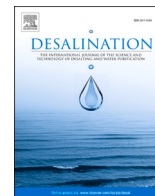


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Item Type	Article
Authors	Al-hotmani, Omer M.A.;Al-Obaidi, Mudhar A.A.R.;John, Yakubu M.;Patel, Rajnikant;Mujtaba, Iqbal
Citation	Al-hotmani OMA, Al-Obaidi MAAR, John YM et al (2022) Optimisation of hybrid MED-TVC and double reverse osmosis processes for producing different grades of water in a smart city. Desalination. 534: 115776.
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Download date	2026-03-14 13:49:06
Link to Item	http://hdl.handle.net/10454/18893



Optimisation of hybrid MED-TVC and double reverse osmosis processes for producing different grades of water in a smart city

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HIGHLIGHTS

- A hybrid system of MED-TVC and double RO is designed to yield several water types.
- Developing 5 scenarios to generate max. productivity of different types of water
- The optimisation found the optimum variables at lowest specific energy consumption.
- The disposed brine of the hybrid system is reduced to sustain a green environment.
- Results confirmed the viability of constructing the hybrid system for a smart city.

ARTICLE INFO

Keywords:

Seawater desalination
MED-TVC and double RO processes
Multi objective optimisation
Grades of water
Smart city

ABSTRACT

The integration of two or more processes in a hybrid system is one of the most desirable options to provide flexibility, interoperability and data sharing between the connected processes. Various examples of hybrid systems have been developed with seawater desalination systems such as the combination of thermal and membrane technologies. This paper focuses on the simulation and optimisation of an integrated (hybrid) system of multi effect distillation and double Reverse Osmosis (RO) processes to produce different grades of water needed in a smart city from seawater resources. The optimisation-based model investigates five scenarios to obtain the highest productivity of drinking water, irrigation water, livestock water and power plant water at the lowest specific energy consumption and with the product water salinities within the required standards. For this purpose, multi objective optimisation problem was formulated using the gPROMS (general Process Modelling System) software. The results confirm the superiority of the developed hybrid system to sustain different grades of water in a smart city.

1. Introduction

The energy-water nexus is a new term which relates the security of energy and water in one chain that simply denotes any change of any particular sector would clearly affect the associated sector and vice versa. Therefore, a consistent relationship links the energy and water resources of several applications that necessitates water production and energy conversion simultaneously. This principle has been widely used to measure the development of smart cities as it enables the correlation of sustainability, economic and environmental considerations [1]. For instance, the index of energy-water nexus has been successfully employed in the Gulf Arab Countries which induces to modify the

thermal desalination systems in a way to reduce the greenhouse gases emissions and the overall energy consumption [2]. In this regard, the success of the energy-water nexus consideration in any city means that there is good management of these sectors. Water is an essential resource to boost the energy sector whilst electric power is important to produce, treat, distribute and recycle water. Also, gases emissions from energy generation have a significant effect on climate change. However, water scarcity due to growing population and urbanization, coupled with increase in energy demand and severe climate change, are the responsible factors that are unbalancing the two sectors. Any increase in population or depleting water supplies would clearly affect the provision of energy. In other words, a finite source of water would resolve the issue of water

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<https://doi.org/10.1016/j.desal.2022.115776>

Received 30 September 2021; Received in revised form 6 April 2022; Accepted 6 April 2022

Available online 21 April 2022

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scarcity as it compensates the progressive increase of world population and basic services of energy [3,4]. Water is used intensively for agriculture and livestock and also in several industrial applications as a coolant. The world's natural resources of water are not able to meet the demands of fresh water, irrigation water and industrial water. This shows the importance of carrying out research into novel and permanent water source to cope with the challenges of energy-water nexus consideration. In other words, the continued growth of fresh water and inexpensive energy resources are the main reasons for seeking alternative options to secure these resources. Therefore, it is not surprising to see the rise of energy-water nexus research to resolve the challenges related to the energy and water circle. In this regard, the development of an efficient water desalination method or the improvement of an existing thermal desalination process would be an affordable option to meet the requirements of a smart city via balancing the elements of the relationship related the energy-water nexus. Furthermore, there is a necessity of different grades of water of different qualities for a smart city since water is an indispensable component in a smart city for its sustainability and resilience [5]. This basically requires the implementation of a sustainable paradigm of high-efficient processes especially for developed countries of growing population. On top of this, it is often recommended to apply the integration of various disciplines of water desalination processes and power systems as a possible option to ensure sustainable development of cities [6].

Desalination is an obvious solution to overcome water scarcity as it treats several sources of water such as seawater, brackish water and industrial water [7]. Ubiquitously, thermal separation methods and membrane technology are the most successful desalination methods used to desalinate seawater efficiently [8]. However, membrane technology is a more cost effective method compare to thermal one as it consumes less energy per m^3 of water produced. The typical large size RO seawater desalination system consume between 2.5 and 4.75 kWh/m^3 [9,10] compared to multistage flash desalination between 10 and 20 kWh/m^3 [11]. The hybrid system of these technologies (thermal and membrane processes) would improve the overall performance of the combined processes and provide a more sustainable single system of higher quantity and acceptable quality of drinking water [12]. The concept of hybrid system is conventionally expanded as an emerging technology to fulfil the necessity of high efficient operation. The scale-up challenges are functionally resolved by integrating several processes in a synergistic system that enables to combine the advantages of the associated processes and limit their disadvantages. This is specifically a primitive solution to tackle the shortage of fresh water in arid and semi-arid regions. However, the improved design of the hybrid system and the individual processes combined with the selection of appropriate operating conditions are vital keys for improvement purposes [13]. Therefore, raising awareness about the improvement of water desalination systems including the hybrid systems of thermal and membrane technologies is essential for a smart city to provide different grades of water.

An important question is whether water desalination methods are capable of meeting the different demands of water for various sectors or not. The hypothesis of deriving drinking water, irrigation water, as well as livestock and industrial water from a sustainable seawater desalination method is under assessment. The evaluation of this is of importance since it would initiate continuous attempts to improve the traditional seawater desalination methods. Therefore, the main concern of this study is to thoroughly analyse the potential of upgrading a hybrid system (membrane technology and thermal technology) and create several opportunities. This will be conducted by developing optimal design and operating conditions for alternative scenarios of the hybrid system to meet the consideration of energy-water nexus via an appropriate approach.

Simulation and optimisation based model developed were used to optimise the RO process and quantify the necessity of different types of water demand (quantity and quality). For instance, an integer nonlinear

programming (MINLP) problem was intensively employed to create a feasible superstructure of RO process based model that can entail different scenarios ensuing in a plethora of optimum solutions for decision makers [14]. Some successful examples of the recent research of RO process considering energy-water nexus based seawater desalination are outlined below.

The energy requirements and profitability of an integrated wind turbine-powered RO process treating brackish water are estimated by Clayton et al. [15] using a spatially resolved performance and economic technique. In this regard, several parameters such as total dissolved solids, capital and operation costs of wind and desalination facilities and wind speeds were considered. From the concept of energy-water nexus, this study asserted the economic feasibility of the integrated system in some regions of west Texas.

Kjellsson and Webber [16] examined the feasibility of solar photovoltaic-powered RO desalination system used to desalinate brackish water. The process analysis was carried out based on the brackish water quality, depth to brackish groundwater, and solar radiation to determine the best regions in Texas of the highest economic performance. This in turn showed that the north western region of Texas is of the highest potential for solar powered desalination. This is due to low salinity of brackish water and comparatively high-sunshine supply.

Pan et al. [9] addressed in a thorough study the energy-water nexus to cover the energy, economic and environmental facets for a large-scale brackish water desalination plant using RO process. The influences of key parameters on the energy-water efficacy, water production costs and environmental effects were discussed besides illustrating the trade-off between kinetics (productivity) and energetics (energy consumption) of RO and CDI. Results confirmed the importance hybridizing for energy-efficient brackish water desalination, co-removal of specific components and sustainable brine management with advanced operation to mitigate the water production cost and the environmental effects.

Di Martino et al. [17] developed an optimisation framework based on a surrogate model for a single stage RO process and looked at different water sources and input energy. Specifically, they varied the RO process design by changing the number of modules and input operating conditions to supply different grades of water for a fixed inlet seawater salinity. The model was applied to regions of water scarcity of South-Central Texas in three distinct scenario analyses and concluded a set of optimal solutions for each scenario. The study affirmed the superiority of implementing modelling and optimisation of RO desalination system based food-energy-water nexus considerations.

Also, several studies have been published in the open literature that have looked at the modelling, simulation and optimisation of thermal water desalination technologies. The well-known thermal methods of desalination are multi stage flash and multi effect distillation comprising thermal vapour compression. The published research of thermal desalination methods focused on resolving the shortcomings of high specific energy consumption and high treatment cost [18,19].

Liu et al. [20] evaluated the energy consumption of constructing and operating the Phase III of the first rank typical thermal multi effect seawater desalination plant in China (9.13 million m^3) to explore the nexus between energy and water resources that would have a critical role in resources conservation. The results showed the a relatively large amount of energy of $18.02 \text{ kWh}/\text{m}^3$ was required for the production of fresh water. Furthermore, the improvement of seawater project would implicitly include a further increase of energy consumption. More importantly, the optimisation of energy and mixing of energy sources are inevitable options to balance the performance indicators of efficacy, productivity and water production cost. From the energy-water nexus viewpoint, it was recommended to replace thermal power with low-grade steam and waste heat generated from a thermal power plant and joining specific streams of the associated thermal power and seawater desalination plants to mitigate the overall energy consumption.

Regarding the innovative designs of hybrid systems of thermal

desalination and RO processes, several examples are discussed below.

Gabriel et al. [2] developed a non-linear MINLP optimisation framework to ascertain the superstructure of dual purpose plant of steam turbine utility network, electric power and water production systems. The intention was to allocate an optimal superstructure to integrate the heat and steam level of the turbine network and at the same time optimising the hybrid system of multi effect desalination and thermal vapour compression (MED-TVC) and RO process. In this regard, different scenarios were developed to maximise the generated power of the turbine network, maximise water production and to identify an ideal case of fixed water demand without restricted generated power.

Sadri et al. [21] studied the irreversibility of a hybrid system of MED-TVC and RO processes with calculation of chemical and physical exergy destruction. The exergy performance of this system was evaluated and the optimum point was determined via a multi objective optimisation based genetic algorithm. The important finding of this study was the evaluation of trade-off between the associated processes that aided in the selection of the most efficient hybrid system of the highest exergetic efficiency.

Al-Aboosi and El-Halwagi [22] established a design optimisation framework of MINLP to improve water production for shale gas production and integrate multiple energy sources of fossil fuels (conventional) with solar energy (renewable) to produce electricity. The first water treatment plant of MED is operated via solar energy or indirect supply whilst the energy produced was used to operate the second water treatment plant of RO system without the need of grid electricity. The final optimisation identified the maximum annual profit of the system via the selection of the best mix of solar energy, thermal storage and fossil fuel taking into account solar diurnal fluctuations.

A novel design of multi effect distillation (MED) and double Reverse Osmosis (RO) process of two configurations to purify seawater was developed by Al-hotmani et al. [23]. Two RO processes were used as upstream and downstream processes including the Permeate Reprocessing RO (PRRO) and Retentate Reprocessing RO (RRRO), respectively. The results confirmed the production of drinking water within the standards using PRRO+MED-TVC + RRRO whilst a distilled water of high quality was produced from PRRO+MED-TVC + PRRO.

The above mentioned studies have addressed feasible methods of improving the operation of individual and hybrid system of MED-TVC and RO processes. In this regard, the optimisation of the MED-TVC and RO process has accomplished the production of only drinking water. However, the basics of energy-water nexus have not been implicitly practiced especially for the hybrid system of MED-TVC and RO processes. As far as the authors are aware, a holistic energy-water nexus approach has not yet been investigated in terms of meeting local water demand of a smart city using hybrid system of MED-TVC and RO process. In respect of producing multi-grade water, Martino et al. [24] considered renewable sources of energy in RO process but with simple surrogate-based RO process model. And most recently, Martin et al. [25] presented a perspective paper highlighting what needs to be done in a smart city in terms of energy-water-environment nexus. However, there was no numerical examples presented on the production of different grades of water required in a smart city. Thus, using model based optimisation technique, this study aims on developing several scenarios of hybrid system of MED-TVC and double RO processes for meeting the demand of different grades of water in a smart city at reduced energy consumption. The demands of drinking water, irrigation water, water for livestock, distilled water, hospital and lab water and power plant water are considered.

Finally note, the performance of desalination systems was measured in the past against any the following parameters [26,27]:

a) Performance Ratio (*PR*) or Gained Output Ratio (*GOR*): defined as a ratio between the amount of distillate produced and the steam supplied as heating medium.

- b) Specific total heat transfer area (*sA*): defined as the ratio between the total heat transfer area and the amount of distillate produced.
- c) Recovery Ratio (*RR*): defined as the ratio between the amount of distillate produced and the feed seawater flow rate.
- d) Specific energy consumption (*SEC*): defined as the ratio between the total heat and the total amount of distillate produced.
- e) Total Annualised Cost (*TAC*): defined as sum of annualised capital cost and annualised operating cost.
- f) Specific Total Annualised Cost (*sTAC*): defined as a ratio of total annualised cost and the total amount of distillate produced.

Whilst each of the above criteria has its own merits, in this work, we have chosen *SEC* as the criteria for measuring the performance of the hybrid process.

2. Description of integrated of MED-TVC and double RO processes

An integrated hybrid system of MED-TVC and double RO processes, developed and presented for the first time by the same authors [28], is shown schematically in Fig. 1. The feed seawater (stream 1 of 39,000 ppm and 25 °C) is fed to the permeate reprocessing RO process and MED system via streams 2 and 3 respectively. The first RO process (PRRO) is designed to treat 5011.2 m³/day of seawater. Two different configurations of the RO process are used including the permeate reprocessing and retentate reprocessing designs on the right and left sides of the MED system. To fulfil the requirement of a driving pressure throughout the module, a high-pressure pump (50 atm) of 85% efficiency is used for each RO process. In this regard, three blocks of parallel pressure vessels (each pressure vessel holds eight spiral wound polyamide thin-film composite Toray membranes connected in series) are connected in 20, 15, and 8 PVs configuration in the first RO process. However, 40, 30, and 16 PVs configuration is used in the retentate reprocessing design of the second RO process. The permeate reprocessing design is important for producing low salinity water of low throughput in the third block by polishing the collected permeate of the first and second blocks. This also includes the use of an energy recovery device (ERD, 80% efficiency) between the second and third blocks to enable absorption of the high energy from the disposed stream of the 2nd block and transfer it to the low pressure permeates of the first and second blocks. This would be enough to raise the permeate pressure and ensure safe operation in the third block of RO process. On the other hand, the use of a higher number of PVs in the retentate reprocessing configuration is essential to deal with the high inlet flowrate of seawater (retentate) collected from the MED system and the first RO process. Thus, the advantage of using the second RO process is to further polish the collected brine of the first RO process and MED system to obtain higher productivity. Furthermore, utilising the second RO process of retentate reprocessing would decrease the total quantity of discharged brine into the sea, which specifies as one of the merits of this environmentally friendly novel design. However, it is fair to confirm that such design of RO process produces a higher salinity of water compared to the permeate reprocessing design.

The second process of the hybrid system, MED system, contains 10 effects connected as forward design with thermal vapour compression (TVC) as an external source of steam. The steam flow rate, pressure and temperature are 8 kg/s, 1300 kPa, and 70 °C, respectively. Specifically, the effect constitutes a spray nozzle, evaporator and demister. Also, seawater is fed to preheater to maintain the inlet temperature of the first effect (top brine temperature) at 70 °C. The freshwater of the first RO process (stream 4) combines with the distillate (very low salinity water) of MED system (stream 5) in mixer 2 to form stream 6. Stream 6 is then connected to the permeate of the second RO process (stream 8) in mixer 3 to form the final product line of stream 9. Furthermore, the rejected brine of MED (60,000 ppm and 40 °C of brine salinity and temperature respectively), is connected to the retentate of the first RO process in mixer 1 to constitute the inlet feed stream of the second RO process. The

Table 2
 Characteristics of inlet and selected product water streams of MED-TVC and double RO processes.

Stream number	Description	Flow rate (m ³ /day)	Salinity (ppm)	Water type
1	Inlet seawater to the hybrid system	21,878.812	39,000	Feed seawater
2	Inlet seawater to PRRO process	5011.2	39,000	-
3	Inlet seawater to MED-TVC system	16,867.612	39,000	-
4	Product water of PRRO process	1867.326	13.67	Hospital and lab water
5	Rejected brine of PRRO process	3143.874	62,156.2	-
6	Rejected brine of MED-TVC system	10,963.702	60,000	-
7	Product water of MED-TVC system	5903.533	0	Distilled water
8	Inlet water to RRRO process	14,107.576	60,493.84	-
9	Product water of RRRO process	750.402	2973	Power plant water
10	Blended fresh water of PRRO process and MED-TVC system	7770.859	10.88	Hospital and lab water
11	Product water of hybrid system of PRRO+MED-TVC + RRRO processes	8521.26	278.66	Drinking water
12	Disposed stream of brine water from RRRO process.	12,976.2	63,820.2	Disposed stream: Brine water

requirements of different applications of a smart city. The specifications of these types of water and process optimisation for each individual scenario are discussed below.

4.1. Scenario 1: drinking water

The simulation of the hybrid system of MED-TVC and double RO processes (presented by [23]) confirms the production of drinking water of 8521.26 m³/day with salinity of 278.66 ppm (Table 2). There is a clear diverge between TDS guidelines issued by different panels of tasters labelling water that is mainly related to personal preference. Australian Drinking Water Guidelines regard good quality drinking water to be of salinity level of less than 600 ppm [30]. The WHO does not have a fixed standard of drinking water. Nevertheless, an aesthetic guideline value of 200 ppm has been outlined in the published guideline of 2017 [31]. Thus, it has been decided to maintain the original design of MED-TVC and double RO processes and produce drinking water with salinity of less than 250 ppm.

In order to produced water of acceptable salinity from the original hybrid system, the optimisation will be carried out to minimise the overall specific energy consumption (the objective function) whilst maintaining the product salinity of lower than 250 ppm. In this regard, the growth of water productivity would minimise the overall energy consumption of the hybrid system.

The optimisation of MED-TVC intends to minimise the total specific energy consumption by identifying the optimal operating conditions of the MED-TVC and double RO processes. These include the optimal steam temperature and mass flow rate of MED-TVC, the inlet feed flow rate and pressure of PRRO process and the inlet pressure of RRRO process. The optimisation has considered the lower and upper limits of feed flow rate for each membrane in the RO processes as recommended by the manufacturer whilst maintaining the salinity of product water to be lesser than 250 ppm to satisfy the best standards of drinking water.

The optimisation problem of the hybrid system of MED-TVC and double RO processes is mathematically expressed as follows.

$$Q_{f(PRRO)}, P_{f(PRRO)}, M_{s(MED-TVC)}, T_{s(MED-TVC)}, P_{f(PRRO)}$$

Min SEC_{Hybrid system}

Subject to: Equality constraints: MED-TVC and double RO processes model

Inequality constraints:

a) lower and upper limits of feed flow rate and pressure of the PRRO and RRRO processes

$$(1742.394 \text{ m}^3/\text{day}) Q_{f(PRRO)}^L \leq Q_{f(PRRO)} \leq Q_{f(PRRO)}^U (9268.800 \text{ m}^3/\text{day})$$

$$(3484.788 \text{ m}^3/\text{day}) Q_{f(RRRO)}^L \leq Q_{f(RRRO)} \leq Q_{f(RRRO)}^U (18,537.60 \text{ m}^3/\text{day})$$

$$(10 \text{ atm}) P_{f(PRRO)}^L \leq P_{f(PRRO)} \leq P_{f(PRRO)}^U (81 \text{ atm})$$

$$(10 \text{ atm}) P_{f(RRRO)}^L \leq P_{f(RRRO)} \leq P_{f(RRRO)}^U (81 \text{ atm})$$

$$(6 \text{ kg/s}) M_{s(MED-TVC)}^L \leq M_{s(MED-TVC)} \leq M_{s(MED-TVC)}^U (10 \text{ kg/s})$$

$$(60 \text{ }^\circ\text{C}) T_{s(MED-TVC)}^L \leq T_{s(MED-TVC)} \leq T_{s(MED-TVC)}^U (90 \text{ }^\circ\text{C})$$

b) lower and upper limits of feed flow rate of each membrane module in the PRRO and RRRO processes

$$(87.119 \text{ m}^3/\text{day}) Q_{f(\text{membrane-PRRO})}^L \leq Q_{f(\text{membrane-PRRO})} \leq Q_{f(\text{membrane-PRRO})}^U (463.44 \text{ m}^3/\text{day})$$

$$(87.12 \text{ m}^3/\text{day}) Q_{f(\text{membrane-RRRO})}^L \leq Q_{f(\text{membrane-RRRO})} \leq Q_{f(\text{membrane-RRRO})}^U (463.44 \text{ m}^3/\text{day})$$

c) A salinity of freshwater of the hybrid system is constrained within equal or lower than 250 ppm

End-point constrain:

$$C_{p(\text{Hybrid system})} \leq 250 \text{ ppm}$$

The process model is built within the optimisation framework in gPROMS software. Fig. 2 illustrates the calculation sequence for the simulation and optimisation problem. The calculation sequence starts with an initial estimate of the vector *n* (the decision variables). For each iteration, (of the OPTIMISER) optimisation requires full solution of the model equations to evaluate the objective function *J*, the constraints (*h* and *g*) and the gradients of (*J*, *h*, *g*) with respect to all the decision variables (*x*). This information is then passed to the OPTIMISER. The OPTIMISER then takes a step in *n* decision variables, and the process is repeated until convergence is achieved within an acceptable accuracy. Note, the model equations can be a set of linear or nonlinear Algebraic Equations (AEs) depending on the process. Further details can be found in Villafafila and Mujtaba [32], Mujtaba [33] and Al-Obaidi et al. [34].

Table 3 shows the optimal values of control variables that must be implemented in the integrated processes of the hybrid system to obtain

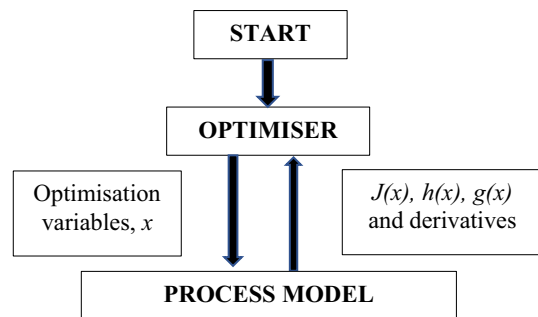


Fig. 2. Computational sequence for simulation and optimisation. Adapted from [32].

Table 3 Optimal operating conditions of PRRO and RRRO processes and MED-TVC and optimal performance indicators compared to the simulation results of the hybrid system for the production of drinking water.

Applied method	Optimal conditions					Performance indicators													
	Qf PRRO (m ³ /day)	Qf RRRO (m ³ /day)	Pf PRRO (atm)	Pf RRRO (atm)	Ms (kg/s)	Ts (°C)	Qf MED-TVC (m ³ /day)	Productivity PRRO (m ³ /day)	Productivity MED-TVC (m ³ /day)	Productivity RRRO (m ³ /day)	Total productivity of hybrid system (m ³ /day)	SEC PRRO (kWh/m ³)	SEC MED-TVC (kWh/m ³)	SEC RRRO (kWh/m ³)	Total SEC Hybrid system (kWh/m ³)	Total %Rec Hybrid system	Total disposed flow rate RRRO (m ³ /day)	Salinity of freshwater of hybrid system (ppm)	
Simulation (base case of Al-hotmani et al. [23])	5011.2	13,726.60	50	50	8.0	70	16,867.24	1867.32	5903.53	750.40	8521.26	2.62	17.99	30.29	15.70	33.62	12,976.2	278.66	
Optimisation	9268.8	15,279.50	52.8	81	6.0	60	13,313.91	2342.61	4659.86	6783.92	13,786.4	4.05	15.08	6.04	8.756	59.55	8495.58	249.98	
Benefits of total energy saving = 44.22%	Benefits of total water productivity = 61.7%																		
	Benefits of total disposed brine = 34.5%																		

the objective function (lowest SEC). This is specifically demanding an increase in feed flow rate of inlet seawater to the PRRO and RRRO processes, a slight increase in the pressure of PRRO process, a maximum feed pressure of RRRO process and the lowered values of supplied steam mass flow rate and temperature of MED-TVC system. In this regard, Table 3 shows a comparison between the original simulation results of the hybrid system of MED-TVC and double RO processes (not-optimised values of [23]) and the optimisation results. It can be seen that the optimisation at a given seawater salinity and temperature (39,000 ppm and 25 °C) has reduced considerably the total specific energy consumption of the hybrid system by 44.2%, an increase of water productivity by 61.7%, a decrease of disposed brine flow rate from RRRO process by 34.5%, whilst maintaining the water salinity at around 250 ppm. The increase of feed pressure at lower feed flow rate is the main reason for increasing the water recovery (productivity) and achieving the promising energy saving of 44.2% due to increasing the driving force of water permeation through the membrane pores and increasing the residence time of seawater inside the modules [35]. Also, lowering the mass flow rate and temperature of supplied steam of MED-TVC is profitable to obtain the optimal performance for the total hybrid system. Although the improvement of distillate of MED-TVC requires an increase of both mass flow rate and temperature of steam [18,36], the optimisation selected the lowest permitted values of mass flow rate and temperature of steam to quantify the required salinity of the whole hybrid system (250 ppm) where the distillate of MED is blended with fresh water of PRRO process (Fig. 1). The reason behind this, any reduction of mass flow rate of motive steam of the TVC system would reduce the vapour temperature and evaporation rate in the first effect of the MED. Therefore, the brine flow rate of MED system increases that mixed with the brine of PRRO process to be treated in the second RRRO process. In other words, the optimisation has considered the inlet feed flow rate of the RRRO process by reducing the mass flow rate and temperature of motive steam of MED-TVC system. Another important point to be noticed is the decrease of the inlet flow rate of seawater by 21% of the MED-TVC system as an optimal parameter. Reducing the cooling seawater flow rate causes an increase of seawater temperature and condenser pressure inside each effect of the MED [37]. This in turn promotes the productivity of distilled water and reduce the level of brine due to enhancement of the evaporation rate. Seemingly, this would compensate the reduction of motive steam temperature as indicated in the optimisation results of Table 3. Furthermore, an important feature of optimising the hybrid system of MED-TVC and double RO processes is the reduction of disposed brine flow rate to the sea, which benefits the environment.

4.2. Scenario 2: distilled water and hospital or lab water

The simulation of the hybrid system of MED-TVC and double RO processes of Al-hotmani et al. [23] confirmed that the MED-TVC system produces high quality water of zero salinity at a rate of 5903.53 m³/day (stream 7 of Fig. 1) whilst producing low salinity water of 13.67 ppm at a rate of 1867.32 m³/day from the PRRO process (stream 4). The main intention of this section is to introduce a new scenario to produce distilled water and hospital or lab water by generating a new design of the hybrid system from the one developed by Al-hotmani et al. [23] (Fig. 1). The updated hybrid design considers only the MED-TVC and PRRO process to entail the required water and remove the last RRRO process. Fig. 3 shows the schematic diagram of the proposed new design of the hybrid system. More specifically, the proposal here is to simply relax mixer 2 to permit the production of distilled water from the MED-TVC system and hospital or lab water from the PRRO process. Accordingly, the updated design would introduce stream 4 as a product stream of hospital or lab water and stream 7 as a product stream of distilled water as shown in Fig. 3. In this regard, the updated design would also provide a new source of water from the second RRRO process with different quality and quantity to be investigated in the optimisation

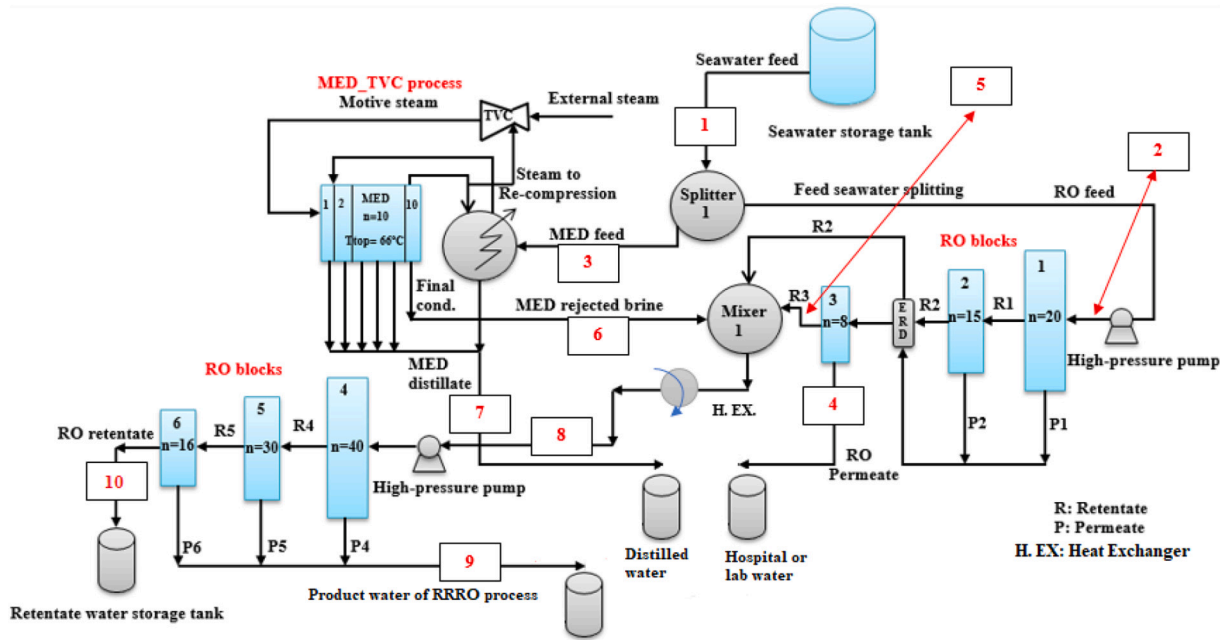


Fig. 3. Updated design of MED-TVC and double RO processes to generate distilled water and hospital or lab water.

section.

To maximise the productivity (objective function) of the two streams of hospital or lab water and distilled water, streams 4 and 7 respectively, at the lowest energy consumption whilst maintaining the dissolved salts at 10 ppm for the hospital or lab water, two optimisation cases were carried out to fulfil these requirements and to investigate the specifications of the associated third product water from RRRO process. The inlet water specifications of RRRO process is related to the associated brine water of the integrated MED-TVC and PRRO processes as they are considered the main sources of inlet water.

The two optimisation problems for this scenario are described below with the detailed results.

The first optimisation problem focuses on maximising the total productivity of MED-TVC as the main objective function by adjusting the control variables of mass flow rate and temperature of the motive steam. Maximising the productivity means lowering the related total energy consumption. The optimisation of MED-TVC can be mathematically expressed as follows.

$$Max \quad Productivity_{MED-TVC}$$

$$M_{s(MED-TVC)}, T_{s(MED-TVC)}$$

Subject to: Equality constraints: MED-TVC model
 Inequality constraints:

- a) lower and upper limits of feed flow rate and pressure of the PRRO and RRRO processes

$$(6 \text{ kg/s}) M_{s(MED-TVC)}^L \leq M_{s(MED-TVC)} \leq M_{s(MED-TVC)}^U (10 \text{ kg/s})$$

$$(60 \text{ }^\circ\text{C}) T_{s(MED-TVC)}^L \leq T_{s(MED-TVC)} \leq T_{s(MED-TVC)}^U (90 \text{ }^\circ\text{C})$$

The optimisation problem is solved at fixed seawater salinity and temperature of 39,000 ppm and 25 °C, respectively. Table 4 shows the simulation and optimisation results of MED-TVC including the optimal control variables and the associated performance indicators of the system. Also, the calculation of specific energy consumption for the simulation and optimisation with the energy saving are outlined in Table 4.

For a single MED-TVC system, it can be seen that the optimisation of MED-TVC increases the motive steam mass flow rate besides reducing the motive steam temperature to deliver higher quantity of distilled water. These result are corroborated with the findings of Manesha et al. [36] who confirmed the necessity of an increase of mass flow rate of motive steam to generate higher productivity of fresh water. Also, it can be noticed that the inlet seawater flow rate has been increased by 31.36% to correspond with the increase of fresh water productivity. This is the opposite result of inlet seawater flow rate of the MED-TVC system compared to the first scenario. Basically, an increase of inlet seawater flow rate (cooling water) is important for a fixed number of effects of MED-TVC system, to improve the overall productivity (the objective function) since this would decrease the condenser seawater temperature in each effect that causes an increase in the driving force of evaporation besides increasing the temperature droplet along each effect (Eq. (5) in Table A.1 of Appendix A) [38].

The second optimisation problem focuses on delivering maximum productivity of hospital and lab water from the PRRO process (stream 4).

Table 4
 Optimal inlet operating conditions of MED-TVC and optimal performance indicators for the production of distilled water.

Applied method	Optimal conditions of MED-TVC system		Performance indicators				
	Ms (kg/s)	Ts (°C)	Q _f MED-TVC (m ³ /day)	SEC MED-TVC (kWh/m ³)	Salinity of freshwater of MED-TVC (ppm)	Productivity MED-TVC (m ³ /day)	Disposed flowrate MED-TVC (m ³ /day)
Simulation (base case of Al-hotmani et al. [23])	8	70	16,867.24	17.988	0.0	5903.533	10,963.70
Optimisation	10	60	22,158.17	15.084	0.0	7755.36	14,402.79
Benefits of total energy saving = 16.14%			Benefits of total water productivity = 31.36%			Benefits of total disposed brine = 31.36%	

The control variables of the PRRO process including the feed flow rate and pressure are moderated to gain the objective function whilst constraining the product water salinity to be lower than 10 ppm. The optimisation problem of PRRO process is mathematically expressed as follows:

$$\text{Max } \text{Productivity}_{PRRO} \\ Q_{f(PRRO)}, P_{f(PRRO)}$$

Subject to: Equality constraints: PRRO processes model

Inequality constraints:

- a) lower and upper limits of feed flow rate and pressure of the PRRO and RRRO processes

$$(1742.394 \text{ m}^3/\text{day}) Q_{f(PRRO)}^L \leq Q_{f(PRRO)} \leq Q_{f(PRRO)}^U (9268.800 \text{ m}^3/\text{day})$$

$$(10 \text{ atm}) P_{f(PRRO)}^L \leq P_{f(PRRO)} \leq P_{f(PRRO)}^U (81 \text{ atm})$$

- b) lower and upper limits of feed flow rate of each membrane module in the PRRO process

$$(87.119 \text{ m}^3/\text{day}) Q_{f(\text{membrane-PRRO})}^L \leq Q_{f(\text{membrane-PRRO})} \leq Q_{f(\text{membrane-PRRO})}^U (463.44 \text{ m}^3/\text{day})$$

- c) A salinity of hospital and lab water of PRRO process is constrained to equal or lower than 10 ppm

End-point constraint:

$$C_{p(PRRO)} \leq 10 \text{ ppm}$$

The optimisation problem is solved at fixed seawater salinity and temperature of 39,000 ppm and 25 °C, respectively. The optimisation results are given in Table 5 together with the simulation results of the base case of Al-hotmani et al. [23]. It can be seen that the optimisation has gained a lower productivity than the simulation one which can be considered as a specific case for such design of RO system. Thus, the optimisation attempts to find the maximum productivity of the PRRO process whilst maintaining the fresh water salinity at lower than 10 ppm (compared to the simulation value of 13.67 ppm of stream 4 of the PRRO process) and maintaining safe operation by ensuring the feed flow rate to be within the upper and lower limits of the membranes. Also, it was important to utilise a lower feed pressure to obtain a lower salinity compared to the simulation one (13.67 ppm). This resulted in a decrease of water productivity and an increase in the specific energy consumption by 8.28% due to the reduction of water permeation through the membranes. Also, it can be noticed that the inlet seawater feed flow rate has been increased by 18.41%. It is important to realise that increasing feed flow rate inside the membrane modules of the PRRO process would enhance the mass transfer coefficient and therefore would enhance the quality of water passing the membrane's pores. The optimisation has also shown the increase of the brine flow rate of the PRRO process by 32.14% whilst reducing its salinity by 10.38%. In other words, the improvement of product salinity of the PRRO process has a penalty of

mitigating the productivity and elevating the energy consumption.

Finally, the two optimisation cases discussed above have already controlled the characteristics of seawater entering the RRRO process. Therefore, the current simulation has obtained new inlet operating conditions of this process compared to the original ones of Al-hotmani et al. [23]. A new scenario of water type will be developed in the next section for the RRRO process.

4.3. Scenario 3: power plant water

The main intension of this section is to introduce a new scenario to produce power plant water from the hybrid system of MED-TVC and double RO processes shown in Fig. 1. The simulation of the original design of hybrid system of MED-TVC and double RO processes indicates the specification of water, from the second RRRO process, in stream 9 of 2973 ppm and 750.402 m³/day. Thus, there is scope to refine the specification of this water via optimisation to permit the production of power plant water from the second RRRO process of salinity equal or less than 2500 ppm. This guideline was elaborated by the Electric Power Research Institute (EPRI) in 2003 [43]. However, the original design of the hybrid system needs to be altered by relaxing mixer 3 whilst maintaining mixer 2 (Fig. 1). This in turn would provide stream 9 as a product water of RRRO process whilst maintaining the blended water of MED-TVC and PRRO process as another source of high quality water (stream 10) that can be used as hospital and lab water (Fig. 4). Accordingly, the updated design would introduce stream 9 as a product stream of power plant water and stream 10 as a hospital or lab water. Fig. 4 shows the new modified design of the hybrid system.

The optimisation of this hybrid design will be carried out to produce a high quantity (Productivity_{RRRO}) of power plant water at a lower energy consumption compared to the simulation one of Al-hotmani et al. [23] whilst constraining the salinity of product water equal to or less than 2500 ppm. As mentioned above, the inlet feed flow rate and salinity of seawater entering the RRRO process will be specified based on the optimal operating conditions of MED-TVC and PRRO process depicted in Tables 4 and 5, respectively, for the optimisation of distilled water and hospital or lab water as given in Table 6. Furthermore, the inlet temperature of the seawater entering RRRO process will be optimised to sustain the objective function of the process optimisation. In this regard, it would be useful to increase the inlet temperature to more than 25 °C (seawater temperature) to increase the productivity. Therefore, the heat exchanger in stream 8 will be used to maintain the optimisation temperature. The maximum seawater feed temperature, recommended by the manufacturer, that RO process can stand is 45 °C (Table 1). Furthermore, it can be useful to exploit the high temperature of brine (40 °C) disposed from the MED system.

Accordingly, the optimisation problem of RRRO process can be mathematically expressed as follows:

$$\text{Max } \text{Productivity}_{RRRO \text{ process}} \\ P_{f(RRRO)}, T_{f(RRRO)}$$

Subject to: Equality constraints: RRRO process model

Inequality constraints:

Table 5

Optimal inlet operating conditions of PRRO process and optimal performance indicators for the production of hospital or lab water.

Applied method	Optimal conditions		Performance indicators						
	Q _{f PRRO} (m ³ /day)	P _{f PRRO} (atm)	Productivity _{PRRO} (m ³ /day)	SEC _{PRRO} (kWh/m ³)	%Rec _{PRRO} (-)	%Rej _{PRRO} (-)	Salinity of product water _{PRRO} (ppm)	Disposed flowrate _{PRRO} (m ³ /day)	Brine salinity _{PRRO} (ppm)
Simulation (base case of Al-hotmani et al. [23])	5011.20	50	1867.32	2.621	37.26	99.965	13.67	3143.87	62,156.20
Optimisation	5934.06	46.597	1779.57	2.838	29.99	99.975	9.68	4154.48	55,701.54
Benefits of total energy saving = -8.28%			Benefits of total water productivity = -4.69%				Benefits of total disposed brine = 32.14%		

energy consumption by 47.89% compared to the original results of Al-hotmani et al. [23]. However, it is important to note that achieving these benefits has a penalty of increasing the flow rate of disposed water by more than 23%.

It is also important to note that the product water of stream 10 (product water of MED-TVC and PRRO process) has gained new characteristics after optimising the related processes individually. Specifically, the productivity of stream 10 has been increased from 7770.859 m³/day of Al-hotmani et al. [23] to 9534.937 m³/day whilst decreasing its salinity from 10.88 ppm to 9.94 ppm i.e. an enhancement of 22.7% and 8.64% in productivity and salinity, respectively.

4.4. Scenario 4: water for livestock

This section utilises the possible method of producing water, of less than 1000 ppm, as affirmed by Pick [39] for livestock use, from the hybrid system of MED-TVC and double RO processes. To achieve this goal, the optimisation method presented in Section 4.3 to produce power plant water will be used to produce water for livestock at its maximum productivity. This is achieved by relaxing mixer 3 and therefore two product streams will be introduced; the product water of RRRO process and the blended water stream of MED-TVC and PRRO process. In this regard, the optimal operating conditions of the MED-TVC system (given in Table 4) and the optimal operating conditions of PRRO process (given in Table 5) will be used to determine the inlet conditions of feed flow rate and salinity of RRRO process (given in Table 6). These values are considerably changed when compared to those of Al-hotmani et al. [23]. Thus, the RRRO process will be optimised to investigate the appropriate operating conditions of feed pressure and temperature to gain a salinity of 1000 ppm of product water in stream 9 shown in Fig. 5. The seawater temperature of RRRO process has been included in the optimisation to raise the water productivity. A heat exchanger is suited in stream 8 to manage the required seawater temperature. However, it should not exceed the maximum recommended operating temperature of the membranes. In this regard, the outlet brine of MED-TVC can also be used to raise the seawater temperature of RRRO process. Undoubtedly, applying an optimisation attempt on the RRRO process to elevate the productivity would reduce the specific energy consumption of RRRO process.

The optimisation problem of RRRO processes can be mathematically expressed as follows:

$$\text{Max } Productivity_{RRRO\text{ process}} \\ P_{f(RRRO)}, T_{f(RRRO)}$$

Subject to: Equality constraints: RRRO process model
Inequality constraints:

- a) lower and upper limits of feed pressure of the RRRO process

$$(10 \text{ atm}) P_{f(RRRO)}^L \leq P_{f(RRRO)} \leq P_{f(RRRO)}^U (81 \text{ atm})$$

$$(25 \text{ }^\circ\text{C}) T_{f(RRRO)}^L \leq T_{f(RRRO)} \leq T_{f(RRRO)}^U (45 \text{ }^\circ\text{C})$$
- b) lower and upper limits of feed flow rate of each membrane module in the RRRO process

$$(87.12 \text{ m}^3/\text{day}) Q_{f(\text{membrane-RRRO})}^L \leq Q_{f(\text{membrane-RRRO})} \leq Q_{f(\text{membrane-RRRO})}^U (463.44 \text{ m}^3/\text{day})$$
- c) The salinity of product water of the RRRO process is constrained to 1000 ppm or lower and the specific energy consumption to be lower than of Al-hotmani et al. [23].

End-point constrain:

$$C_{p(RRRO \text{ process})} \leq 1000 \text{ ppm}$$

$$SEC_{(RRRO \text{ process})} < 30.285$$

The results of the optimisation of the RRRO process for the production of water for livestock are shown in Table 7. Also shown in the table are the inlet conditions, performance indicators and the simulation results of Al-hotmani et al. [23]. Again, the product water of stream 10 (blended water of MED-TVC and PRRO process) has gained another water type after optimising the related processes individually to produce hospital or lab water as discussed in Section 4.3.

Table 7 shows the importance of exploiting the feed pressure of the RRRO process whilst maximising the seawater temperature up to the

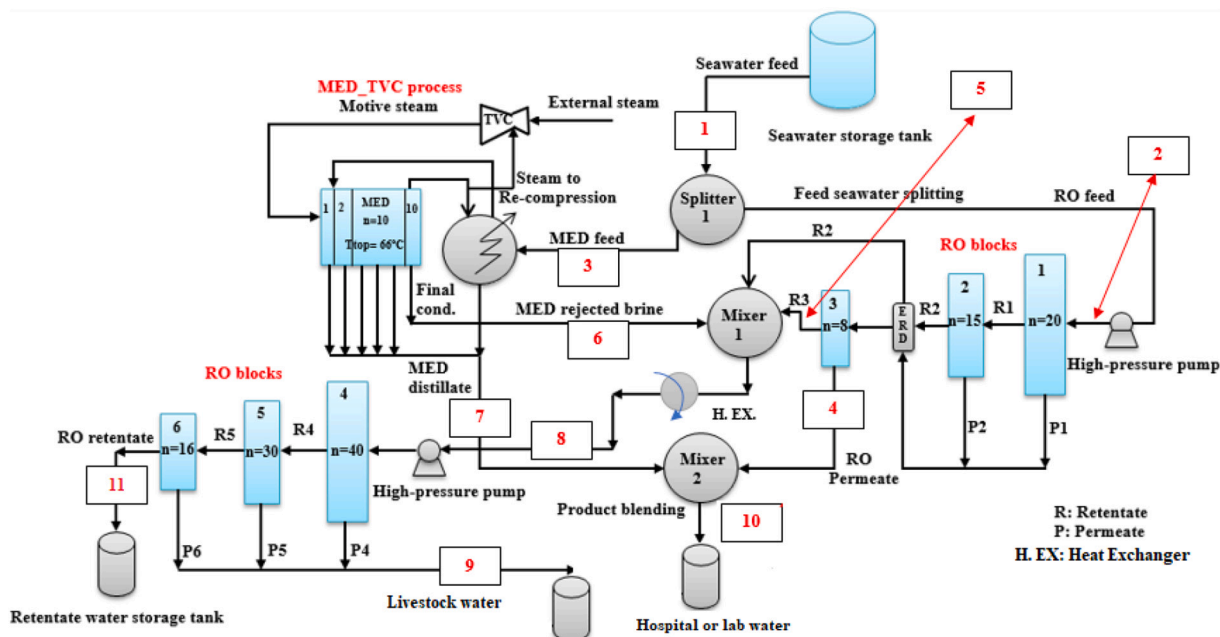


Fig. 5. Updated design of MED-TVC and double RO processes to generate water for livestock and hospital or lab water.

Table 7

Optimal inlet operating conditions of RRRO processes and optimal performance indicators for the production of water for livestock.

Applied method	Inlet conditions of RRRO process		Optimal conditions		Performance indicators						
	Q_f RRRO (m ³ /day)	C_f RRRO (ppm)	P_f PRRO (atm)	T_f RRRO (°C)	Productivity RRRO (m ³ /day)	SEC RRRO (kWh/m ³)	%Rec RRRO (-)	%Rej RRRO (-)	Salinity of product water RRRO (ppm)	Disposed flowrate RRRO (m ³ /day)	Brine salinity RRRO (ppm)
Simulation (base case of Al-hotmani et al. [23])	13,726.60	60,493.84	50	25	750.40	30.285	5.46	95.08	2973.07	12,976.20	63,820.22
Optimisation	18,057.89	59,009.12	75.36	45	7075.29	6.369	39.18	98.31	996.97	10,982.59	96,382.14
Benefits of total energy saving = 78.97%				Benefits of total water productivity = 842.86%				Benefits of total disposed brine = 15.36%			

maximum allowed value of 45 °C. The simultaneous actions of these operating conditions is enough to reduce the salinity of the product from 2973 ppm to less than 1000 ppm. This is quite different than the optimisation results of the power plant water that demonstrated a significant increase of only seawater temperature. This in turn has resulted in an extreme increase of productivity of water for livestock by around 843% whilst reducing the specific energy consumption of the RRRO process by 78.97% compared to the original simulation results of Al-hotmani et al. [23]. Moreover, the optimisation of this scenario has showed another important advantage of limiting the total disposed water from the RRRO process which entails a reduction of 15.36% compared to the scenario of power plant water.

4.5. Scenario 5: irrigation water

Based on the optimisation method used in the previous section of ‘water for livestock’ scenario, this section utilises the same idea of relaxing mixer 3 to produce two streams of product water. These are the product water of stream 9 of RRRO process and the blended water of MED-TVC and PRRO process (stream 10) (Fig. 6). The inlet feed flow rate and salinity of seawater entering the RRRO process will be based on the optimal operating conditions of the associated processes as presented in Tables 4 and 5. In this regard, the RRRO will be optimised to produce irrigation water with salinity of 600 ppm or lower. This value has been reported in Fipps [40] and Pick [39]. The optimisation will aim

to maximise the productivity of the RRRO process whilst having a specific energy consumption of lower than the simulation one of Al-hotmani et al. [23]. Furthermore, the inlet seawater temperature of RRRO process (stream 8) will be controlled using a heat exchanger to maintain the constrain of 600 ppm salinity of produced water of stream 9.

The optimisation problem of RRRO processes to produce an irrigation water can be mathematically expressed as follows.

$$\text{Max } Productivity_{RRRO\text{ process}} \\ P_{f(RRRO)}, T_{f(RRRO)}$$

Subject to: Equality constraints: RRRO process model
Inequality constraints:

a) lower and upper limits of feed pressure of the RRRO process

$$(10 \text{ atm}) P_{f(RRRO)}^L \leq P_{f(RRRO)} \leq P_{f(RRRO)}^U (81 \text{ atm}) \\ (25 \text{ }^\circ\text{C}) T_{f(RRRO)}^L \leq T_{f(RRRO)} \leq T_{f(RRRO)}^U (45 \text{ }^\circ\text{C})$$

b) lower and upper limits of feed flow rate of each membrane module in the RRRO process

$$(87.12 \text{ m}^3/\text{day}) Q_{f(\text{membrane-RRRO})}^L \leq Q_{f(\text{membrane-RRRO})} \leq Q_{f(\text{membrane-RRRO})}^U (463.44 \text{ m}^3/\text{day})$$

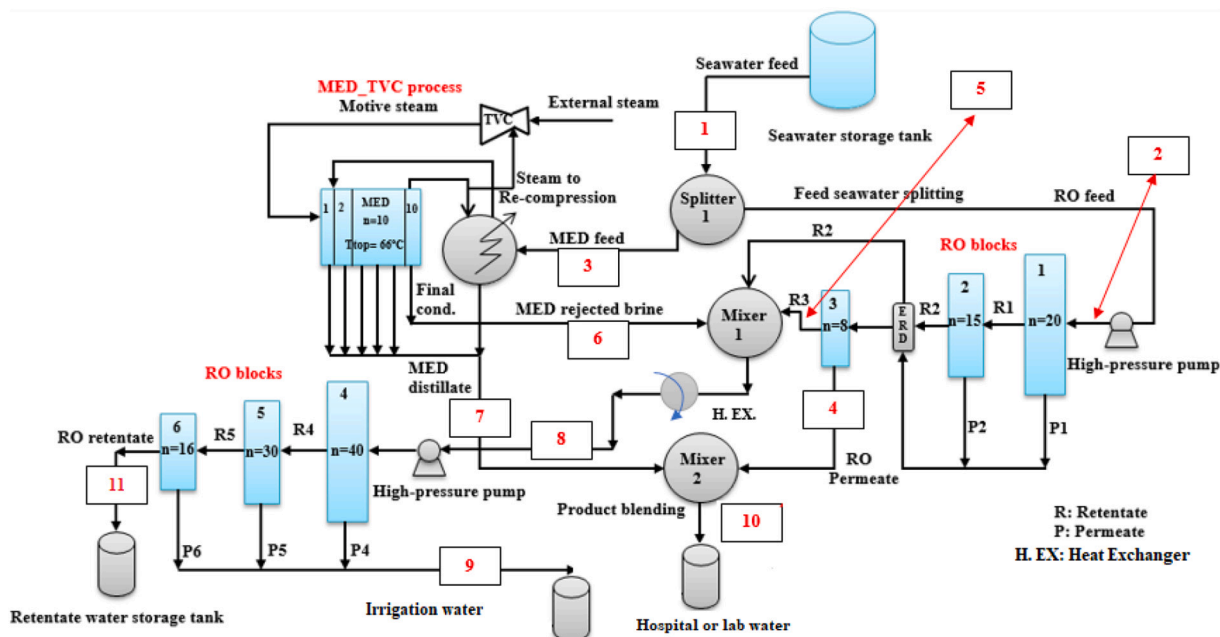


Fig. 6. Updated design of MED-TVC and double RO processes to generate irrigation water and hospital or lab water.

Table 8
Optimal inlet operating conditions of RRRO processes and optimal performance indicators for the production of irrigation water.

Applied method	Inlet conditions of RRRO process		Optimal conditions of RRRO process		Performance indicators of RRRO process						
	Q _f RRRO (m ³ /day)	C _f RRRO (ppm)	P _f RRRO (atm)	T _f RRRO (°C)	Productivity RRRO (m ³ /day)	SEC RRRO (kWh/m ³)	%Rec RRRO (-)	%Rej RRRO (-)	Salinity of product water RRRO (ppm)	Disposed flowrate RRRO (m ³ /day)	Brine salinity RRRO (ppm)
Simulation (base case of Al-hotmani et al. [23])	13,726.60	60,493.84	50	25	750.40	30.285	5.46	95.08	2973.07	12,976.20	63,820.22
Optimisation	18,057.89	59,009.12	81	29.27	7411.86	6.534	41.04	98.97	599.63	10,646.02	99,672.52
Benefits of total energy saving = 78.42%				Benefits of total water productivity = 887.72%				Benefits of total disposed brine = 17.95%			

c) The salinity of product water of the RRRO process is constrained to 600 ppm or lower and the specific energy consumption to be lowered than that of Al-hotmani et al. [23].

End-point constrain:

$$C_{p(RRRO\ process)} \leq 600\ ppm$$

$$SEC_{(RRRO\ process)} < 30.285$$

Table 8 shows the optimisation results of the RRRO process, the inlet conditions and performance indicators that produced irrigation water and the simulation results of the RRRO process. The specifications of water of stream 10 (blended water of MED-TVC and PRRO process) has been changed based on the optimal conditions of the associated processes. In this regard, the productivity has been increased from 7770.86 m³/day to 9534.93 m³/day as well as decreasing its salinity from 10.88 ppm to 9.94 ppm.

In this scenario of irrigation water, Table 8 affirms the importance of applying the highest value of feed pressure to enforce the RRRO process to significantly decrease the product salinity from 2973.07 ppm to close to 600 ppm. Thus, the feed pressure has been increased from 50 atm to the maximum value of 81 atm that RO membranes can withstand (Table 1). Also, it can be seen that the seawater temperature of the RRRO process has been increased by around 4.5 °C to enable the maximisation of water productivity and product quality. For the assessment of performance indicators, Table 8 demonstrates the best optimisation results compared to all the tested scenarios; the water productivity and energy saving of the RRRO process have been increased by 887.72% and 78.42%, respectively. In this regard, the total energy saving of the RRRO process in producing irrigation water is almost same as the one achieved in the production of water for livestock. This is due to maximising the feed pressure of the RRRO process in irrigation water simulation that increases the specific energy consumption (Eq. (14) in Table A.4 of Appendix A). However, a further reduction of disposed water from the RRRO process has been conducted in the irrigation water scenario that helps the environment. The disposed water of the scenario of irrigation water has been decreased by around 18% compared to 15% of the scenario of water for livestock.

5. Critical evaluation of optimisation results of five scenarios of MED and double RO processes

Table 9 shows a summary of the optimisation results of the five

scenarios developed in this study and comparing with the simulation results of the original design of MED-TVC and double RO processes developed by Al-hotmani et al. [23] (base case). The parameters under focus include the salinity and total productivity of water, disposed water flow rate, specific energy consumption for the hybrid system and associated processes, and finally energy saving for each scenario developed. The following points can summarise the overall results of Table 9:

1. The optimisation and design modification of the hybrid system developed by Al-hotmani et al. [23] are promising options to generate different types of waters for a smart city.
2. The outlined grades of water and possible methods of their attainment would confirm the necessity of updating the process operation through optimisation or relaxing specific equipment.
3. All the designed scenarios have provided the targeted salinity of the required water.
4. Most scenarios developed are designed to produce two types of water simultaneously.
5. Scenario number 5, which produces irrigation water and hospital or lab water, shows maximum water productivity of 16,946.47 m³/day compared to 8521.26 m³/day of the original one.
6. Scenario number 1, which produces drinking water, has showed the lowest disposed brine flow rate of 8495.58 m³/day. This is lower than the disposed water of the original design of Al-hotmani et al. [23] by 34.53%.
7. Scenario number 1, which produces drinking water, has showed the maximum energy saving of 44.22% compared to the original design.

Several challenges that can be stated related to the developed scenarios of this study are as follows:

- It is vital to testify the scale up (expansion) of the scenarios developed to different scales to precisely assess the viability and durability under real applications.
- There is an important challenge of maintaining stable water production from the associated processes for long-term operation. This is due to the susceptibility of fouling that would deteriorate water productivity and decreasing the overall performance, especially for RO processes.
- Investigating a superior method to limit the dispose line of high salinity is an important task to familiarize an ecofriendly and attractive solution to maintain a safe environment.

Table 9
Summary of optimisation results of performance indicators of five scenarios and the base case of hybrid system of MED and double RO processes.

Scenario	Salinity of product water (ppm)	Total productivity (m ³ /day)	Productivity PRRO (m ³ /day)	Productivity MED-TVC (m ³ /day)	Productivity RRRO (m ³ /day)	Total disposed brine flow rate (m ³ /day)	Total SEC PRRO+MED-TVC+RRRO (m ³)	SEC PRRO (kWh/m ³)	SEC MED-TVC (kWh/m ³)	SEC RRRO (kWh/m ³)	Total energy saving% PRRO+MED-TVC+RRRO	Type of produced water
Base case [23]	278.66	8521.26	1867.32	5903.53	750.40	12,976.20	15.70	2.62	17.98	30.28	0.0	Drinking water
1	249.98	13,786.40	2342.61	4659.86	6783.92	8495.58	8.76	4.04	15.08	6.04	44.22	Drinking water
2	MED-TVC (0.0) PRRO (9.68)	9534.93	1779.57	7755.36	Relaxed	18,057.89	-	2.83	15.08	Removed	MED-TVC (16.14) PRRO (-8.28)	Distilled water
3	RRRO (2498.99) MED-TVC and PRRO (9.94)	11,525.37	1779.25	7755.36	1990.43	16,067.46	13.31	2.83	15.08	15.78	15.22	Hospital or lab water
4	RRRO (996.97) MED-TVC and PRRO (9.94)	16,609.90	1779.25	7755.36	7075.29	10,982.59	10.06	2.83	15.08	6.37	35.94	Power plant water
5	RRRO (599.63) MED-TVC and PRRO (9.94)	16,946.47	1779.25	7755.36	7411.86	10,646.02	10.06	2.83	15.08	6.53	35.94	Hospital or lab water

- Special attention should be devoted to assess different optimisation approaches such as MINLP in order to investigate different possible scenarios from the hybrid system of MED-TVC and double RO process that would improve production of drinking water, distilled water, irrigation water, hospital and lab water, power plant water and water for livestock from seawater resource.
- Lastly, the current study assumed fixed salinity and temperature of seawater and as such has not discussed the seasonality variation on seawater salinity and temperature.

Therefore, it is imperative that the hybrid system of membrane technology and MED-TVC system is improved in order to address the above challenges. Also, the utilisation of any renewable energy including an integrated energy system or waste heat or low grade heat will reduce the dependency on the fossil fuel based energy and then reduce the overall water production cost [41].

6. Conclusions

Water desalination is an adaptable technology with potential to overcome the scarcity of fresh water. However, it is crucial to moderate the water desalination systems in order to generate different grades of water rather than producing drinking water only, whilst resolving the environmental concerns. One of the major challenges related to seawater desalination is the provision of different grades of water for different applications simultaneously. Therefore, the present study focuses on improving the design of an integrated system of MED-TVC and membrane technology to fulfil the final expectations of an efficient process of water desalination for a smart city based on the principles of the food-energy-water nexus. In other words, the main concern of this study is to thoroughly analyse the possibilities of improving the seawater desalination using a hybrid system of thermal and membrane technology to meet the consideration of energy-water nexus. More specifically, this study introduces a hybrid system of MED-TVC and double RO process to the market as a competitive design of optimal operating conditions to produce different grades of water for a given set of inlet seawater conditions.

Five different scenarios were developed to provide six different types of water via optimisation and redesign of the hybrid system. The optimisation results obtained the appropriate control variables for each scenario developed that can attain the maximisation of water productivity with the lowest possible energy consumption and targeted salinity of produced water. Moreover, a number of scenarios developed have reduced the disposed brine water as an ecofriendly solution to sustain a green environment. Also, it can be affirmed that the redesign of the original MED-TVC and double RO process has introduced the possibility of producing two different types of water simultaneously.

Finally note, for the smart city with certain power and water demand, optimisation can be considered to calculate the ratio between water volumes obtained by different methods that corresponds to minimum of power required for water production. This should also account for waste heat to produce distilled water and to reduce RO operation costs. Further investigations are required that will use dependencies of energy consumption on RO/distilled ratio depending on power plant characteristics.

CRedit authorship contribution statement

All authors contributed equally in all aspects of this paper.

Declaration of competing interest

There is no conflict of interests.

Appendix A

Table A.1
Modelling of MED system [29].

Eq. no.	Description	Equation	Unit
1	Feed flowrate	$Mf = \frac{Ms \lambda(Ts)}{Q_{sensible} + Q_{latent}}$	kg/s
2	Sensible heat in the 1st stage	$Q_{sensible} = Mf \int_{T1}^{T1} cp(T1, x1) dT$	kJ/s
3	Latent heat existed in the 1st stage	$Q_{latent} = D1 \lambda(Tv1)$	kJ/s
4	Temperature droplet along each stage	$\Delta T = \frac{Ts - Tb}{n}$	°C
5	Temperature droplet along preheaters	$\Delta T = \Delta t$	°C
6	Inlet temperature of the 1st effect	$t1 = tn + (n - 1) \Delta t$	°C
7	Temperature of vapour phase	$Tv = T - BPE(T, x)$	°C
8	Flowrate of flashed freshwater	$D_{flash, i} = \alpha B_{i-1}$	kg/s
9	Portion of freshwater by flashing	$\alpha = \frac{cp(T_{mean}, x_{mean}) \Delta T}{\lambda(T_{mean})}$	-
10	Mean temperature	$T_{mean} = \frac{T1 + Tb}{2}$	°C
11	Mean salinity	$x_{mean} = \frac{xf + xb}{2}$	ppm
12	Portion of freshwater by evaporation	$\beta = \frac{\alpha [xb(1 - \alpha)^n - xf]}{(xb - xf) [(1 - \alpha)^n]}$	-
13	Flowrate of evaporated freshwater	$D_{i, boiled} = \beta M D$	kg/s
14	Total distilled water	$D_i = D_{i, boiled} + D_{i, flashed}$	kg/s
15	Disposed brine flowrate	$B_i = B_{i-1} - D_i$	kg/s
16	Salinity of each stage	$x_i = \frac{x_{i-1} B_{i-1}}{B_i}$	ppm
17	Estimated area of each stage	$\frac{Q_i}{U_{ev, i} \Delta T_{ev, i}} = A_{ev, i}$	m ²
18	Heat load in each stage	$Q_i = D_{boiled, i-1} \lambda(T_{v, i-1})$	kJ/s
19	Temperature droplet in heat exchangers	$\Delta T_{ev, i} = \Delta T - BPE_{i-1}$	°C
20	Area of each preheater	$Mf \cdot \int_{t_{i+1}}^{t_i} cp(t, x) dt = U_{ph, i} A_{ph, i} \Delta T_{log, i}$	m ²
21	Logarithmic temperature variance in preheater	$\Delta T_{log, i} = \frac{\Delta T}{\log\left(\frac{T_{v_i} - t_{i+1}}{T_{v_i} - t_i}\right)}$	°C
22	Area of the final condenser	$Q_{COND} = U_{COND} A_{COND} \Delta T_{log, COND}$	m ²
23	Conductivity heat in the final condenser	$Q_{COND} = D_n \lambda(T_{v_n})$	kJ/s
24	Logarithmic temperature variance in final condenser	$\Delta T_{log, COND} = \frac{tn - Tw}{\log\left(\frac{T_{v_n} - Tw}{T_{v_n} - tn}\right)}$	°C

Table A.2
Modelling of TVC system [42].

Eq. no.	Description	Equation	Unit
1	Temperature and pressure correction parameters	$TCF = 2e - 8 \cdot Tv_n^2 - 0.0006 \cdot Tv_n + 1.0047$ $PCF = 2e - 7 \cdot Tpm^2 - 0.0009 \cdot Pm + 1.6101$	-, -
2	Pressure at vapour temperature	$Pv = P_{crit} e^{\left(\frac{T_{crit}}{Tv_n} + 273.15\right) - 1} \cdot \sum_{j=1}^8 f_j$	bar
3	Pressure at steam temperature	$Ps = P_{crit} e^{\left(\frac{T_{crit}}{Ts} + 273.15\right) - 1} \cdot \sum_{j=1}^8 f_j$	bar
4	Compression and entrainment ratios	$CR = \frac{Pv}{Ps}$ $Ra = 0.296 \frac{Ps^{1.19}}{Pev^{1.04}} \frac{Pm^{0.015}}{Pev^{0.015}} \frac{PCF}{TCF}$	-, -
5	Motive steam flowrate	$Mm = Ms \frac{Ra}{1 + Ra}$	kg/s

Table A.3
Modelling of a single RO process [29].

Eq. no.	Description	Equation	Unit
1	Freshwater Flux	$Q_p = A_{w(T)} \left(P_f - \frac{\Delta P_{drop, E}}{2} - P_p - \pi_w - \pi_p \right) A_m$	m ³ /s
2	Solute flux	$Q_s = B_{s(T)} (C_w - C_p)$	m ³ /s
3	Osmotic pressure in high-concentration and permeate sides	$\pi_w = 0.76881 C_w, \pi_p = 0.7994 C_p$	atm
4	Effect of temperature on water transport coefficient	$A_{w(T)} = A_{w(25\text{ }^\circ\text{C})} \exp [0.0343 (T - 25)] < 25\text{ }^\circ\text{C}$ $A_{w(T)} = A_{w(25\text{ }^\circ\text{C})} \exp [0.0307 (T - 25)] > 25\text{ }^\circ\text{C}$	-
5	Effect of temperature on solute transport coefficient	$B_{s(T)} = B_{s(25\text{ }^\circ\text{C})} (1 + 0.08 (T - 25)) < 25\text{ }^\circ\text{C}$ $B_{s(T)} = B_{s(25\text{ }^\circ\text{C})} (1 + 0.05 (T - 25)) > 25\text{ }^\circ\text{C}$	-

(continued on next page)

Table A.3 (continued)

Eq. no.	Description	Equation	Unit
6	Pressure droplet for each membrane and Reynolds number	$\Delta P_{drop,E} = \frac{9.8692 \times 10^{-6} A^* \rho_b Q_b^2 L}{2 d_h Re_b^2 (W t_f \epsilon)^2} Re_b = \frac{\rho_b d_h Q_b}{t_f W \mu_b}$	atm, -
7	Bulk flowrate and concentration	$Q_b = \frac{Q_f + Q_r}{2}, C_b = \frac{C_f + C_r}{2}$	m ³ /s, ppm
8	Membrane wall concentration	$\frac{(C_w - C_p)}{(C_b - C_p)} = \exp\left(\frac{Q_p/A_m}{k}\right)$	ppm
9	Schmidt number and Mass transfer coefficient	$Sc = \frac{\mu_b}{\rho_b D_b}$ $k = 0.664 k_{dc} Re_b^{0.5} Sc^{0.33} \left(\frac{D_b}{d_h}\right) \left(\frac{2d_h}{L_f}\right)^{0.5}$	-, m/s
10	Physical properties	Density	kg/m ³
		$\rho_b = 498.4 m_f + \sqrt{[248400 m_f^2 + 752.4 m_f C_b]}$	
11		Diffusivity	m ² /s
		$m_f = 1.0069 - 2.757 \times 10^{-4} T$ $D_b = 6.72510^{-6} \exp\{0.154610^{-3} C_b - \frac{2513}{T + 273.15}\}$	
12		Viscosity	Pa s
		$\mu_b = 1.234 \times 10^{-6} \exp\{0.0212 C_b + \frac{1965}{T + 273.15}\}$	
13	Overall mass and material balances	$Q_f = Q_r + Q_p, Q_f C_f - Q_r C_r = Q_p C_p$	-
14	Permeate concentration	$C_p = \frac{B_s C_f e^{\frac{J_w}{k}}}{J_w + B_s e^{\frac{J_w}{k}}}$	ppm
15	Rejection and water recovery rate	$Rej = \frac{C_f - C_p}{C_f}, Rec = \frac{Q_p}{Q_f}$	-

Table A.4

Modelling of PRRO and RRRO processes [23].

Eq. no.	Description	Equation	Unit
1	Material balance of the RO plant	$Q_f(plant) = Q_r(plant) + Q_p(plant)$	m ³ /s
2	Mass balance of the RO plant	$Q_f(plant) C_f(plant) = Q_r(plant) C_r(plant) + Q_p(plant) C_p(plant)$	ppm
3	Plant retentate flowrate of PRRO	$Q_r(plant) = Q_r(Block 2) + Q_r(Block 3)$	m ³ /s
4	Plant retentate flowrate of RRRO	$Q_r(plant) = Q_r(Block 3)$	m ³ /s
5	Plant retentate concentration of PRRO	$C_r(plant) = \frac{(C_r(Block 2) Q_r(Block 2)) + (C_r(Block 3) Q_r(Block 3))}{Q_r(plant)}$	ppm
6	Plant retentate concentration of RRRO	$C_r(plant) = C_r(Block 3)$	ppm
7	Plant permeate concentration and permeate flowrate of PRRO	$C_p(Plant) = C_p(Block 3), Q_p(Plant) = Q_p(Block 3)$	ppm, m ³ /s
8	Plant permeate concentration and permeate flowrate of RRRO	$C_p(Plant) = C_p(Block 1) + C_p(Block 2) + C_p(Block 3), Q_p(Plant) = Q_p(Block 1) + Q_p(Block 2) + Q_p(Block 3)$	ppm, m ³ /s
9	Plant retentate pressure and retentate temperature of PRRO and RRRO	$P_r(plant) = P_r(Block 3), T_r(plant) = T_f(plant)$	atm, °C
10	Permeate flowrate, concentration, total rejection, and recovery rate of any block of PRRO and RRRO	$Q_p(Block 1) = \sum_{PV=1}^n Q_p(PV),$ $C_p(Block 1) = \frac{\sum_{PV=1}^n C_p(PV) Q_p(PV)}{Q_p(Block 1)},$ $Rej_{(Block 1)} = \frac{C_f(Block 1) - C_p(Block 1)}{C_f(Block 1)} \times 100,$ $Rec_{(Block 1)} = \frac{Q_p(Block 1)}{Q_f(Block 1)} \times 100$	m ³ /s, ppm, -, -
11	Feed flowrate, concentration, and pressure of block 3 of PRRO	$Q_f(Block 3) = Q_p(Block 1) + Q_p(Block 2)$ $C_f(Block 3) = \frac{(Q_p(Block 1) C_p(Block 1)) + (Q_p(Block 2) C_p(Block 2))}{Q_f(Block 3)}, P_f(Block 3) = P_f(plant)$	m ³ /s, ppm, atm
12	Plant recovery rate and solute rejection	$Rec(plant) = \frac{Q_p(plant)}{Q_f(plant)} \times 100,$ $Rej(plant) = \frac{C_f(plant) - C_p(plant)}{C_f(plant)} \times 100$	-, -
13	Specific energy consumption of PRRO	$E_{s,RO} = \left\{ \frac{[(P_f(plant) \times 101325) Q_f(plant)]}{\frac{\eta_{pump} Q_p(plant)}{3600000}} \right\} - \frac{(P_r(block2) \times 101325) Q_r(block3) \eta_{ERD}}{\frac{Q_p(plant)}{3600000}}$	kWh/m ³
14	Specific energy consumption of RRRO	$E_{s,RO} = \left\{ \frac{[(P_f(plant) \times 101325) Q_f(plant)]}{\frac{\eta_{pump} Q_p(plant)}{3600000}} \right\}$	kWh/m ³

Table A.5
Modelling of a hybrid system of MED-TVC and RO processes [29].

Eq. no.	Description	Equation	Unit
1	Inlet feed water to MED system	$Mw_{MED} = Mr_{RO} + M_{bypass}$	kg/s
2	Material balance for MED system	$Mw_{MED}x_{fMED} = Mr_{RO}x_{fRO} + M_{bypass}x_{seawater}$	ppm
3	Total freshwater production	$Md_{MED} + Mp_{RO} = M_{freshwater}$	kg/s
4	Salinity of freshwater	$Md_{MED}x_{dMED} + Mp_{RO}x_{pRO} = M_{freshwater}x_{freshwater}$	ppm
5	Total disposed brine	$Mb_{MED} = M_{reject}$	kg/s
6	Salinity of disposed brine	$x_{fMED} = x_{reject}$	ppm

Relationships for MED process [42]:

Boiling point elevation:

The applied range: $1\% < w < 16\%$, $10\text{ }^{\circ}\text{C} < T < 180\text{ }^{\circ}\text{C}$

$$w = \frac{x}{100000} \left[\frac{w}{w\%} \right]$$

$$BPEa = 8.325x10^{-2} + 1.883x10^{-4} T + 4.02x10^{-6} T^2$$

$$BPEb = -7.625x10^{-4} + 9.02x10^{-5} T - 5.2x10^{-7} T^2$$

$$BPEc = 1.522x10^{-4} - 3x10^{-6} T - 3.2x10^{-8} T^2$$

$$BPE = BPEa w + BPEb w^2 + BPEc w^3 \text{ [}^{\circ}\text{C]}$$

Specific heat at fixed pressure:

The applied range: $20,000\text{ ppm} < x < 160,000\text{ ppm}$, $20\text{ }^{\circ}\text{C} < T < 180\text{ }^{\circ}\text{C}$

$$s = \frac{x}{1000} \left[\frac{gm}{kg} \right]$$

$$cpa = 4206.8 - 6.6197 s + 1.2288x10^{-2} s^2$$

$$cpb = -1.1262 + 5.4178x10^{-2} s - 2.2719x10^{-4} s^2$$

$$cpc = 1.2026x10^{-2} - 5.3566x10^{-4} s + 1.8906x10^{-6} s^2$$

$$cpd = 6.8777x10^{-7} + 1.517x10^{-6} s - 4.4268x10^{-9} s^2$$

$$cp = \frac{cpa + cpb T + cpc T^2 + cpd T^3}{1000} \left[\frac{kJ}{kg^{\circ}\text{C}} \right]$$

Latent heat of evaporation:

$$\lambda = 2501.89715 - 2.40706 T + 1.19221x10^{-3} T^2 - 1.5863x10^{-3} T^3 \left[\frac{kJ}{kg} \right]$$

Global heat exchange parameters:

$$U_{ev} = 1.9695 + 1.2057x10^{-2} T - 8.5989x10^{-5} T^2 + 2.5651x10^{-7} T^3 \left[\frac{kW}{m^2^{\circ}\text{C}} \right]$$

$$U_{cond} = U_{ph} = 1.7194 + 3.2063x10^{-3} T + 1.597x10^{-5} T^2 - 1.9918x10^{-7} T^3 \left[\frac{kW}{m^2^{\circ}\text{C}} \right]$$

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Nomenclature

- A_m : membrane area (m^2)
 $A_{w(T)}$: water transport parameter at feed temperature of RO process ($m/s \text{ atm}$)
 $A_{ev, i}$: exchange area of i -th evaporator of MED process (m^2)
 $A_{ph, i}$: exchange area of i -th pre-heater of MED process (m^2)
 A_{cond} : exchange area of final condenser of MED process (m^2)
 $A_{ev, mean}$: mean exchange area of evaporators of MED process (m^2)
 $A_{ph, mean}$: mean exchange area of pre-heaters of MED process (m^2)
 B_i : rejected brine of the i -th effect (kg/s)
 $B_s(T)$: solute transport parameter at feed temperature of RO process (m/s)
 C_b : bulk concentration of a single membrane of RO process (kg/m^3)
 C_f : feed concentration of a single membrane of RO process (kg/m^3)
 $C_f(plant)$: plant feed concentration (kg/m^3)
 C_p : permeate concentration at the permeate channel of a single membrane of RO process (kg/m^3)
 C_r : brine concentration of a single membrane of RO process (kg/m^3)
 CR : compression ratio in the steam ejector of MED process (–)
 C_w : wall membrane concentration of a single membrane of RO process (kg/m^3)
 D_b : diffusivity parameter (m^2/s)
 $D_{boil, i}$: distillate produced by boiling in i -th evaporator of MED process (kg/s)
 $D_{flash, i}$: distillate produced by flashing in i -th flashing box of MED process (kg/s)
 d_h : hydraulic diameter of the feed spacer channel of a membrane of RO process (m)
 D_i : total distillate produced in i -th effect of MED process (kg/s)
 ERD : energy recovery device (–)
 E_s : specific energy consumption of MED process (kJ/kg)
 $E_{s, RO}$: specific energy consumption of RO process (kWh/m^3)
 J_w : water flux through a single membrane of RO process (m/s)
 k : mass transfer coefficient (m/s)
 k_{dc} : constant (–)
 L : length of membrane of RO process (m)
 L_f : length of filament in the spacer mesh of RO process (m)
 M_b : rejected brine flowrate of MED process (kg/s)
 M_{COND} : flowrate of steam in the final condenser of MED process (kg/s)
 M_d : distillate from MED process (kg/s)
 M_f : water intake in the first effect of MED process (kg/s)
 m_f : coefficient
 Mm : motive steam flowrate of MED process (kg/s)
 Ms : total steam flow rate of MED process (kg/s)
 M_{TVC} : vapour flowrate entrained in TVC section of MED process (kg/s)
 Mw : intake water flow rate of MED process (kg/s)
 n : number of effects of MED process (–)
 P_{crit} : critical pressure of water (kPa)
 P_{ev} : pressure of saturated entrained vapour of MED process (kPa)
 P_f : feed pressure of a single membrane of RO process (atm)
 $P_f(plant)$: plant feed pressure of RO process (atm)
 PFC : pressure Correction Factor of RO process (–)
 P_m : pressure of saturated steam at temperature T_m of MED process (kPa)
 P_p : permeate pressure at the permeate channel of RO process (atm)
 P_r : retentate pressure of a single membrane of RO process (atm)
 $P_r(plant)$: plant retentate pressure of RO process (atm)
 $P_r(block)$: retentate pressure of any block of RO process (atm)
 P_s : pressure of saturated steam at temperature T_s of MED process (kPa)
 P_v : pressure of saturated steam at temperature T_v of MED process (kPa)
 Q_b : bulk flow rate of a single membrane of RO process (m^3/s)
 Q_{COND} : thermal load in final condenser of MED process (kW)
 Q_f : feed flow rate of a single membrane of RO process (m^3/s)
 $Q_f(plant)$: plant feed flow rate of RO process (m^3/s)
 $Q_f(block)$: feed flow rate of any block of RO process (m^3/s)
 Q_i : thermal load at i -th evaporator of MED process (kW)
 Q_{latent} : latent heat used in first effect of MED process (kJ/kg)
 Q_p : total permeate flow rate of a single membrane of RO process (m^3/s)
 $Q_p(plant)$: plant permeate flow rate of RO process (m^3/s)
 $Q_p(PV)$: permeate flow rate of single pressure vessel of RO process (m^3/s)
 Q_r : retentate flow rate of a single membrane of RO process (m^3/s)
 $Q_r(plant)$: plant retentate flow rate of RO process (m^3/s)
 Q_s : thermal load of steam of MED process (kW)
 $Q_{sensible}$: sensible heat used in first effect of MED process (kJ/kg)
 Ra : entrainment ratio of MED process (–)
 Re_b : reynolds number (–)
 Rec : recovery rate of a single membrane of RO process (–)
 $Rec(plant)$: total plant water recovery rate of RO process (–)
 Rej : solute rejection of a single membrane of RO process (–)
 $Rej(plant)$: total plant solute rejection of RO process (–)
 RO : reverse osmosis

SEC : specific energy consumption (kWh/m³)
 Sc : Schmidt number (-)
 T_I : top brine temperature (T_{top}) of MED process (°C)
 T_b : temperature of rejected brine of MED process (°C)
 T_{CF} : temperature Correction Factor of RO process (-)
 T_{crit} : critical temperature of water (°C)
 t_i : feed temperature after i-th pre-heater of MED process (°C)
 t_f : height of feed channel of the membrane of RO process (m)
 $T_{f(plant)}$: plant operating temperature of RO process (°C)
 T_{mean} : mean temperature in the plant (°C)
 t_n : feed temperature after final condenser of MED process (°C)
 $T_{r(plant)}$: retentate plant temperature of RO process (°C)
 T_s : steam temperature of MED process (°C)
 T_{v_i} : temperature of the vapour phase in i-th effect of MED process (°C)
 T_w : temperature of the cooling water of MED process (°C)
 U_b : cross flow velocity of a single membrane of RO process (m/s)
 U_{cond} : global heat exchange coefficient in final condenser of MED process (kW/m² °C)
 $U_{ev,i}$: global heat exchange coefficient in i-th evaporator of MED process (kW/m² °C)
 $U_{ph,i}$: global heat exchange coefficient in i-th pre-heater of MED process (kW/m² °C)
 W : membrane width of RO process (m)
 xb : salinity in rejected brine of MED process (ppm or w/w%)
 xf : salinity in the feed of MED process (ppm or w/w%)
 x_i : salinity in i-th evaporator of MED process (ppm or w/w%)
 x_{mean} : mean salinity in the plant (ppm or w/w%)

Greek

α : fraction of rejected brine from previous effect flashed in the associated pre-heater of MED process (-)
 β : fraction of total distillate boiled in each evaporator of MED process (-)
 $\Delta A_{ev}\%$: percentage error on evaporators' areas of MED process (%)
 $\Delta A_{ph}\%$: percentage error on pre-heaters areas of MED process (%)
 $\Delta T_{ex, i}$: driving force for heat exchange in i-th evaporator of MED process (°C)
 $\Delta t_{log, i}$: driving force for heat exchange in i-th pre-heater of MED process (°C)
 $\Delta T_{log, cond}$: driving force for heat exchange in final condenser of MED process (°C)
 ΔT_i : temperature drop between two evaporators of MED process (°C)
 Δt_i : temperature increase between two pre-heaters of MED process (°C)
 $\Delta P_{drop, E}$: total pressure drop along the membrane element of RO process (atm)
 λ : latent heat of evaporation of MED process (kJ/kg)
 π_p : total osmotic pressure at the permeate channel of RO process (atm)
 π_w : total osmotic pressure at the membrane surface of RO process (atm)
 ρ_b : density parameter (kg/m³)
 μ_b : kinematic viscosity (kg/m s)
 ϵ : membrane porosity (-)
 η_{pump} : pump efficiency (-)
 η_{ERD} : efficiency of energy recovery device of RO process (-)