



Heat pump evaporation: An alternative of membrane filtration system aiming pure water production

Reem Shaheen, Krisztián Kovács, Edit Cséfalvay^{*}

Department of Energy Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Műegyetem rpk.3, Budapest, H-1111, Hungary

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ABSTRACT

The daily electrical power generation and consumption in Hungary were analyzed, and a 2-h-long interval was specified for the 5000 MW excess power generation, and 1,500,000 MJ energy was identified as an excess. Two pure-water-producing systems (membrane-based system and heat pump evaporator) were compared to utilize this excess electrical energy at industrial scale. Heat pump evaporation was tested as an alternative method for pure water production because its role in pure water production hasn't been discussed. Suspended-solid-free feed water was used for both systems. Lab-scale experiments proved that in the case of freshwater, the four-step membrane filtration technology can be replaced by a one-step heat pump evaporation, resulting in almost the same quality of pure water characterized by the conductivity; 2 and 4 $\mu\text{S}/\text{cm}$ for membrane filtration and heat-pump evaporation, respectively. When using seawater at a lab-scale, the proposed membrane technology resulted in desalted water having a conductivity of 425 $\mu\text{S}/\text{cm}$; meanwhile, by heat pump evaporation, pure water could be attained, having a conductivity of 19 $\mu\text{S}/\text{cm}$. Considering the specific electric energy consumption at laboratory scale, the one-step heat pump evaporator surely exhibits an energy-saving method for pure water production; 6.12 MJ/L and 2.31 MJ/L were measured for membrane system and heat pump evaporator, respectively. Considering an industrial-scale make-up water demand, up-scaling calculations, including hydraulic calculations and pump selection producing the same amount of pure water, resulted in a reverse trend regarding specific electric energy consumption; 25.35 MJ/m³ and 14,850 MJ/m³ estimated for membrane system and heat pump evaporator, respectively. Both systems were analyzed in terms of environmental impacts. According to wastewater quality and their disposability, the wastewater of freshwater treatment can be drained into the sewage system, but in case of seawater, crystallization of concentrated NaCl solutions is possible. Based on our analysis, the theoretically producible water quantity is more than physically attainable by the treatment technologies, thus more options shall be considered for the utilization of excess energy generation.

1. Introduction

EU energy strategy recommends increasing the green and renewable energy share in the overall energy production up to 32% by 2030 ("Renewable energy targets"), and consequently, has been increasing all over the world ("Renewable energy highlights Electricity generation, 2024). Attaining this aim, Hungary has raised the inbuilt capacity of solar panels (3500 MW at the industrial-scale and 2200 MW household scale in 2024), exhibiting exponential growth, which meets the National Energy Strategy recommendations ("National Energy Strategy"). By analyzing the daily variation of the electric energy consumption and production data, in general, consumption and production must be in balance. Still, on a sunny day, the produced electricity from renewable

energy can cover or even overcome the Hungarian consumers' electrical energy needs (see the grey line in Fig. 1.) ("Energy MIX"). The excess electrical energy produced (shown with a red dash circle in Fig. 1.) shall be stored for future purposes and needs. Energy storage is a hot research topic, covering electrical energy storage in different types of batteries or compressed air energy storage, hydroelectric storage, and flywheel electric storage. More recently, researchers recommended chemical energy storage, such as hydrogen production via electrolysis, or continued further by using hydrogen to convert CO₂ to methane in the power-to-methane process, where the produced methane could be blended into the natural gas transportation system (Imre, 2022). Noteworthy, commercially available electrolyzers need ultrapure water as feed to produce hydrogen. This study proposes to use the excess

^{*} Corresponding author.

E-mail address: csfalvay.edit@gpk.bme.hu (E. Cséfalvay).

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electrical energy in ultrapure water production.

By practicing stringent guidelines with proper monitoring and assessment of water quality parameters, it is possible to increase the reliability of critical equipment and prevent the failure of power plants (Rajaković-Ognjanović et al., 2011). The importance of producing feed water for power plants comes from its role in controlling corrosion and scaling in boilers, condensers, and turbines to avoid chemical precipitation in the entire system ("Water Quality Requirement for Various" (Puckorius, 2015). Feed water losses primarily result from evaporation in cooling systems, steam losses in boilers, and blowdowns. Water that is lost due to evaporation and blowdown is replaced with make-up water. Make-up water compensates for the feed water losses that occur during various processes, and its quality must meet the high quality of feed water. It can be produced by treating raw water through a series of technological steps consisting of proper pretreatment, desalination, and post-treatment phases to mitigate corrosion, scaling, and biological fouling problems that can arise due to lower water quality reaching the highest level of water purity.

Total suspended solid content is removed in the pretreatment phase, which is followed by the removal of organics from the raw water; in the meanwhile, a disinfection stage can be inserted if needed. After that, desalination takes place, which is realized via a series of reverse osmosis membranes. Post-treatment is usually carried out using an electrodialysis membrane or mixed-bed ion-exchanger equipment, resulting in ultrapure water with a specific electric conductivity of less than 1 $\mu\text{S}/\text{cm}$.

Pure water production by heat pump vacuum evaporator (HPE) aiming to produce ultrapure water for the power industry hasn't been studied yet; its applications are available to produce clean water from wastewater/process water. Still, this technique hasn't been studied and proposed as a part of ultra-pure water (UPW) technology.

HPE has been considered as an effective technology in wastewater treatment, even when conventional technologies are not viable, to produce highly purified water (with low conductivity) and highly concentrated water simultaneously. By evaporation, all volatile organic content and water can be removed simultaneously. Still, their ratio in

the vapor phase varies according to the pressure and temperature set in the evaporation chamber, moreover, greatly depending on the relative volatility of compounds. When having volatile-organic-content-free salty water as feed, the lonely volatile and evaporating compound is water; by evaporation, water – in vapor form – can be separated from salts, which remain in the concentrated phase in the evaporation chamber. From an operational viewpoint, heat-pump-driven evaporation can offer a reduced energy-consuming solution because the working fluid serves as a heating medium in the shell of the evaporation chamber and a coolant in the water vapor condensing heat exchanger. This technology is highly advantageous from an economic and operational viewpoint since that same working fluid is responsible for evaporation and condensation during the process, which is maintained by electrical power ("Low temperature heat pump vacuum). Notably, this technology requires a suspended-solid-free feed with no need for further pre-treatment. While sharing similarities with RO in certain treatment aspects, the heat pump evaporator distinguishes itself through operational costs and requirements (Turchi, 2004; "Evaporation Technology).

HPE is advantageous because it can handle a wide range of feedwater qualities and can be integrated with other techniques if the separation of different types of compounds needs to be executed. HPE can be integrated into wastewater treatment technology: a distillation-HPE-reverse osmosis system was introduced by Haáz and coworkers for surfactant-containing wastewater treatment, producing high-quality water suitable for reuse. A similar pilot heat pump evaporator was used (Aquamove™ EVALED™ R-150 v3) and placed before the RO. In order to treat the process water, they recommended the sequence of vacuum evaporator followed by RO for proper treatment of preconcentrated surfactant- and heavy metal-containing wastewater. It was determined that 75% of initial process wastewater could be recycled/reused in the cleaning process (Haaz et al., 2019).

Low-temperature vacuum evaporators with heat pumps are ideal for treating low to medium volumes of wastewater from a wide range of industrial processes, as well as reverse osmosis rejects ("Low temperature heat pump vacuum).

Since HPE is a flexible technology, it can reflect immediately any

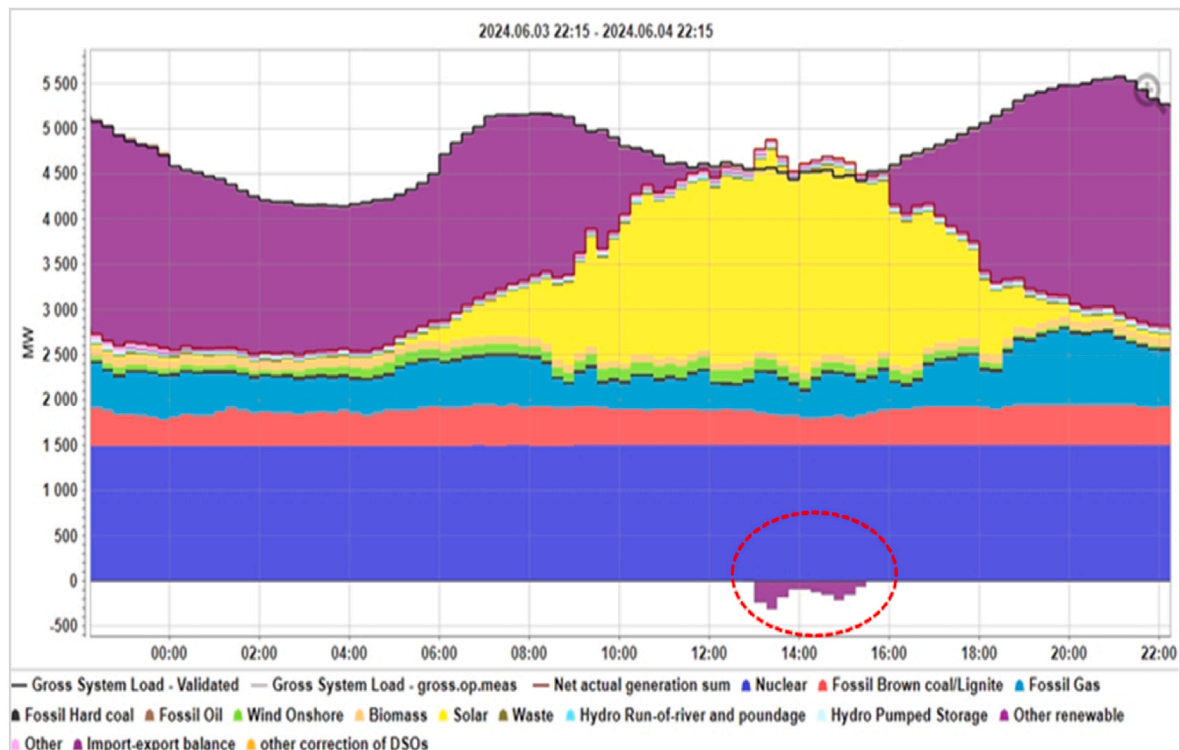


Fig. 1. Power generation by different power plants and consumption (grey line) in Hungary in 24 h on June 4, 2024 ("Energy MIX).

change in the electricity, *i.e.* it can start and stop easily. This study proposes to use the excess energy for pure water production in terms of covering the electrical energy needs of purification technology. This comparative study aims to determine the electrical energy requirements of our previously proposed make-up water-producing system using a sequence of membrane filtration steps that were tested previously (Shaheen and Cséfalvay, 2024) and a heat pump evaporator too, which could serve as an alternative replacing the desalination step of that system. It also studies whether the HPE could replace several filtration steps in pure water production technology. It should be noted that HPE has not been reported as a tested method in natural fresh and salty water treatment, nor in make-up water production yet. The basis of the comparison is the produced water quality in terms of conductivity and energy consumption of the studied systems.

2. Materials and methods

2.1. Heat pump evaporator

The experimental equipment is R150 v03 type heat pump evaporator ("Heat pump Vacuum evaporator with") using a working medium R407C (Fig. 2). The R series vacuum evaporators have a heating system based on a heat pump designed to produce the highest possible concentrate and very low conductivity distillate ("Heat pump Vacuum evaporator with"). The R series vacuum evaporators have a heating system based on a heat pump under a vacuum of 5 kPa (37.5 mmHg) and around 30°C ("Low temperature heat pump vacuum"). The equipment can theoretically produce 150 kg/d of vapor condensate (as a nominal value) when operating with tap water at the lowest operating pressure. The heat transfer surface of the evaporation chamber is 0.2883 m². The cross-section of the evaporation chamber is 0.418 m², which acts as the mass transfer area of the evaporation. At start-up, 1.6–2 L condensate leaves the equipment through the vapor condensate tank (indicated with V in Fig. 2), which must be measured; in the meanwhile, 17 L of feed water is sucked into the evaporation chamber. Approximately 30 min

are required to reach the final vacuum value and steady-state phase. The equipment operates in a semi-batch mode: continuous evaporation leads to a continuous distillate flow; meanwhile, the level controller maintains the level of the boiling liquid in the evaporation chamber at 17 L by frequently sucking the feed, which can be treated as continuous feed flow during the cycle; liquid in the evaporation chamber is continuously concentrated and can be withdrawn only at the end of the process when the equipment returns to ambient pressure. During the experiment in steady-state operation, measuring time, temperature of the R407C working fluid at certain stages, and the actual power value read from an electric power consumption meter are measured; the vacuum in the tank, the pressure of the working fluid on the compressor's discharge branch are monitored, and the pure water's volumetric rate is determined. Vacuum maintains the evaporation of water in the evaporation chamber, which is assisted by the heat released by the working medium in the condenser part of the heat pump cycle.

The heat pump cycle consists of a compressor (1), condenser (2), sub-cooler (3), expansion valve (4), evaporator (5), and a superheater coil (6) (see cycle marked with red lines in Fig. 2). Working fluid has a dual role in the heat pump circuit: it can be used for heating and cooling. In the vapor phase, the working fluid is compressed and heated up by the compressor (1), passing through a heating jacket heat exchanger (2) and sub-cooler (3) to release its heat. The working fluid, now in liquid form, undergoes cooling during its expansion through an expansion valve (4). Then, it is led into a coil heat exchanger, namely an evaporator (5), to reach the saturated vapor phase. This working fluid in the vapor phase enters another coil, which acts as a superheater (6), which is located in the distillate tank (V).

The water cycle – marked with blue lines in Fig. 2 – begins at the feed (F) water tank (I), and water enters the evaporation chamber (II). Feed water absorbs heat from the heat exchanger (*i.e.*, the condenser of the working fluid, (2)) and starts boiling. A scraper is used to ensure the cleaning of the heat exchanger walls. The vapor produced by boiling rises through a demister (III) to dampen the droplets, if any. Vapor is then condensed against a coil heat exchanger (5). The vacuum system is

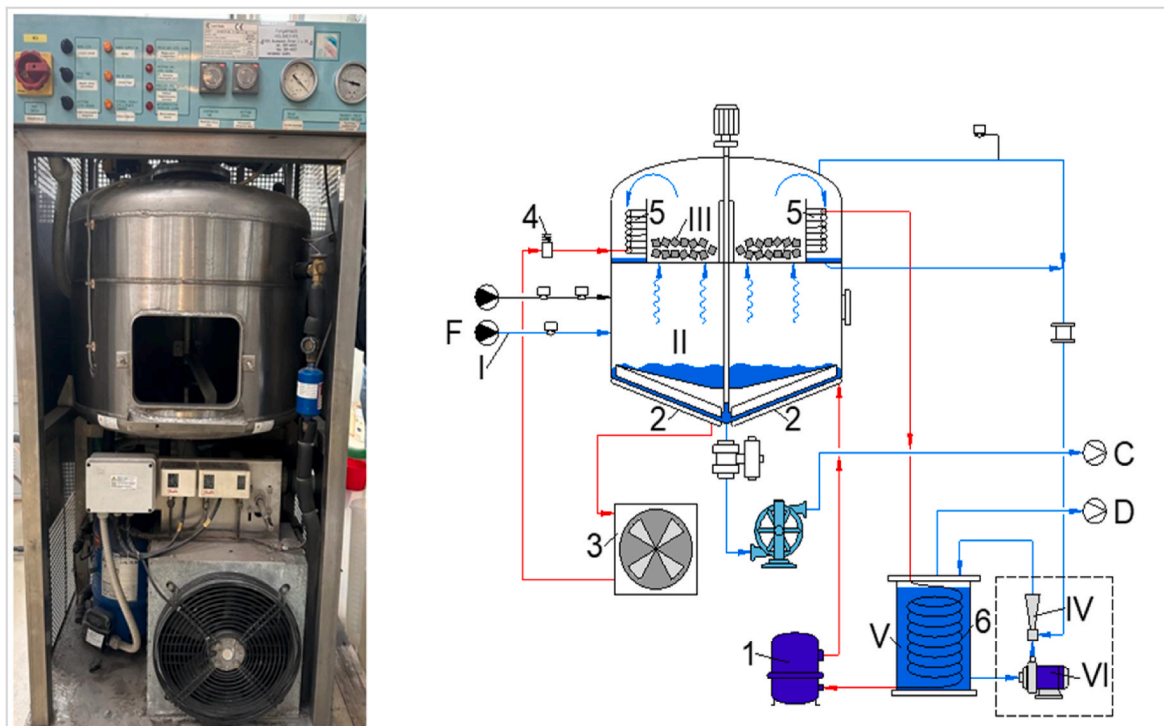


Fig. 2. Heat pump evaporation system for pure water production. Red arrows and numbers indicate the working fluid cycle, and blue lines and Roman letters represent the water cycle. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

composed of an ejector (IV) and a centrifugal pump (VI). The ejector works on the Venturi principle and uses the distillate produced by the evaporator as a motor fluid. The efficiency of the vacuum system depends on the temperature of the motor fluid. It extracts the condensed distillate together with any incondensable gases and sends them to the distillate tank (V).

The distillate (D) is discharged by overflow, and the non-condensing gases are vented with the liquid. The concentrate (C) is discharged at the end of the operation cycle. Distillate was collected in a cylinder; its flowrate was measured manually by recording the distillate volume every 5 min and calculated by using the equation dV/dt . Distillate's specific electric conductivity was measured with a WTW440i conductivity meter every 5 min, while the conductivity values of feed and concentrate were measured at the beginning and the end of the experiment, respectively; the detection limit of the used conductivity meter was $2 \mu\text{S}/\text{cm}$. Each experiment was repeated three times, and the standard deviations are shown in the graphs. The variation of distillate flowrate versus the operation time can be evaluated. Flux equivalent values are proposed for possible comparison with pure water production by a membrane system.

Electric energy is consumed by the compressor (1), the motor that drives the scraper, the ventilator (sub-cooler, (3)), and the vacuum pump (VI). The electric power consumption of the HPE is measured by a BASETech-type EM-3000 power meter, whose value was recorded every 5 min.

2.2. Membrane test equipment

Membrane filtration experiments were carried out on a universal laboratory scale membrane filtration apparatus (CM-Celfa P28; CM-Celfa Membrantrenntechnik AG, Bahnhofstrasse 92, 6423 Sewn, Switzerland), see Fig. 3. Batch filtrations were conducted in cross-flow mode: a circulation pump maintained the continuous flow and recirculation on the feed side, permeate left the equipment continuously, and the retentate was released at the end of the experiment. The electric power consumption of the circulation pump was measured by a BASETech-type EM-3000 power meter. The maximum feed volume of 500 mL could be concentrated until reaching 50 mL of retentate, which is the minimum volume required for the proper operation of the circulation pump. Consequently, a maximum of 90% recovery could be reached, as recovery is defined as the volume of the permeate over the volume of the feed. The maximum applicable operating pressure is 35 bar, maintained by inert nitrogen gas. Membranes with an effective area of 28 cm^2 were used for filtration rounds and conditioned with distilled water before use. Membranes were purchased from Sterlitech Company,

Table 1

Types of membranes applied overpressures on the feed side and recoveries attained during membrane filtration experiments.

Membrane	Type	Applied over pressure on feed side [bar]	Recovery [%]
UF	JW	10	90
NF	DL	20	90
RO-I	AG	35	85
RO-II	AG	35	80

and all of them are polyamide thin film membranes. Types of membranes applied overpressures on the feed side and recoveries attained during membrane filtration experiments are summarized in Table 1. Assessment of ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) experiments by flux and permeate quality were published in our previous work (Shaheen and Cséfalvay, 2024). During the series of membrane filtration processes, the permeate of each step was fed to the next step for further purification; meanwhile, the retentate was collected separately as wastewater.

2.3. Feed solutions

Three different water samples are used as feed of the HPE as representatives of freshwater (FW), pretreated seawater (P-SW), and seawater (SW), see Table 2. Tap water is used as FW, having a conductivity of $431 \mu\text{S}/\text{cm}$, produced by Fővárosi Vízművek Ltd. from the Danube River basin, meeting the drinking water quality. In our recent study, SW was treated by a sequence of membrane filtrations, namely two-step microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). In the end, the permeate leaving the RO was called pretreated seawater (P-SW), obtaining a conductivity of $11.7 \text{ mS}/\text{cm}$, containing mainly sodium and chloride ions (Shaheen and Cséfalvay, 2024). Modeling this permeate on a large scale, a 40-L-volume model solution is prepared by the dissolution of NaCl in tap water, reaching the approximate conductivity obtained previously by the membrane experiment ($11.9 \text{ mS}/\text{cm}$). Artificial seawater is prepared similarly to P-SW; NaCl is added to 40 L of tap water until reaching a similar conductivity measured for seawater originating from the Adriatic Sea, which was used in our previous work (Shaheen and Cséfalvay, 2024).

Conductivity values of the feed water and the concentrate are measured at the beginning and end of experiments, and the distillates produced by HPE are measured continuously with a 340I type WTW combined pH/conductivity meter having an average error of 2%.

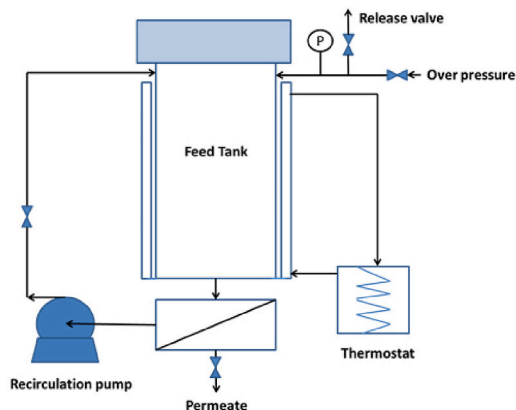


Fig. 3. Photo and schematic drawing of Celfa P-28 test membrane apparatus.

Table 2

Parameters of feed waters of heat-pump evaporator experiments.

Parameters of feed of HPE	Particle- and organic-content-free freshwater (FW)	Artificial pretreated seawater (P-SW)	Artificial seawater (SW)
K [$\mu\text{S}/\text{cm}$]	431	11,900	52,600
T [$^{\circ}\text{C}$]	25.2	30.7	30.2

3. Results and discussion

3.1. Evaluation of the heat pump cycle

In the absence of in-built thermometers, thermocouples are inserted under the insulation of the elements (compressor, condenser, sub-cooler, expansion valve, and evaporator) to be in direct contact with the equipment parts in order to measure the approximate temperatures of each point of the working fluid cycle (1 ... 6) (Fig. 4). Based on the measurements, a thermodynamic cycle of R407C is sketched in a log-p-h diagram using CoolPack software version 1.49. The measured temperatures are in accordance with the pressure values observed on the manometer.

The evaporator uses 230 V electricity to operate the compressor (1), vacuum pump (VI), sub-cooler (3), and a scraping element. The latter can be separately measured, but its value (8W) can be neglected compared to the overall electric energy consumption.

The condensation of working fluid takes place between points No. 2 and 3. The enthalpy difference between them represents the released heat of the working medium, which is absorbed by the treated water present in the evaporation chamber, heating the concentrate to around 35 $^{\circ}\text{C}$. In terms of using the HPE for heating the feed water, the coefficient of performance for heating (COP_H) can be defined as follows:

$$\text{COP}_H = \frac{h_2 - h_3}{h_2 - h_1} = 7.8 \quad (1)$$

which represents an excellent efficiency.

In terms of the cooling section, the working fluid evaporates between points No. 5 and 6 and then superheated to reach point No.1. where the working fluid absorbs heat from the water vapor inside the evaporation chamber, resulting in an almost total condensation of vapor to the outside surface of the heat exchanger (5) (Fig. 2). The coefficient of performance for cooling (COP_C), which reflects the efficiency of cooling provided by the working medium, can be calculated according to Eq. (2):

$$\text{COP}_C = \frac{h_6 - h_5}{h_2 - h_1} = 6.8 \quad (2)$$

It can be concluded that the heat pump cycle worked under excellent COP for both heating and cooling purposes. Noteworthy, the measured temperatures belong to the piping and equipment and can slightly differ from the working fluid bulk temperatures; thus, COPs could be overestimated.

3.2. Heat balance and thermal efficiency

The condensation of working fluid and sub-cooling is represented by the enthalpy difference between points No. 2 and 3 (Fig. 4). represents the released heat of the working medium as:

$$q_{\text{released}} = (h_2 - h_3) = (449.28 - 265.40) = 183.88 \frac{\text{kJ}}{\text{kg}} \quad (3)$$

Considering the mass of the working fluid ($m_{\text{wf}} = 1.75 \text{ kg}$) and $t_{\text{wf}} = 100 \text{ s}$ as working fluid cycle time:

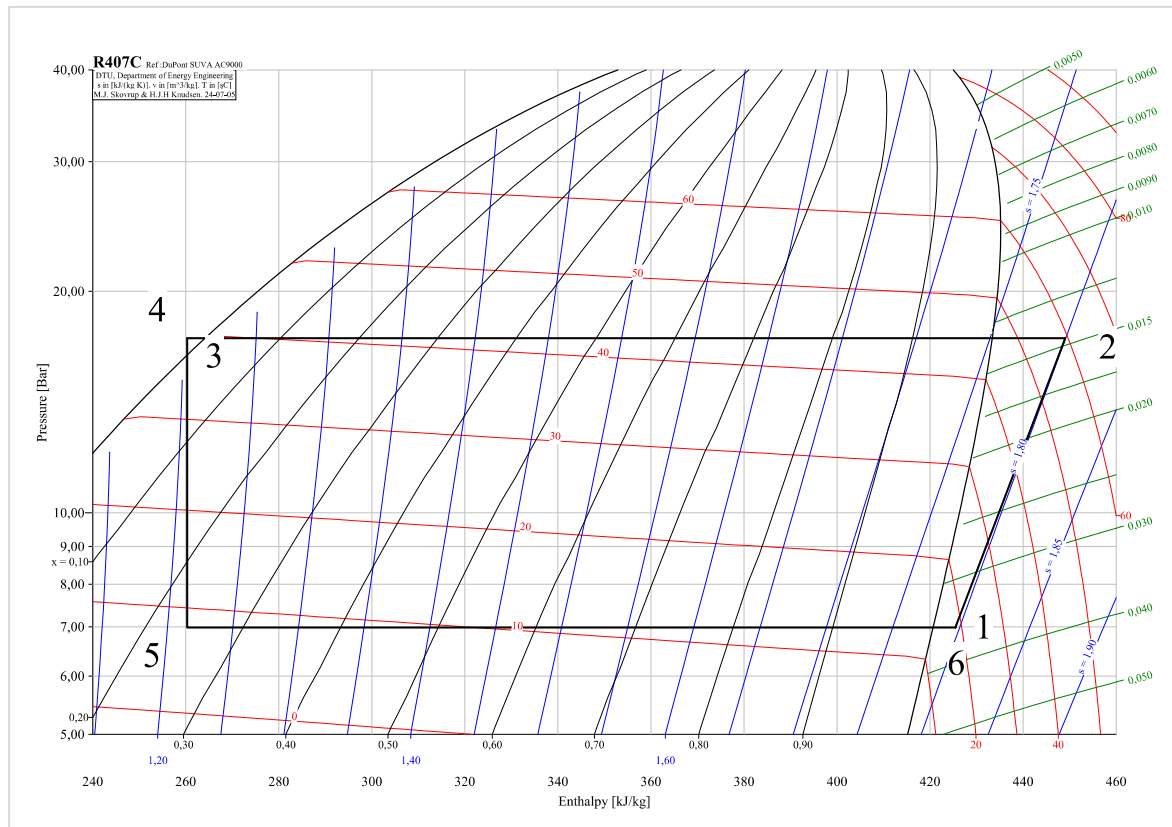


Fig. 4. The thermodynamic cycle of R407C was visualized using CoolPack software. The software shows decimal commas instead of decimal points on the axis, ordinate, specific steam content, isothermic-, isochoric- and isentropic lines. Numbering is in accordance with the red-arrowed cycle in Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

$$\dot{Q}_{\text{released}} = \frac{q_{\text{released}} \cdot m_{\text{wf}}}{t_{\text{wf}}} = \frac{183.88 \frac{\text{kJ}}{\text{kg}} \cdot 1.75 \text{ kg}}{100 \text{ s}} = 3.218 \frac{\text{kJ}}{\text{s}} \quad (4)$$

The theoretical pressure value of the vacuum unit is determined by the temperature of the condensed water (i.e., pure water or distillate) recirculating in the ejector. The average distillate temperature is 21 °C, providing a theoretical pressure of 19 mmHg; meanwhile, an approximate vacuum of 37.5 mmHg is set in the manual. In general, lower pressure enhances the vapor removal, accelerating the pure water flowrate. Actual ambient pressures, vacuum values, and actual pressure in the evaporation chamber can be seen in Table 3.

Heat balance analysis was performed for all types of feedwater used in the HPE experiment, but only the FW calculations are shown here.

The heat released by the working fluids must be absorbed by the water inside the tank. To analyze the water cycle in the experiment, unsteady and steady-state phases are treated separately.

During the unsteady state (the first 30 min of an experiment), heating of the 17 L of feed water, sucked immediately into the evaporation chamber, takes place, which absorbs heat as:

$$\dot{Q} = \dot{m} \cdot c_{p, \text{at feed temperature}} \cdot (T_{\text{saturation}} - T_{\text{feed}}) \quad (5)$$

Specified for FW:

$$\begin{aligned} \dot{Q}_{\text{unsteady state}} &= \dot{m}_{\text{unsteady state}} \cdot c_{p, 25^\circ \text{C}} \cdot \Delta T \\ &= \frac{17 \text{ kg}}{0.5 \text{ h}} \cdot 4.1816 \frac{\text{kJ}}{\text{kg} \cdot ^\circ \text{C}} \cdot (31.7 - 25)^\circ \text{C} = 0.265 \frac{\text{kJ}}{\text{s}} \end{aligned} \quad (5a)$$

where the boiling temperature of water inside the evaporation chamber is calculated at 31.7 °C as the latent temperature of FW. The absorbed heat during the steady state phase (when having a continuous distillate and feed flow) can be calculated as follows:

$$\begin{aligned} \dot{Q}_{\text{steady state}} &= \dot{m}_{\text{steady state}} \cdot c_{p, 25^\circ \text{C}} \cdot \Delta T = 4.219 \frac{\text{kg}}{\text{h}} \cdot 4.1816 \frac{\text{kJ}}{\text{kg} \cdot ^\circ \text{C}} \\ &\quad \cdot (31.7 - 25)^\circ \text{C} \\ &= 0.033 \frac{\text{kJ}}{\text{s}} \end{aligned} \quad (5b)$$

The evaporation heat during the steady state

$$\dot{Q}_{\text{steady state}} = \dot{m}_{\text{feed}} \cdot h_{\text{vap}, 31^\circ \text{C}} \quad (6)$$

$$\dot{Q}_{\text{steady state}} = 4.219 \frac{\text{kg}}{\text{h}} \cdot 2428.18 \frac{\text{kJ}}{\text{kg}} = 2.845 \frac{\text{kJ}}{\text{s}} \quad (6a)$$

Considering the heat calculation during an experiment, and by using the values obtained in Eqs. (5a), (5b) and (6a) then total absorbed heat is 3.143 kJ/s.

Heat balance:

$$\dot{Q}_{\text{released}} = \dot{Q}_{\text{total absorbed}} + \dot{Q}_{\text{excess}} \quad (7)$$

0.075 kJ/s was obtained as $\dot{Q}_{\text{excess}}$, which is identified as a heat released during the subcooling phase of the working fluid (between points No. 3 and 4. in Fig. 4).

Table 3
Pressure values and saturation temperatures during the HPE experiments.

Sample	Actual Ambient Pressure [mmHg]	Vacuum [mmHg]	Actual Absolute Pressure in the Tank [mmHg]	Saturation Temperature in the Tank [°C] ^a
FW	765.1	−730	35.1	31.7
SW	758.8	−720	38.8	35
P-SW	758.3	−720	38.3	35

^a Interpolation was used to calculate the saturation temperature for the different feed waters.

3.3. Flowrate analysis of HPE

The actual absolute pressure in the tank can influence the vapor and condensate flowrate; however, in all cases, the feed water is salty water at different concentrations, and water is the lonely volatile compound in the feed; thus, water (in the vapor phase) is removed from the feed while salt compounds remain in the feed liquid. Noteworthy, when the heat flux is very intensive, coupled with high vacuum, droplets of the feed (containing salts) can be dragged, resulting in an elevated conductivity of the produced pure water.

To evaluate the efficiency of the HPE in pure water production, the flowrate of the produced pure water is calculated. Averages of three replicates of the pure water flowrate with standard deviations are shown in Fig. 5.

HPE works under steady-state conditions after the first half an hour of the experiments; steady-state distillate flowrates are calculated as averages of three rounds of each experiment. Considering the standard deviations, the three curves overlap, resulting in 3.95, 3.97, and 3.71 L/h flowrates for FW, SW, and P-SW, respectively, in the steady-state range (Fig. 5). These values are used for prognosing the continuous operation reaching 50% recovery, defined in Eq. (8).

$$\text{Recovery} = V_{\text{PW}}/V_{\text{F}} \cdot 100\% \quad (8)$$

where V_{PW} is the volume of pure water, and V_{F} is the volume of the feed. Almost the same 5-h-processing time is estimated for all water samples when assessing 50% of the feed as pure water.

3.4. Lab-scale comparison of heat pump evaporation and membrane filtration

3.4.1. Flux and flux equivalent

The vapor removal rate is calculated to create a parameter that is similar to the volumetric flux used in membrane filtration. The proposed parameter is a Flux Equivalent ($J_{\text{v-HPE}}$, which is the flowrate of pure water (dV_{D}/dt [L/h]) over the cross-section of the evaporation chamber A_{c} , [m²] = 0.418 m², Eq. (9).

$$J_{\text{v-HPE}} = \frac{1}{A_{\text{c}}} \cdot \frac{dV_{\text{D}}}{dt} \left[\frac{\text{L}}{\text{m}^2 \cdot \text{h}} \right] \quad (9)$$

As shown in Fig. 6, the standard deviations of the three experiments are overlapping; hence, no significant difference in variability among the experiments can be recorded and no tendency based on the feed water quality can be observed. Therefore, it can be concluded that Flux Equivalent through the HPE is not affected by the salt content of the feed water, as was observed in the membrane filtration process (Shaheen and Cséfalvay, 2024).

Regarding the filtration system, the permeate flow started along with the process operation. The unsteady period was observed when starting the UF experiment and lasted approximately half an hour, similarly as observed in the case of HPE. Despite the separate batch filtrations, by the combination of UF, NF, RO-I, and RO-II fluxes, merging them to formulate a series of filtration systems, the flux versus the operation time (Fig. 7) could be compared with the HPE flux-equivalent (Fig. 6). Noteworthy, each filtration step operated at different applied pressures matching the proposed operating pressure intervals at each step. RO-II showed a stable average flux of 95.63 L/(m²h) at 35 bar applied pressure, representing the pure water flux having the same quality as observed for HPE (shown in the next section).

By comparing the permeate fluxes with the flux-equivalent values, it can be stated that the final step of the series of membrane filtration steps, i.e., RO-II, can provide about ten times higher flux (95.63 L/(m²h) as pure water flux) than 9.47 L/(m²h) observed for HPE for FW. Considering the pure water production rates, membrane series can produce a higher amount of pure water than HPE.

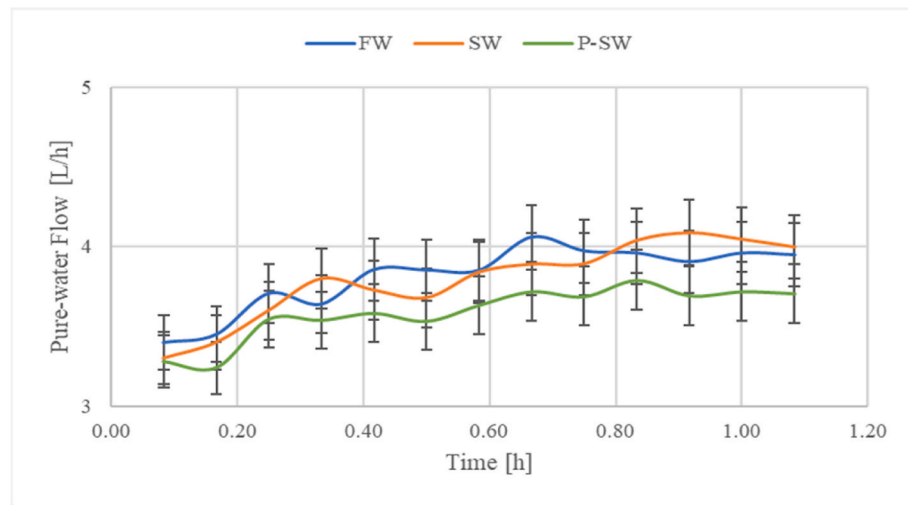


Fig. 5. Flowrate of the produced pure water for three different water samples, measuring time starts by having the first drop of pure water after the typical 30-min- unsteady period. FW: freshwater, SW: seawater, P-SW: pretreated seawater.

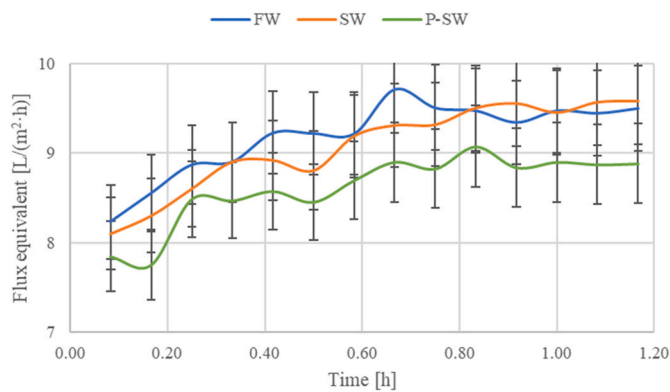


Fig. 6. Calculated flux-equivalent through the HPE; STDEV: 0.282, 0.198, and 0.032 for Freshwater (FW), seawater (SW), and pretreated seawater (P-SW), respectively.

3.4.2. Produced water quality

Different scenarios are set up to map the possible replacement (full or partial) of membrane filtration technology in pure water production from both fresh- and seawater as raw water. Fig. 8 shows a schematic visualization of how HPE can replace the previously proposed (Shaheen and Cséfalvay, 2024) pure water-producing method.

Based on the conductivity values, HPE can produce almost the same quality as pure water with a conductivity of 4 $\mu\text{S}/\text{cm}$, which is similar to the value observed for the second RO permeate, *i.e.*, 2 $\mu\text{S}/\text{cm}$. It can be stated that one stage of HPE can replace the four-step membrane filtration series (UF, NF, and two-step RO) in the case of the FW experiments. At ambient conditions, the carbon dioxide (CO_2) content of the air is physically then chemically dissolved into pure water, increasing its conductivity, resulting in a typical value of 4–6 $\mu\text{S}/\text{cm}$ measured at 25°C. Meanwhile, in the SW experiments, the distillate produced by HPE with a conductivity of 19 $\mu\text{S}/\text{cm}$ is lower than the permeate's conductivity observed for the four-step membrane filtration series, *i.e.*, UF, NF, and two-step RO (observed at 36 °C is 425 $\mu\text{S}/\text{cm}$) (Shaheen and Cséfalvay, 2024), showing a better performance (see

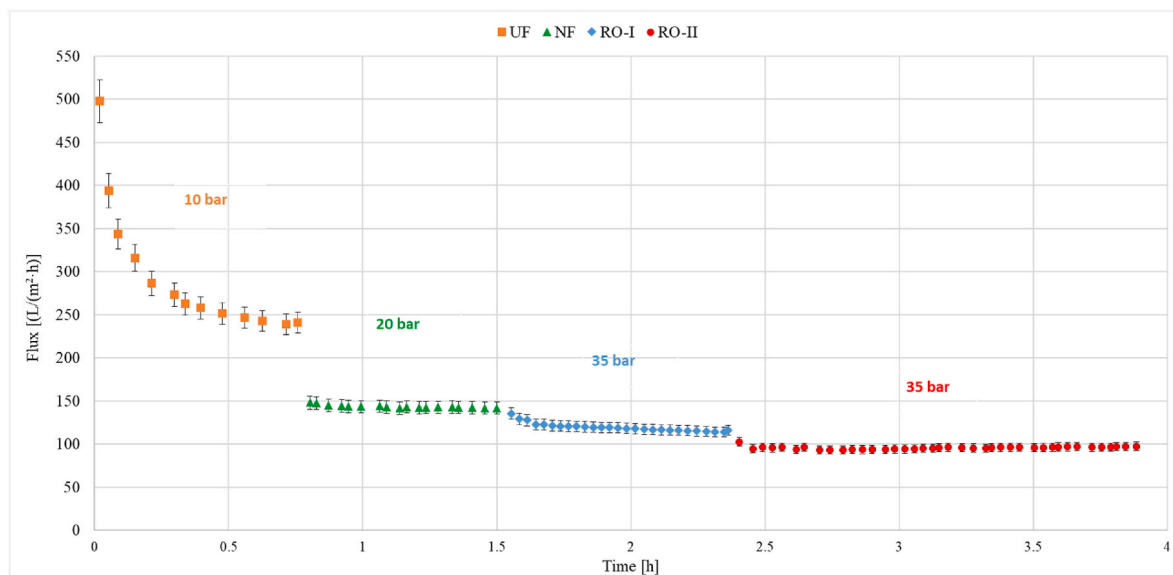


Fig. 7. Average permeate flux observed at each filtration step in the case of the membrane treatment system using freshwater as raw water (STDEV: 11.942, 0.667, 4.860, and 0.973 for UF, NF, RO-I, and RO-II, respectively).

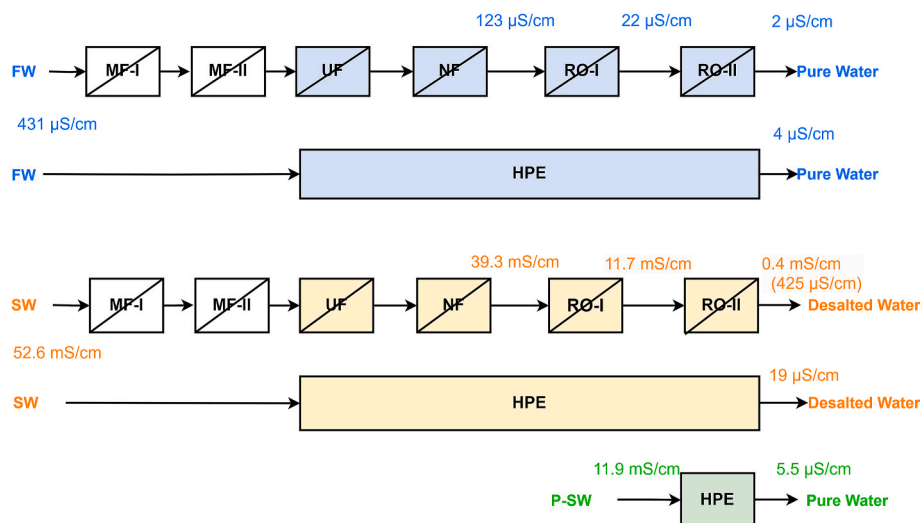


Fig. 8. Membrane filtration vs heat pump evaporation in water purification. MF-I: first step of microfiltration, MF-II: second step of microfiltration, UF: ultrafiltration, NF: nanofiltration, RO-I: first step of reverse osmosis, RO-II: second step of reverse osmosis, HPE: heat pump evaporator. Permeate of each membrane filtration step is fed to the next step for further treatment. Retentates and the concentration of HPE are not shown in this figure.

Fig. 8). In this case, the produced water is in the range of 19–425 $\mu\text{S}/\text{cm}$, which can be classified as desalted water. An additional experiment is carried out on HPE using P-SW as feed, aiming to study the possible replacement of the second RO step by HPE. P-SW, having an initial conductivity of 11.9 mS/cm – like the RO-II feed of the SW treatment by membrane technology (11.7 mS/cm) – is used as feed. HPE shows a significant decrease in conductivity, producing pure water of 5.5 $\mu\text{S}/\text{cm}$, which is 98.7% lower than the one obtained by RO-II (425 $\mu\text{S}/\text{cm}$). The produced water in all cases can be classified based on conductivity values: either pure water ($<6 \mu\text{S}/\text{cm}$) or desalted water. Therefore, a further RO step is needed in the desalination stage, followed by electrodialysis in the post-refining stage, when aiming towards producing the ultrapure water ($<1 \mu\text{S}/\text{cm}$).

It can be concluded that as the four-step membrane filtration can be replaced by one equipment of HPE, in cases of both FW and SW, regular cleaning and maintenance would be easier and probably cheaper for HPE, making it more suitable and preferable from an operational viewpoint. Noteworthy, installation costs are not the focus of this study. Although HPE provides good quality pure water, having low conductivity, initial pretreatment using MF is essential for both HPE and UF since suspended solid-free pretreated water is advised to use as feed aiming to avoid the deposit on the heat exchanger surface and the

fouling of UF membrane's pores. Thus, microfiltration is an indispensable part of the treatment.

3.4.3. Specific energy consumption

In addition to water quality, energy consumption is an important parameter for the comparison between membrane filtration technologies and HPE; thus, the electrical energy consumed by the pumps must be identified.

Considering the previously proposed membrane filtration process, the hydrostatic pressure provided the driving force of MF-I; consequently, the electric energy requirements of the further process – consisting of MF-II, UF, NF, RO-I, and RO-II – are considered in terms of pump operation.

As membrane filtration experiments were carried out in batch mode using one test equipment, a circulation pump with a power of 27 W is applied five times (for each filtration step), which is essential for the specific electrical energy consumption (SEC) calculations, see Fig. 9. Noteworthy, the operation pressure was regulated by a reducer matching each filtration step's pressure requirements and maintained by nitrogen gas. In the case of industrial-scale applications, high-pressure pumps are used, which can maintain the driving force through the membrane and provide a continuous flow through the different stages.

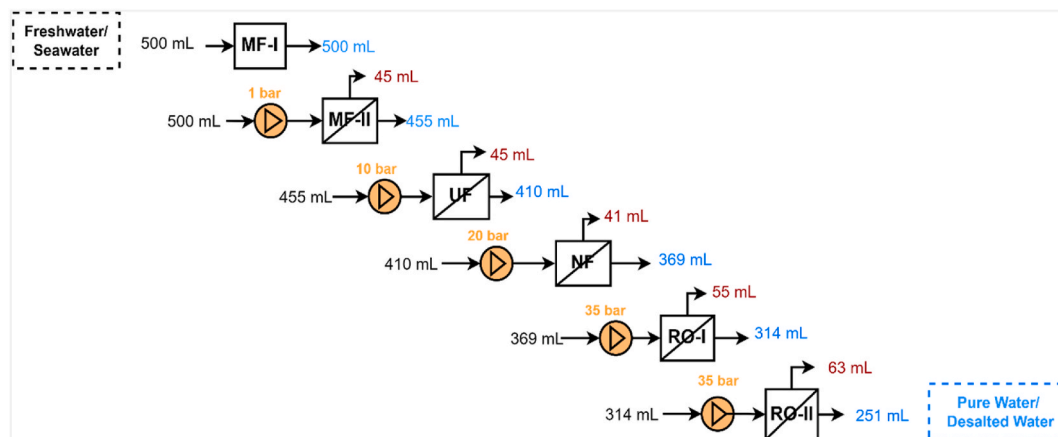


Fig. 9. Scheme of the batch membrane filtration experiments at laboratory-scale with a total system recovery of 50%. Permeate volumes are indicated with blue, concentrates (i.e., retentates) with red color. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

By using this sequence of membrane filters, 251 mL of pure water could be obtained from 500 mL of feed water (both FW and SW), showing a 50% system recovery calculated according to Eq. (8).

Due to the different salt content of the feed (FW and SW), generating 1 L of pure water requires different operation times, reaching the same recovery (50%) of the complete membrane filtration process and leading to different electrical energy consumption. Longer operation time coupled with higher SEC is obtained for SW using Eq. (10).

$$SEC [kJ/L] = Power [kW] \cdot Operation time [s] / product volume [L] \quad (10)$$

The operation time was calculated for five steps of membrane filtrations, and the circulation pump's power must be considered five times, as shown in Eq. (10a).

$$SEC [MJ/L] = 5 \cdot 27 [W] \cdot operation time [s] / 0.251 [L] / 1,000,000 [J/MJ] \quad (10a)$$

By feeding 500 mL FW to the proposed series of membrane filtration steps, 3.16 h operation time is required to produce 251 mL permeate, experienced and summed up based on our previous study (Shaheen and Csefalvay, 2024), which means an electric energy consumption of 6.12 MJ to produce 1 L of pure water from FW. Three times more operation time, thus almost three times higher electrical energy consumption is calculated in the case of SW than FW, by which a permeate with a conductivity of 425 $\mu S/cm$ could be produced and named as desalted water (Fig. 8). 8.95 h operation time and 17.53 MJ electrical energy are required to produce 1 L of desalted water from SW (Table 4) by this membrane technology at laboratory scale.

Assuming a continuous separation by the series of membrane filtration steps, 0.079 L/h and 0.028 L/h continuous pure water flows are calculated for FW and SW, respectively. Therefore, 28.37 and 10.02 L/(m²·h) overall flux values could be estimated for a continuous membrane treatment system (Table 5).

In the case of HPE, to have a comparable value with the membrane filtration system, SEC related to 50% recovery is calculated using Eq. (8). Thirty minutes of start-up time was considered for all types of water sources (4.4 MJ). Notably, the production time is accounted for after the start-up time under steady-state conditions; 5 h is accounted as a production time for the three different feed waters (FW, P-SW, and SW) treated with HPE to produce 20 L of pure water from 40 L of feed obtaining 50% recovery. This time must be multiplied by the average power consumption (2561 W) measured throughout the whole process for all types of water, including start-up time and pure water production time, and divided by the volume of the produced water. As a result, 2.31 MJ/L is derived as a common SEC value for all types of water sources reaching 50% recovery. When using FW as feed, laboratory-scale HPE can completely replace the four-step membrane filtration process, providing the same quality of pure water using 62% less electrical energy at the same recovery.

Meanwhile, in the case of SW, better quality of pure water could be obtained in one-step HPE than obtained for the four-step membrane

Table 4

SEC comparison of lab-scale experiments by the proposed membrane filtration system of FW and SW considering the circulation pump with a power of 27 W for each filtration step.

	FW	SW
Number of membrane filtration steps	5.00	5.00
Operation time of MF-II, s	120	140
Operation time of UF, s	2,53	2,42
Operation time of NF, s	2,79	7,49
Operation time of RO-I, s	2,45	17,29
Operation time of RO-II, s	3,48	4,88
Total operation time reaching 50% recovery, s	11,37	32,22
Total operation time reaching 50% recovery, h	3.16	8.95
Pure water volume, mL	251.00	251.00
Specific electrical energy consumption (SEC), MJ/L	6.12	17.53

Table 5

Comparison of lab-scale pure water production technologies obtaining 50% recovery. M represents membrane filtration technology, HPE heat pump evaporator, FW freshwater is used as feed, and SW seawater is used as feed.

	M (FW)	M (SW)	HPE (FW)	HPE (SW)
Number of treatment steps	5.00	5.00	1	1
Overall pure water flux calculated for a continuous operation membrane system, L/(m ² ·h)	28.37	10.02	–	–
Flux Equivalent for HPE, L/(m ² ·h)	–	–	9.47	9.45
Specific electrical energy consumption (SEC), MJ/L	6.12	17.53	2.31	2.31

filtration system with 87% less electrical energy consumption. It can be concluded that laboratory-scale HPE is preferable in pure water production in terms of energy requirements. A summative comparison of the lab scale experiments is shown in Table 5. Due to the significant difference between the cross-section of lab-scale membranes (28 cm² in each step) and the heat transfer surface in the HPE (0.2883 m²), it is worth comparing the flux and the Flux Equivalent of two technologies describing the membrane technology and HPE, respectively. These values are very similar for the membrane technology when SW is the feed and for HPE when using FW or SW as feed: all of them fluctuate around 10 L/(m²·h). Despite the similar values observed for SW, the overall flux value of FW is almost three times higher.

3.4.4. Industrial-scale comparison for pure water production from freshwater

Considering the industrial-scale pure water production either by membrane filtration technology or HPE, the technology determines the pure water quality independently of the scale, thus same pure water quality is assumed for both technologies.

Theoretical calculations are conducted for industrial-scale membrane filtration steps for FW as feed. The make-up water requirements for high-pressure thermal power plant block ("Gergely Büki) are estimated as 26 m³/h ultrapure water. Assuming 100% efficiency of the post-treatment method (electrodeionization or mixed bed ion-exchange), 26 m³/h flowrate is used as an essential value, as required pure water produced by both membrane filtration series and HPE systems to have comparable values.

The industrial-scale design of our proposed membrane technology is performed as follows: aiming to have 26 m³/h pure water produced by membrane filtrations as RO-II permeate, a reverse calculation is carried out based on the recoveries to select the proper pumps for the first step of designing an industrial-scale pure water production system. By knowing the requirements and the recoveries, the retentate and feed flowrate of each step of membrane filtration can be calculated for the pump selection stage. In the case of RO-II, the permeate flowrate is assumed to be 26 m³/h, and using 80% as a recovery, the feed flowrate of RO-II – which represents the permeate of RO-I – is calculated accordingly (32.2 m³/h). Using 85% recovery for the RO-I stage, a 37.9 m³/h is obtained as a feed of RO-I, which represents the NF permeate's flowrate. These calculations are continued, so feed flowrates of NF, UF, and MF-II are determined using 90% recovery for each membrane filtration step. The hydraulic pressure maintains the driving force of MF-I and MF-II similarly to the laboratory scale; meanwhile, a high-pressure pump must be located after this step, which proves the sufficient operation of the series of UF, NF, and RO-I. A second pump is placed before the RO-II step. Considering the regular maintenance, cleaning of the membranes is scheduled in line A, the valves in this line are closed, and the treatment process is directed to line B, and vice versa (Fig. 10). Low-pressure chemical-resistant pumps are selected for the Clean-In-Place (CIP) procedure for each stage. Pressure drops through the treatment steps are also indicated in Fig. 10. Based on these considerations, the specific energy consumptions are calculated.

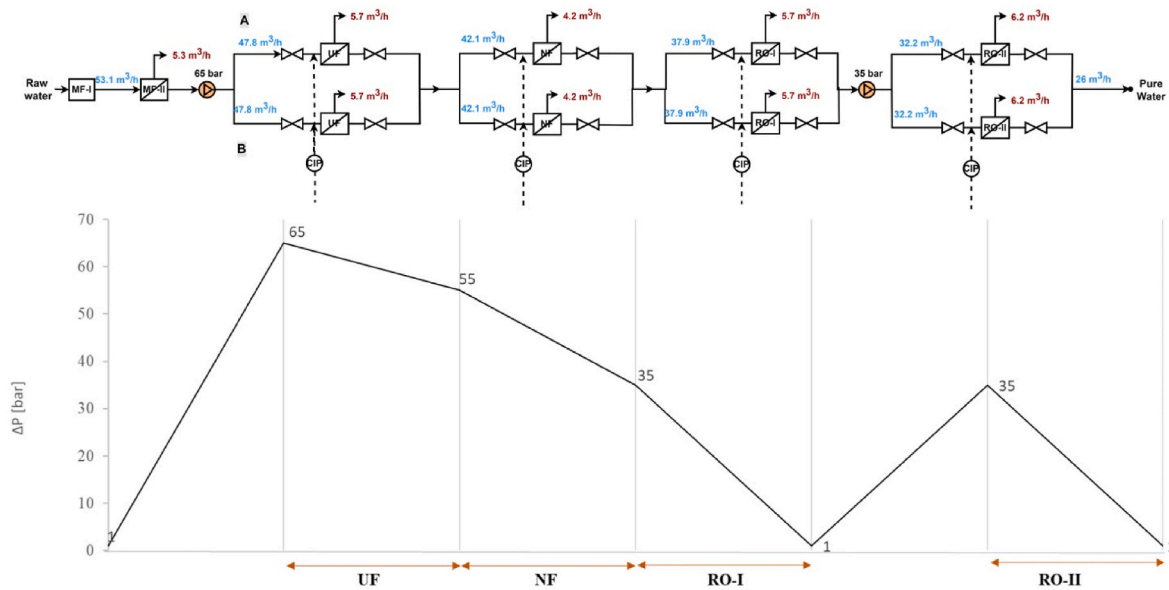


Fig. 10. Scheme of the proposed membrane filtration system for pure water (PW) production at industrial scale, based on the proposed membrane filtration technology.

Considering the pumps' pressures and flowrates and assuming a mechanical efficiency of 70%, the pumps' power can be calculated using Eq. (11):

$$P = \frac{p \cdot Q}{\eta} \quad (11)$$

Where P is the power [W], Q is the flowrate [m^3/s], p is the pressure [Pa], η : mechanical efficiency [-] of the pump. Selected pumps, their parameters, and the calculated power consumption are summarized in Table 6.

The total electric power consumption by the selected pumps is $139 + 44 = 183$ kW (see Table 6). Considering the regular cleaning 5 min are accounted for this after each 115 min normal operation. By substituting our values into Eq. (10) SEC can be calculated as follows:

$$\begin{aligned} \text{SEC} &= \frac{183 [\text{kW}] \cdot 115 [\text{min}] \cdot 60 \left[\frac{\text{s}}{\text{min}} \right] + 4 \cdot 0.33 [\text{kW}] \cdot 5 [\text{min}] \cdot 60 \left[\frac{\text{s}}{\text{min}} \right]}{26 \left[\frac{\text{m}^3}{\text{h}} \right] \cdot 115 \left[\frac{\text{min}}{\text{h}} \right]} \\ &= 25.35 \text{ MJ} / \text{m}^3 \end{aligned}$$

Table 6

Power consumption of selected pumps designed for industrial-scale pure water production by a sequence of membrane filtration steps assuming 70% mechanical efficiency.

	Pump type	Flowrate (Q) [m^3/h]	Pressure (p) [bar]	Power consumption (P) [kW]	No. of pumps
1st pump	DF85-67, ("Multistage Centrifugal Pump")	53.1	65	139	1
2nd pump	TBAK, ("TBAK Low NPSH Magnetic Drive")	32.2	35	44	1
CIP pump	Prominent Makro TZMb 042100	2.1	4	0.33	4

Aiming to produce 1 m^3 of pure water by the designed industrial-scale membrane filtration technology, $25.35 \text{ MJ}/\text{m}^3$ of specific electrical energy consumption is required for the operation.

On the other hand, theoretical calculations are performed aiming to produce the same amount of $26 \text{ m}^3/\text{h}$ of pure water by HPE. These calculations are conducted with a selected model PCF24, providing the maximum distillate flowrate of $24 \text{ m}^3/\text{d}$. The nominal value of electric energy consumption of this model is 150 kWh (540 MJ) over 1 m^3 of distillate ("EVALED PC"). To produce $26 \text{ m}^3/\text{h}$ pure water, 27 pieces of HPE units are required from this model connected in parallel; thus, theoretically, $14,580 \text{ MJ}$ of electrical energy is consumed to produce 1 m^3 of pure water, which is very high in comparison to the consumption of the designed membrane filtration system (Table 7).

3.5. The potential of excess electrical energy utilization

Considering the electrical power generation, there was a significant amount of excess power between 13:00 and 15:00 on June 4, 2024. By processing the power generation data – provided by MAVIR ("Energy MIX") – the excess electrical energy (E_{excess}) can be calculated according to Eq. (12).

$$E_{\text{excess}} = \sum P_i \cdot \Delta \tau_i \quad (12)$$

where P_i [MW] refers to the excess power at time i , and $\Delta \tau_i$ [s] is the time interval of P_i power. Since the time intervals, $\Delta \tau_i$ are identical and can be treated as $\Delta \tau$, Eq. (12) can be rearranged as follows:

$$E_{\text{excess}} = \Delta \tau \cdot \sum P_i \quad (13)$$

The total excess power in the given time interval on the named day is

Table 7

Comparison of SEC of industrial scale pure water production systems, M represents membrane filtration technology, HPE heat pump evaporator, FW fresh-water is used as feed.

	M (FW)	HPE (FW)
Number of treatment series	2	27
Overall pure water flowrate calculated for a continuous operation membrane system, m^3/h	26	26
Specific electrical energy consumption (SEC), MJ/m^3	25.35	14,580

$\sum P_i = 5000$ MW, $\Delta\tau = 5$ min = 300 s, thus, 1,500,000 MJ excess electrical energy can be used for water treatment purposes. Taking into consideration the proposed membrane technology designed for industrial-scale pure water production from FW and its specific electric energy consumption (25.35 MJ/m³), the volume (V) of produced pure water can be calculated according to Eq. (14):

$$V = \frac{E_{\text{excess}}}{SEC} \quad (14)$$

which means an assumed value of 59,171 m³. Noteworthy, the designed system can produce 26 m³/h. When the excess electrical energy is available only for 2 h, it means that 52 m³ of pure water can be generated as designed, which is three orders of magnitude lower than the assumed value if all excess energy is utilized for pure water production.

At this point, the origin of power generation shall be treated separately. As we focus on the house-hold-scale 2200 MW inbuilt capacity of solar panels in Hungary (in 2024), and the same 2-h interval is assumed as the time for the excess power generation, 4400 MWh = 15,840,000 MJ electrical energy appears to be the excess, which is ten-times higher than the value measured by MAVIR. Consequently, the electrical energy generated by house-hold solar panel are probably consumed on site.

By these considerations, it can be concluded that the excess power provided is only part of the solar power generation, and the excess utilization for pure water production, in case of the given example, does not provide a proper solution in the time interval when exactly the excess power is generated, so other purposes, such as electrical energy storage in batteries or energy use for water electrolysis to produce hydrogen as a gaseous fuel can be considered.

3.5.1. Environmental impact

3.5.1.1. Global Warming Potential of electricity generation. As both tested water treatment systems use electricity for operation: pumps in case of membrane filtration system and vacuum pump, compressor, motor (that drives the scraper), and sub-cooler in case of HPE, the electrical energy production and its Global Warming Potential (GWP) allows comparison at a given location, where the electricity is generated. Different countries use different primary energy sources characterized by different GWPs. By analyzing the carbon intensity values in electricity generation, the import and export make the values fluctuate, so an average value of 258 g CO₂/kWh was considered as a representative of the year 2023 in Hungary ("Electricity map). The diversity of electrical energy sources and their installed capacities determine this GWP value. Noteworthy that Hungary has a significant inbuilt solar capacity, represented by a 31 g CO₂/kWh GWP value. A comparison of GWPs of the two different technologies is shown in Table 8, which is in great correspondence with the SEC. Since HPE is considered as one unit, lower GWP values are obtained compared to membrane systems (see Table 9).

3.5.1.2. Ozone depletion potential. Working fluids can be characterized by ozone depletion potential (ODP). The test equipment is an R150 v03 type heat pump evaporator using a working medium R407C, which has

Table 8

Comparison of specific GWP values of the lab-scale membrane system (M), heat pump evaporator (HPE) tested for freshwater (FW) and seawater (SW), [g CO₂/1 L pure water]. 258 g CO₂/kWh was considered as a representative of the year 2023 in Hungary.

Calculated values/L pure water	M (FW)	M (SW)	HPE (FW)	HPE (SW)
SEC, MJ/L	6.12	17.53	2.31	2.31
SEC, kWh/L	1.7	4.87	0.64	0.64
GWP from electricity, g CO ₂ /L	5684	16282	2146	2146
GWP from solar energy only), g CO ₂ /L	683	1956	258	258

Table 9

Comparison of specific GWP values of the industrial-scale designed membrane system (M), heat pump evaporator (HPE) tested for freshwater (FW) [g CO₂/1 L pure water] 258 g CO₂/kWh was considered as a representative of the year 2023 in Hungary.

Calculated values/m ³ pure water	M (FW)	HPE (FW)
SEC, MJ/m ³	25.35	14,580
SEC, kWh/m ³	7.04	4050
GWP from electricity, g CO ₂ /m ³	1816	1,044,900
GWP from solar energy only, g CO ₂ /m ³	218	125,550

an ODP value of 1774 ("Ecological Refrigerants). As no life-cycle assessment has evolved for lab-scale experiments, technologies cannot be compared according to ODP values.

3.5.1.3. Wastewater quality. HPE works in semi-batch mode, meaning a continuous feed inlet and distillate outlet. Still, the concentrate is released at the end of the evaporation cycle, which time must be precisely estimated and set. Noteworthy, the concentrated solution remaining after evaporation of SW is very salty, which should not be drained into the sewage system, especially must not be led into natural water bodies. By using the component balance equation and knowing that the distillate contains water only, the component balance of NaCl is reduced to feed (F) and concentrate (C). The volume of the evaporation chamber determines the concentrate's volume as 17 L in the case of the lab-scale HPE. The cycle must terminate before reaching the solubility limit of NaCl in the evaporation chamber, i.e., the concentrate. The solubility limit of NaCl in 100 g of water at 40 °C is 36.6 g (Hencsei et al., 1999), which value must be converted to mass ratio and applied in the following equation (Eq. (15)).

$$t \cdot \dot{m}_F \cdot c_{F,NaCl} = m_C \cdot c_{C,NaCl} \quad (15)$$

where t is the operation time of a cycle [h], $\dot{m}_F$ is a feed mass rate [kg/h], $c_{F,NaCl}$ is the feed's NaCl concentration in mass ratio [-], m_C is the mass of the concentrate at the end of the cycle [kg], and $c_{C,NaCl}$ is the solubility limit of NaCl (taken as 0.268 m/m). Component balance-based, calculated operation times for P-SW and SW are shown in Table 10.

In the case of FW as feed, the solubility limit of NaCl does not determine the cycle time, and it can be set according to the operator or for convenience.

When dealing with P-SW, it represents an organic-pollutant-free solution, so the concentrate is a dense NaCl, which can be crystallized and used for other purposes. This suggestion is not applicable to the other two raw water samples because they are polluted with natural organic matter; they cannot be used in their current form, and further action is needed in these cases.

Considering the proposed membrane filtration system, UF retentate contains the natural organic content of the raw water, which can be led into the sewage system. The retentates of nanofiltration and reverse osmosis steps are concentrated salt solutions; their conductivity and total salt content shall meet the emission limit of local regulations. By calculating the NaCl_{eq} values (Table 11), it can be stated that the FW waste streams possess salt contents lower than that of the 2 g/L limit set by the Hungarian regulation ("5th Annex to 28); thus, they can be drained into the Hungarian sewage system.

Table 10

Component balance-based, calculated operation time to reach the solubility limit of NaCl in the concentrate and the amount of produced pure water (distillate) during the laboratory-scale HPE cycle.

Feed water type	Feed concentration, [m/m]	Maximum operation time of a cycle [h]	Distillate flowrate [L/h]	Distillate [L]
P-SW	0.0076	189	3.71	702.87
SW	0.0293	45	3.97	178.31

Table 11

Sodium Chloride equivalent calculations of waste streams using 1 $\mu\text{S}/\text{cm}$ = 0.585 mg NaCl/kg equivalency. The values are converted to m/m for easier comparison.

Feed water	UF retentate	NaCl _{eq}		
		NF retentate	RO-I retentate	RO-II retentate
FW	Concentrated natural organic matters	1255 $\mu\text{S}/\text{cm}$	613 $\mu\text{S}/\text{cm}$	23 $\mu\text{S}/\text{cm}$
		NaCl _{eq} =	NaCl _{eq} =	NaCl _{eq} =
		0.734 g/kg = 0.073 m/m	0.359 g/kg = 0.036 m/m	0.013 g/kg = 0.001 m/m
SW	Concentrated natural organic matters	73.5 mS/cm	53 mS/cm	49.5 mS/cm
		NaCl _{eq} =	NaCl _{eq} =	NaCl _{eq} =
		42.997 g/kg = 4.300 m/m	31.005 g/kg = 3.100 m/m	28.957 g/kg = 2.896 m/m

Considering SW treatment, the conductivity of NF retentate is over the calibration limit of the conductivity meter used (linearity between salt concentration and conductivity was overserved at 25 °C between 2.08 and 53.7 mS/cm range). Therefore, extremely high NaCl_{eq} could be calculated, which exceeds the solubility limit of pure NaCl. This can be explained by the existence of other salts in the NF retentate that increase the NaCl_{eq} value. Noteworthy, extremely high NaCl_{eq} could be observed for RO-I and RO-II retentates, leading to an unacceptable value; however, they contain NaCl only, which makes them feasible for further crystallization. Salt production from brines and RO rejects is feasible by different techniques such as vacuum crystallization (Efendy et al., 2023) (Nayar et al., 2019), and by obtaining further products instead of having wastewater or by-products, the economic feasibility is rather attractive.

4. Conclusion

The daily electrical power generation and consumption in Hungary were analyzed, and the period of excess electrical power production was determined. A 2-h-long interval was specified for the 5000 MW excess power generation, and 1,500,000 MJ energy was identified as an excess. Analysis was performed to evaluate the feasibility of excess energy utilization in pure water production. It can be concluded that the excess power is only part of the total solar power generation, and the excess utilization for pure water production, in case of the given example, does not provide a proper solution in the time interval when exactly the excess power is generated, so other purposes, such as electrical energy storage in batteries or energy use for water electrolysis to produce hydrogen as a gaseous fuel can be considered.

Heat pump vacuum evaporator was tested in terms of efficiency such as the coefficient of performance for heating and cooling was determined using the enthalpy values derived from the log p-h diagram. The studied equipment showed excellent performance. Heat balance analysis was carried out for the verification of the proper operation: heat release by the working fluid was absorbed by the water inside the evaporation chamber and the small amount of excess heat was released by a ventilator in the sub-cooling section.

A comparison between a heat pump vacuum evaporator and a membrane-based pure water producing system was performed to assess the viability of substituting membrane filtration techniques with HPE and enlighten HPE's feasibility in pure water production. Although HPE's role in wastewater treatment was provided by several researchers, its role in pure water production hasn't been discussed yet. This study revealed that good quality of water could be produced by one step of HPE; pure water having a conductivity of 4 and 19 $\mu\text{S}/\text{cm}$ was produced when using suspended-solid-free freshwater and seawater as feed, respectively. At lab-scale HPE showed an advantage in terms of operation: having one piece of equipment instead of several ones, therefore the cleaning and maintenance was easier than using a membrane system

having several stages.

Laboratory-scale experiments showed that using five-step membrane filtration in separate equipment one after another significantly increases the specific electrical energy consumption; meanwhile, when using only one stage of HPE, specific electric consumption could be significantly decreased to 2.31 MJ/L independently of the raw water type. Although the principle of separation between the two units is different – different selectivity of the membrane for different components in case of membrane filtration and different volatilities of feed components in case of evaporation – Flux Equivalent parameter for the characterization of HPE was created as an alternative of the widely known flux value, used for membrane processes, providing a good base for comparison. It was revealed that the flux greatly differs when treating fresh water and seawater in the membrane system. However, the Flux Equivalent is almost the same (ca. 10 L/(m²·h)) for both types of feedwaters in the case of HPE. Consequently, Flux Equivalent is not affected by the salt content of the feed water, as was observed in the membrane filtration process.

At the laboratory scale, HPE demonstrated superior performance in producing pure water with lower conductivity compared to the membrane filtration series, including UF, NF, and two-step RO. When considering freshwater as feed, lab-scale HPE could entirely replace four-step membrane filtration, delivering equivalent quality purified water while consuming 62% less electrical energy at 50% recovery. Conversely, in the case of seawater, superior quality of pure water could be achieved with one-step HPE, accompanied by an 87% reduction in electrical energy consumption. Thus, lab-scale HPE emerges as a preferable option for pure water production in terms of energy efficiency.

A comparison of specific electrical energy demand of the two studied systems was executed at both lab-scale and industrial-scale levels. Regarding industrial-scale pure water production, a theoretical calculation was performed: taking into consideration the demands of industrial-scale make-up water of an existing thermal power plant, a membrane filtration technology capable of pure water production was designed. Considering the electrical energy consumption of the designed system, hydraulic calculations and proper pump selection were performed. Aiming to produce 26 m³/h of pure water, the designed system required 25.35 MJ/m³ of specific electric energy. It can be concluded that the energy consumption of HPE to produce 1 m³ of purified water i. e. 14,850 MJ is notably higher than the consumption observed in membrane filtration systems, so the proposed membrane filtration series shall be kept as a preferable industrial solution.

Both systems were analyzed in terms of environmental impacts. GWP is greatly corresponded to SEC and by using one unit of HPE a lower GWP values were obtained compared to membrane system. According to wastewater quality and their disposability, the wastewater of freshwater treatment can be drained into the sewage system, but in case of seawater crystallization of concentrated NaCl solutions is possible. Based on our analysis, the theoretically producible water quantity is more than physically attainable by the treatment technologies, thus more options shall be considered for the utilization of excess energy generation.

CRedit authorship contribution statement

Reem Shaheen: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Krisztián Kovács:** Formal analysis, Data curation. **Edit Cséfalvay:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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Authors declare that AI tools weren't used to analyze and draw insights from data as part of the research process, nor writing the literature part of the manuscript.

Authors prove that all the text, figures and tables are based on our own experiments and created by ourselves.

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Data availability

Data will be made available on request.

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