CoC (baseline scenario) and Recovery Rates of Water Treatment System applied.

Table 4

Cost comparison and applied cost factors for option 1 and 2 (Example System Size: Initial CoC of 5.3 and evaporation of 1000 m³/h (cooling capacity of approx. 500 MW_{th}); all costs are based on year 2022.

		Option 1: Blowdown Treatment	Option 2: Enhanced Make Up Treatment
Water Management			
Initial required raw water abstraction (baseline scenario)	[m ³ /h]	1230	
Required raw water abstraction after water minimization	[m ³ /h]	1070	1120
Water treated by advanced treatment	[m ³ /h]	205	1120
Water recoveries of advanced treatment	[%]	70	90
Resulting CoC	[-]	5.9	100
Plant availability	[%]	100	
Water Withdrawal Costs (based on Water Abstraction Charge Law Nordrhein-Westfalen, Germany from 2004)			
Abstraction Fee	[€/m ³]	0.035	
<u>Cost of water withdrawal</u>	<u>[€/h]</u>	<u>37.3</u>	<u>39.3</u>
Make Up Conditioning Costs (based on current operational practices at industrial site and research performed by Pinel (2021))			
Biodispersant costs	[€/kg]	2.5	–
Concentration biodispersant in recirculating water	[mg/L]	30	–
Corrosion Inhibitor I costs	[€/kg]	2	5
Concentration Corrosion Inhibitor I in recirculating water	[mg/L]	20	1000
Corrosion Inhibitor II costs	[€/kg]	5	–
Concentration Corrosion Inhibitor II in recirculating water	[mg/L]	10	–
Biocide costs	[€/dosage]	14000	–
Dosage frequency	[-/year]	183	–
Sodium hydroxide costs	[€/kg]	–	1
Sodium hydroxide dosage	[mg/L]	–	280
Sodium bicarbonate costs	[€/kg]	–	0.3
Sodium bicarbonate dosage	[g/L]	–	2.8
<u>Costs of make up conditioning</u>	<u>[€/h]</u>	<u>326.3</u>	<u>61.7</u>
Advanced Treatment Costs (based on Class 4 cost estimates provided by Plumlee et al. (2014))			
Sum Capital Cost (BACF, UF, RO)	[Mio. €]	14.8	51.9
Sum Operational & Maintenance Cost (BACF, UF, RO)	[Mio. €/a]	0.7	3.6
<u>Costs of Advanced Treatment</u>	<u>[€/h]</u>	<u>252</u>	<u>1014.4</u>
<u>Costs of Advanced Treatment (-30 % contingency)</u>	<u>[€/h]</u>	<u>176.4</u>	<u>710.1</u>
<u>Costs of Advanced Treatment (+50 % contingency)</u>	<u>[€/h]</u>	<u>378</u>	<u>1521.6</u>
Initial Make Up Treatment Costs (based on current operational practices at industrial site)			
Lime costs	[€/kg]	0.2	
Lime dosage	[kg/m ³]	0.03	0
FeCl ₃ costs	[€/kg]	0.2	
FeCl ₃ dosage	[kg/m ³]	0.03	0
Flocculant costs	[€/kg]	2	
Flocculant dosage	[g/m ³]	0.2	0
Energy costs	[€/kWh]	0.2	
Energy demand	[kWh/m ³]	0.02	0
Labor	[h/d]	4	0
Labor costs	[€/h]	60	
<u>Costs of Initial Make Up Treatment</u>	<u>[€/h]</u>	<u>27.5</u>	<u>0</u>
Total LCOW	[€/MW_{th}]	1.3	2.2
Total LCOW (-30 % contingency)	[€/MW_{th}]	1.1	1.6
Total LCOW (+50 % contingency)	[€/MW_{th}]	1.5	3.2

$$r = \frac{(1+z)^n \cdot z}{(1+z)^n - 1} \quad (4)$$

where z is the discount rate, assumed as 8 %, and n is the useful life of the treatment system in years [a], considered 20 a for the following estimates.

Cost estimates are exemplary and detailed for a CT with an approximate cooling capacity of 500 MW_{th}. It currently operates with a CoC of 5.3 in [Table 4](#), showcasing the economic superiority of option 1. CT Make Up Conditioning Costs were taken from consultations with field experts and research published by [Pinel \(2021\)](#). Initial make up treatment costs are based on current operational practices at the selected industrial site case study.

When applying estimated costs to different scenarios of initial CoC, [Fig. 6](#) highlights that the enhanced make up treatment (option 2) is estimated to be significantly higher in leveled, summed-up costs in cases of initial CoC > ~ 3 (higher water input quality). Higher costs are mainly due to the large amounts of water to be treated (no dependency on initial CoC) by the enhanced make up treatment. [Fig. 6](#) further shows that advanced treatment options (particularly RO desalination) are the main contributors to costs per cooling capacity. In a system running with an initial CoC of 2, option 2 may become the more economical option,

especially since make up conditioning (chemicals added to make up) can potentially be further reduced for option 2 (compare new conditioning strategies proposed by [Pinel \(2021\)](#)). However, evaporative (recirculating) cooling systems are open to the atmosphere, leading to input of pollen, dust, or similar contaminations, potentially limiting achievable CoC even with the highest make up qualities.

The management and related costs to RO concentrate management are highly site-specific and are thus not considered in this work. At neglectable additional costs, RO concentrate may be blended with other wastewater treatment streams to mitigate the impacts of the high TDS load while still complying with existing discharge permits.

3.4. Limitations of the study and future research questions

Visible fluctuations despite temperature and flow normalization of the KPIs used to analyze technology performance and long-term stability indicate that the normalization approach needs to be optimized. Further, operational settings of technologies could be optimized for better results during a more extended operational period (> 6 months).

The chemical demand for CT conditioning is diverse in practice. Biocides, scale inhibitors, dispersants, and corrosion inhibitors are added to prevent process failures. Water chemistry and operational

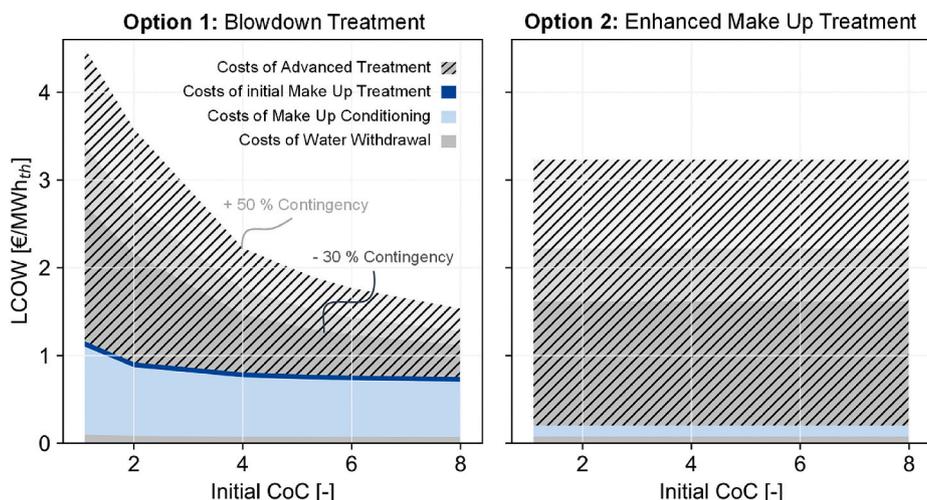


Fig. 6. Cost Estimates (Levelized Cost of Water (LCOW)) of summed up water engineering costs comparing options 1 and 2 for a recirculating cooling system evaporating 1000 m³/h, dependent on initial Cycles of Concentration (CoC) (baseline scenario); all costs are based on year 2022.

changes in the CT will affect the dosing requirements of these chemicals. However, this aspect is only marginally addressed in this work: accessible data are poor, and related water chemistry is extensive. Environmental effects through disinfection by-products and persistent, accumulating chemicals should be assessed in detail. Optimization of CT conditioning, operating with less and more environmentally friendly chemicals, should be accelerated.

Further water minimization can only be achieved with brine management/treatment (i.e., RO concentrate). Here, further studies are required to find optimal ways to deal with, i.e., produced RO concentrates (Joo and Tansel, 2015). In some cases, discharges of industrial plants (i.e. large flows of blowdown) make up significant parts of receiving water bodies. The ecologically necessary flow of these water bodies must be regarded and preserved.

Lastly, not only water use of industrial plants should be considered, but particularly water consumption (i.e., evaporation/drift), which can only be reduced by improved heat integration, application of heat pumps, and expansion of renewable energies (Chew et al., 2013; McKinsey and Company, 2021; Wallerand et al., 2018).

4. Conclusions

Based on experimental results, calculations, and theoretical considerations, CT Blowdown Treatment (option 1) instead of Enhanced Make Up Treatment (option 2) is the most feasible option for the case study to minimize the cooling tower water footprint. The reasons for this finding were the following: (1) higher water savings are expected for option 1 (Initial CoC of existing CT: 5.3, compare Fig. 5), (2) required estimated operational/capital costs are significantly lower for option 1 due to lower amounts of water to be treated, (3) high-quality RO permeate produced by blowdown treatment could be reused at the industrial site as demineralized process water.

Generally, both options presented for water use minimization in recirculating cooling towers may be applicable in practical settings, considering local restrictions and regulations (i.e., discharge requirements, initial water quality, and operational prerequisites of CT). However, treating all make up water by an elaborate desalination step for water minimization, in comparison to treating only parts of the remaining water after evaporation (the blowdown), is estimated to become the preferable option in the following scenarios: (a) low initial CoC of CT (<3) related to poor make up quality, (b) elevated costs related to CT water conditioning (chemicals added for prevention of biofouling/corrosion/scaling in the cooling tower). With a high initial CoC of running a CT system (>4), the relative reduction (evaporation) of

water to be purified increases. Thus, treatment of blowdown is the preferred approach for an industrial site operating its recirculating CT with a CoC of 5.3, producing blowdown with 2 mS/cm conductivity and 21 mg/L TOC content.

The feasibility of the blowdown treatment train consisting of BACF, UF, and RO was tested and validated: BACF will have to be optimized regarding biological growth vs. increased pressure drop but showed an average TOC removal of 23 %. Biology protection in BACF from biocide shock dosages in the cooling system with SBS will not be necessary in full-scale, as the discharge of blowdown and, thus, feed of BACF is usually interrupted during biocide application. UF was shown to be a necessary pretreatment in front of the RO due to a clear decrease in membrane permeability of the RO without UF. Furthermore, despite approximately 85 % permeability decline of UF during operation, initial permeability could be restored by a CIP, highlighting the reversibility of fouling on applied UF membranes. In full-scale, the CIP would need to be performed as soon as possible to maintain energy efficiency. RO was operated successfully with UF pretreatment with a system recovery of 75 %. RO Permeate qualities of 80 µS/cm with a TOC usually (> 80 %) < 100 µg/L were produced.

Extending such water minimization strategies even beyond the cooling system to the entire industrial site level offers significant potential for water and cost reductions. Most industrial installations requiring cooling towers also need locally produced demineralized water. Implementing make up and blowdown treatment units in synergy with existing or planned demineralized water production processes can leverage common steps, providing both economic and environmental benefits.

CRedit authorship contribution statement

Sarah I. Müller: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gergana Chapanova:** Resources, Project administration, Conceptualization. **Thomas Diekow:** Writing – review & editing, Resources, Conceptualization. **Christian Kaiser:** Resources, Conceptualization. **Lies Hamelink:** Resources. **Ivaylo P. Hitsov:** Writing – review & editing, Supervision, Resources. **Lisa Wyseure:** Writing – review & editing, Supervision. **David H. Moed:** Supervision, Conceptualization. **Laurence Palmowski:** Writing – review & editing, Supervision, Project administration. **Thomas Wintgens:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Dataset is shared in the Mendeley Data repository, see References section in Manuscript

Acknowledgements

This work was supported by the European funded project “Advancing Sustainability of Process Industries through Digital and Circular Water Use Innovations” (AquaSPICE) under grant agreement No 958396 within the European Union’s Horizon 2020 research and innovation programme.

The authors would like to express their thanks to all the project partners. Special thanks go to the Analytical Laboratory of Dow, the operating staff at Dow Olefinverbund GmbH (Alex, Tommy and Co.), as well as Eduard de las Heras Garcia.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2024.121949>.

References

- Altman, S.J., Jensen, R.P., Cappelle, M.A., Sanchez, A.L., Everett, R.L., Anderson, H.L., McGrath, L.K., 2012. Membrane treatment of side-stream cooling tower water for reduction of water usage. *Desalination* 285, 177–183. <https://doi.org/10.1016/j.desal.2011.09.052>.
- Aquaprox, 2009. *Treatment of Cooling Water*. Springer Berlin Heidelberg, Berlin, Heidelberg. <https://doi.org/10.1007/978-3-642-01985-2>.
- AWWA, 1981. An assessment of microbial activity on GAC. *J. AWWA (Am. Water Works Assoc.)* 73, 447–454. <https://doi.org/10.1002/j.1551-8833.1981.tb04756.x>.
- Cherchi, C., Kesaano, M., Badruzzaman, M., Schwab, K., Jacangelo, J.G., 2019. Municipal reclaimed water for multi-purpose applications in the power sector: a review. *J. Environ. Manag.* 236, 561–570. <https://doi.org/10.1016/j.jenvman.2018.10.102>.
- Chew, K.H., Klemeš, J.J., Wan Alwi, S.R., Abdul Manan, Z., 2013. Industrial implementation issues of total site heat integration. *Appl. Therm. Eng.* 61, 17–25. <https://doi.org/10.1016/j.applthermaleng.2013.03.014>.
- De Meyer, E., 2020. *The Behavior of Organic Matter in Industrial Demineralization and Steam-Water Cycles*. Ghent University, Faculty of Bioscience Engineering, Ghent, Belgium. Dissertation. <http://hdl.handle.net/1854/LU-8649441>.
- Dhole, V.R., Linnhoff, B., 1993. Total site targets for fuel, co-generation, emissions, and cooling. *Comput. Chem. Eng.* 17, S101–S109. [https://doi.org/10.1016/0098-1354\(93\)80214-8](https://doi.org/10.1016/0098-1354(93)80214-8).
- DIN, 2003. *Wasserrohrkessel und Anlagenkomponenten: DIN 12952 - Teil 12: Anforderungen an die Speisewasser- und Kesselwasserqualität*. Beuth Verlag GmbH, Berlin.
- Dow, 2023. *Dow in mitteleuropa*. <https://de.dow.com/de-de/standorte/mitteleuropa.html>. (Accessed 2 July 2024).
- ElHadidy, A., 2016. *Performance of Biological Filters for Drinking Water Treatment and Their Use for High Pressure Membrane Biofouling Control*. University of Waterloo, Waterloo, Canada. Dissertation. <http://hdl.handle.net/10012/10146>.
- EPA, 2017. *Water efficiency management guide: mechanical systems*. EPA 832-F-17-016c. <https://www.epa.gov/sites/default/files/2017-12/documents/ws-commercial-buildings-waterscore-mechanical-systems-guide.pdf>. (Accessed 2 July 2024).
- European Commission, 2016. *IPPC reference document on the application of best available techniques to industrial cooling systems*. https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/cvs_bref_1201.pdf. (Accessed 2 July 2024).
- Eurostat, 2023. *Annual freshwater abstraction by source and sector*. https://ec.europa.eu/eurostat/databrowser/view/ENV_WAT_ABS_custom_5762164/default/table?lang=en. (Accessed 2 July 2024) <http://www.elsevier.com/xml/linking-roles/research-data>.
- FAO, 2022. *The state of the world’s land and water resources for food and agriculture 2021 - systems at breaking point: main report*. Food and Agriculture Organization of the United Nations 362. <https://doi.org/10.4060/cb9910en>. Rome.
- Gartiser, S., Urich, E., 2002. *Environmentally compatible cooling water treatment chemicals*. UBA, Germany, Berlin. Research Report 200 (24), 233. https://www.hydrotox.de/fileadmin/user_upload/pdfs/forschungen/projekte/UBA_cooling_water_text_05-11-02.pdf. (Accessed 2 July 2024).
- Gemeinde, Roetgen, Enwor, Perlbachwasser, 2017. *Wasserversorgungskonzept gemäß § 38 Absatz 3 LWG für die Gemeinde Roetgen*. <https://buergerportal.roetgen.de/documents/21014/104409/01.1+++Anlage+1+TOP+2.pdf/148fd00a-0b80-4927-8467-1d033dc8e4c2?version=1.2>. (Accessed 2 July 2024).
- Grote, M., Boudenne, J.-L., Croué, J.-P., Escher, B.I., Gunten, U., von Hahn, J., Höfer, T., Jenner, H., Jiang, J., Karanfil, T., Khalanski, M., Kim, D., Linders, J., Manasfi, T., Polman, H., Quack, B., Tegtmeier, S., Werschkun, B., Zhang, X., Ziegler, G., 2022. Inputs of disinfection by-products to the marine environment from various industrial activities: comparison to natural production. *Water Res.* 217, 118383 <https://doi.org/10.1016/j.watres.2022.118383>.
- Guyot, J.P., 2014. *An Introduction to Cooling Tower Water Treatment*. Continuing Education and Development, Inc. (Accessed 2 July 2024).
- Halle, C., Huck, P.M., Peldszus, S., Haberkamp, J., Jekel, M., 2009. Assessing the performance of biological filtration as pretreatment to low pressure membranes for drinking water. *Environ. Sci. Technol.* 43, 3878–3884. <https://doi.org/10.1021/es803615g>.
- Hansen, E., Rodrigues, M.A.S., Aquim, P.M., de, 2016. Wastewater reuse in a cascade based system of a petrochemical industry for the replacement of losses in cooling towers. *J. Environ. Manag.* 181, 157–162. <https://doi.org/10.1016/j.jenvman.2016.06.014>.
- Hill, G.B., 1990. *Cooling Towers: Principles and Practice*, third ed. Butterworth-Heinemann, London, p. 191. ISBN: 0-7506-1005-0.
- Interreg, 2016. *Improved - industrial water use*. <https://www.improvedwater.eu/>. (Accessed 2 July 2024).
- Jain, R., Nigam, H., Mathur, M., Malik, A., Arora, U.K., 2021. Towards green thermal power plants with blowdown water reuse and simultaneous biogenic nanostructures recovery from waste. *Resour. Conserv. Recycl.* 168, 105283 <https://doi.org/10.1016/j.resconrec.2020.105283>.
- Joo, S.H., Tansel, B., 2015. Novel technologies for reverse osmosis concentrate treatment: a review. *J. Environ. Manag.* 150, 322–335. <https://doi.org/10.1016/j.jenvman.2014.10.027>.
- Katsiyiannis, I.A., Gkotsis, P., Castellana, M., Cartechini, F., Zouboulis, A.I., 2017. Production of demineralized water for use in thermal power stations by advanced treatment of secondary wastewater effluent. *J. Environ. Manag.* 190, 132–139. <https://doi.org/10.1016/j.jenvman.2016.12.040>.
- Kehrein, P., Jafari, M., Slagt, M., Cornelissen, E., Osseweijer, P., Posada, J., van Loosdrecht, M., 2021. A techno-economic analysis of membrane-based advanced treatment processes for the reuse of municipal wastewater. *Journal of Water Reuse and Desalination* 11, 705–725. <https://doi.org/10.2166/wrd.2021.016>.
- Koeman-Stein, N.E., Creusen, R., Zijlstra, M., Groot, C.K., van den Broek, W., 2016. Membrane distillation of industrial cooling tower blowdown water. *Water Resour. Ind.* 14, 11–17. <https://doi.org/10.1016/j.wri.2016.03.002>.
- Laforce, E., Stals, I., Cornelissen, E.R., Vermeir, P., Clercq, J., de, 2022. Insights into natural organic matter and its removal by ion exchange resins. *Faculty of Engineering and Architecture Research Symposium 2022 (FEARS 2022)*, Abstracts. <https://doi.org/10.5281/zenodo.7406097>.
- Li, A.Y.L., DiGiano, F.A., 1983. Availability of sorbed substrate for microbial degradation on granular activated carbon. *Journal (Water Pollution Control Federation)* 392–399. <https://www.jstor.org/stable/25041879>.
- Liu, Y.-S., Ying, G.-G., Shareef, A., Kookana, R.S., 2011. Biodegradation of three selected benzotriazoles under aerobic and anaerobic conditions. *Water Res.* 45, 5005–5014. <https://doi.org/10.1016/j.watres.2011.07.001>.
- Liu, S., Zhao, L., Wang, Z., Han, M., 2022. Exploring energy-saving potentials in seawater desalination engineering from the energy-water nexus perspective. *J. Environ. Manag.* 312, 114854 <https://doi.org/10.1016/j.jenvman.2022.114854>.
- McKinsey & Company, 2021. *Managing Water and Climate Risk with Renewable Energy*. McKinsey & Company. <https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/managing-water-and-climate-risk-with-renewable-energy>. (Accessed 2 July 2024).
- Nthunya, L.N., Bopape, M.F., Mahlangu, O.T., Mamba, B.B., van der Bruggen, B., Quist-Jensen, C.A., Richards, H., 2022. Fouling, performance and cost analysis of membrane-based water desalination technologies: a critical review. *J. Environ. Manag.* 301, 113922 <https://doi.org/10.1016/j.jenvman.2021.113922>.
- OECD, 2024. *Purchasing power parities (PPP) (indicator)*. <https://doi.org/10.1787/1290ee5a-en>. (Accessed 2 July 2024).
- Patel, S.K., Biesheuvel, P.M., Elimelech, M., 2021. Energy consumption of brackish water desalination: identifying the sweet spots for Electrodialysis and reverse osmosis. *ACS EST Eng.* 1, 851–864. <https://doi.org/10.1021/acsesteng.0c00192>.
- Pinel, I.S.M., 2021. *Biofouling in Open Recirculating Cooling Systems: Characterization and Control of Biofilms and Legionella pneumophila*. Delft University of Technology. TU Delft OPEN Publishing. <https://doi.org/10.4233/uuid:cef506da-3ec7-40b8-9a2c-30cbfbc9f5c>. Dissertation (TU Delft).
- Plumlee, M.H., Stanford, B.D., Debroux, J.-F., Hopkins, D.C., Snyder, S.A., 2014. Costs of advanced treatment in water reclamation. *Ozone: Sci. Eng.* 36, 485–495. <https://doi.org/10.1080/01919512.2014.921565>.
- Taylor, M., Elliott, H.A., Navitsky, L.O., 2018. Relationship between total dissolved solids and electrical conductivity in Marcellus hydraulic fracturing fluids. *Water Sci. Technol. : a journal of the International Association on Water Pollution Research* 77, 1998–2004. <https://doi.org/10.2166/wst.2018.092>.
- Toreti, A., Bavera, D., Acosta Navarro, J., Cammalleri, C., Jager, A., de, Di Ciollo, C., Hrast Essenfelder, A., Maetens, W., Magni, D., Masante, D., Mazzeschi, M., Niemeyer, S., Spinoni, J., 2022. *Drought in Europe August 2022* EUR 31192 EN. Joint Research Centre. <https://publications.jrc.ec.europa.eu/repository/handle/JRC130493>. (Accessed 10 April 2024).
- UNEP, 2017. *Options for Decoupling Economic Growth from Water Use and Water Pollution: A Report of the Water Working Group of the International Resource Panel*.

- United Nations Environment Programme, Paris, France, p. 73. ISBN: 978-92-807-3534-5.
- UNESCO, 2023. The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water. UNESCO, Paris. ISBN: 978-92-3-100576-3.
- Urfer, D., Huck, P.M., Booth, S.D., Coffey, B.M., 1997. Biological filtration for BOM and particle removal: a critical review. *J. AWWA (Am. Water Works Assoc.)* 89, 83–98. <https://doi.org/10.1002/j.1551-8833.1997.tb08342.x>.
- U.S. Bureau of Labor Statistics, 2024. CPI Inflation Calculator. <https://data.bls.gov/cgi-bin/cpicalc.pl?cost1=1.00&year1=201109&year2=202303>. (Accessed 2 July 2024).
- Wagner, T.V., Wilde, V., de, Willemsen, B., Mutaqin, M., Putri, G., Opdam, J., Parsons, J. R., Rijnaarts, H.H.M., Voogt, P., de, Langenhoff, A.A.M., 2020. Pilot-scale hybrid constructed wetlands for the treatment of cooling tower water prior to its desalination and reuse. *J. Environ. Manag.* 271, 110972 <https://doi.org/10.1016/j.jenvman.2020.110972>.
- Wagner, T., Saha, P., Bruning, H., Rijnaarts, H., 2022. Lowering the fresh water footprint of cooling towers: a treatment-train for the reuse of discharged water consisting of constructed wetlands, nanofiltration, electrochemical oxidation and reverse osmosis. *J. Clean. Prod.* 364, 132667 <https://doi.org/10.1016/j.jclepro.2022.132667>.
- Walker, M.E., Safari, I., Theregowda, R.B., Hsieh, M.-K., Abbasian, J., Arastoopour, H., Dzombak, D.A., Miller, D.C., 2012. Economic impact of condenser fouling in existing thermoelectric power plants. *Energy* 44, 429–437. <https://doi.org/10.1016/j.energy.2012.06.010>.
- Wallerand, A.S., Kermani, M., Kantor, I., Maréchal, F., 2018. Optimal heat pump integration in industrial processes. *Appl. Energy* 219, 68–92. <https://doi.org/10.1016/j.apenergy.2018.02.114>.
- Wang, B., Klemes, J.J., Varbanov, P.S., Shahzad, K., Kabli, M.R., 2021. Total Site Heat Integration benefiting from geothermal energy for heating and cooling implementations. *J. Environ. Manag.* 290, 112596 <https://doi.org/10.1016/j.jenvman.2021.112596>.
- Wunsch, A., Liesch, T., Broda, S., 2022. Deep learning shows declining groundwater levels in Germany until 2100 due to climate change. *Nat. Commun.* 13, 1221. <https://doi.org/10.1038/s41467-022-28770-2>.