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Primary energy and exergy of desalination technologies in a power-water cogeneration scheme

Thomas Altmann[a], Justin Robert[a], Andrew Bouma[b], Jaichander Swaminathan[c], John H. Lienhard V[b,*]

[a] ACWA Power, 41st Floor, The One Tower, Barsha Heights, Sheikh Zayed Road, Dubai, United Arab Emirates
[b] Rohsenow Kendall Heat Transfer Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA
[c] Dr. Kiran C. Patel Centre for Sustainable Development, Mechanical Engineering Discipline, Indian Institute of Technology Gandhinagar, 382355 Gujarat, India

HIGHLIGHTS

- Desalination technologies are compared on the basis of primary energy consumption.
- This comparison basis takes into account the exergetic value of input energy.
- The efficiency gap between technologies shrinks, but RO remains the most efficient.
- Changes in power plant operation due to desalination loads should be considered.
- Hybridizing systems or adding nanofiltration can improve primary energy efficiency.

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ABSTRACT

The primary energy consumption of a spectrum of desalination systems is assessed using operating information and technical bids for real plants configured with coproduction of electricity. The energy efficiency of desalination plants is often rated on a stand-alone basis using metrics such as specific energy consumption, gained output ratio, and second law efficiency, which can lead to inconsistent conclusions because the heat and electrical work inputs to the plant have very different exergies and costs, which must be taken into account. When both the heat and work inputs are drawn from a common primary energy source, such as the fuel provided to electricity-water coproduction systems, these inputs can be compared and combined if they are traced back to primary energy use. In the present study, we compare 48 different configurations of electricity production and desalination on the basis of primary energy use, including cases with pretreatment and hybridized systems, using performance figures from real and quoted desalination systems operating in the GCC region. The results show that, while reverse osmosis is still the most energy efficient desalination technology, the gap between work and thermally driven desalination technologies is reduced when considered on the basis of primary energy. The results also show that pretreatment with nanofiltration or hybridization of multiple desalination systems can help to reduce energy requirements. Additionally, the specific type of power plant in the coproduction scheme and its operating parameters can have a significant impact on the performance of desalination technologies relative to one other.

1. Introduction

Growing global population and rising standards of living have led to increased water demand for domestic use, agricultural irrigation, and industrial processes. The rapid increase in global water demand without a similar growth in natural water supply has driven humanity to create new sources of fresh water. Oceans, with their practically infinite supply of seawater, are a viable and reliable water source when the fresh water needs of a population cannot be met by other sources alone. In recent history, a large number methods for desalinating water have been proposed, developed, and adopted at some level.

In parallel with the water crisis faced by humanity, the world has entered an age of heightened scrutiny surrounding the supply and demand for energy. Implementing more efficient processes wherever

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[*] Corresponding author.
E-mail address: lienhard@mit.edu (J.H. Lienhard).

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Nomenclature

Acronyms

CCGT	combined cycle gas turbine
CSP	concentrated solar power
DWEER	dual work exchange energy recovery
ERD	energy recovery device
FC	flash chamber
FO	forward osmosis
GCC	Gulf Cooperation Council
GOR	gained output ratio
MD	membrane distillation
MED	multi-effect distillation
MEDT	multi-effect distillation with thermal vapor compression
MSF	multi-stage flash
MVC	mechanical vapor compression
NF	nanofiltration
RO	reverse osmosis
SEC	specific energy consumption
SWRO	seawater reverse osmosis
TBT	top brine temperature
TDS	total dissolved solids
TVC	thermal vapor compressor
WHO	World Health Organization

Roman symbols

A	area, m^2
h	specific enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
$\dot{Q}$	heat flow rate, W
s	specific entropy, kJ/kg-K
T	temperature, °C
y	flow rate of solution stream, kg/s

Greek symbols

η	efficiency
Ξ	exergy, W

Subscripts, superscripts

0	dead state
I	first law
II	second law
b	baseline case
c	concentrate
C	Carnot
d	used to power the desalination plant
e	case with steam extraction
f	feed
fg	enthalpy of vaporization
fuel	from fuel after combustion
H	high temperature
HP	high pressure
HHV	higher heating value
L	entering the low pressure turbine
LP	low pressure
least	least work
min	minimum
p	permeate or product
pp	power plant
Q	thermal
rev	reversible
s	separation
sat	saturated state
sep	only considering the separation of water from seawater
sun	solar temperature
vap	vapor
W	electrical work

possible will help to limit the emission of greenhouse gases and lessen the effects of climate change.

Concerns about water and energy are inextricably linked [1], and seawater desalination lies within this nexus. As a result of the rising use of desalinated water (global capacity is approaching 100 million m^3/day [2]) and the inherently large energy cost associated with desalinating seawater, developing efficient desalination technologies has become a major focus of water research.

Many different desalination technologies have been developed, each with a number of variants or modifications that can be made to meet the unique needs of each desalination project. These technologies have different strengths, weaknesses, limitations, and often, different energy input requirements. As a consequence, comparing these different desalination technologies to one another can be difficult.

1.1. Motivation

If two desalination technologies use the same energy source and energy of the same quality, a comparison of plant operating expenditures (opex) or energy consumption is simple: specific energy consumption (SEC, or the amount of energy per unit product produced) is commonly used to compare technologies powered by electrical work, while thermal desalination technologies are often compared on the basis of gained output ratio (GOR), which is a ratio of the enthalpy of vaporization for a given amount of water to the heat input required to produce that amount of water:

$$\mathrm{GOR} = \frac{\dot{m}_{\mathrm{p}} h_{\mathrm{fg}}}{\dot{Q}_{\mathrm{H}}} \tag{1}$$

Additionally, any two desalination technologies using the same quality energy can be compared using second law efficiency ($\eta^{II} = \Xi_{\text{thermodynamic least}}/\Xi_{\text{consumed}}$, where Ξ represents exergy). Comparing desalination technologies that use different sources or qualities of input energy (e.g. electrically-powered reverse osmosis (RO) versus thermally-driven multi-effect distillation (MED)) is not equally straightforward, since one joule of energy in the form of electricity does not have the same exergy (or cost) as one joule of heat at a specified low temperature [3,4]. A direct comparison of the energy used by these two systems would have no meaning. Only a comparison based on exergy would have thermodynamic meaning [5].

To make an energetic comparison of desalination plants that take different sources or qualities of input energy, a better approach is to broaden the system analysis so that all inputs to the system are measured using a common source of primary energy. Many desalination plants operate concurrently with a cogeneration plant that produces both work and heat, and this provides an opportunity to compare different desalination systems on a common basis, namely the amount of additional primary fuel energy required by the cogeneration plant to operate the desalination plant. This value can be established using exergetic calculations [6]. This makes energy from fuel, or primary energy, the basis of the comparison. Primary energy has an equal unit value for all desalination systems powered by cogeneration using the same type of fuel. In particular, this type of analysis allows modern hybrid systems that require both electrical and thermal energy to be compared fairly against alternative technologies, including classical thermal systems that use significant amounts of electricity for circulation pumping (e.g., multistage flash, or MSF systems). Notably, one thing this type of analysis does *not* allow for is the comparison of systems with different types of primary energy inputs into the cogeneration system (e.g. comparing solar energy and natural gas).

The importance of primary energy analysis has been known for decades. El-Sayed and Silver published this type of energetic assessment in 1980 for MSF and MED plants [7]. Spiegler and El-Sayed [8] extended exergetic considerations to a wider set of five technologies in 2001. Similar equivalencies of electricity and low temperature steam were considered by Semiat in 2008 [9]. Mistry and Lienhard [10] applied the second-law efficiency to coproduction in 2013, comparing RO, MED and MSF systems. More recently, Shahzad et al. have proposed a new metric called the universal performance ratio (UPR), which when compared to the thermodynamic limit, is essentially a second law efficiency with respect to primary energy [11]. Various other approaches have been proposed in literature.

In this work, we apply primary energy assessment methods to a number of desalination plants using realistic data to gain a better understanding of the efficiency of various technologies and technology hybrids through the lens of primary energy consumption. Realistic operating parameters and performance data from power plants and desalination plants in the GCC region are used as the basis of this analysis.

2. System configurations

We examine five different core desalination technologies, along with various hybrids, constituting a total of 16 different desalination systems investigated. Each desalination system is combined with different power plant options, including an oil fired power plant, a combined cycle gas turbine (CCGT) power plant, and parabolic trough and power tower-type concentrating solar power (CSP) plants. All together, 48 unique combinations are analyzed. In depth descriptions of each technology, as well as diagrams and operating conditions for many of these systems, are included in the appendices and supporting information.

The desalination technologies considered are divided into mature technologies and emerging technologies. The mature technologies include RO [12], MSF [13], and MED [14] (along with a variant of MED that includes a thermal vapor compressor, MEDT [15]). These technologies are well understood and have been proven to operate predictably at large scale. The emerging technologies evaluated in this paper, forward osmosis (FO) [16] and membrane distillation (MD) [17], have not yet been proven at large scale for seawater desalinaiton. There have been promising pilot scale tests and simulations performed, but until complete large scale systems that include intakes, pretreatment, post-treatment, and all other energy-consuming processes that constitute an entire system are operated reliably for a substantial amount of time, the results shown for these systems should be taken as an estimate or projection of what a system may be able to achieve in the future.

3. Methods

In order to achieve a fair comparison for all desalination systems described in Section 2, we consider the efficiency of each technology when powered by a cogeneration power plant. The goal of this analysis is to determine the amount of additional fuel energy (either post-combustion or post-solar-absorption) that is required by the power plant in order to power the desalination plant. In this way, the power needs of the desalination plant are all traced back into primary energy, which allows for one-to-one comparison of desalination technologies [10]. Depending on how much information is known about the cogeneration plant and how its performance changes with varying amounts of heat extraction, two possible methods can be used to determine how much additional fuel energy is required. Both are presented below, along with a discussion of their limitations and applicability. These methods could be extended to nearly any fuel source and power plant type, including systems powered by refinery waste gases [18], novel solar power configurations [19], geothermal energy [20], nuclear power [21], and more.

3.1. Generalized cogeneration-desalination system

If we consider a system that includes both the power plant and the desalination plant inside a single control volume as shown in Fig. 1, then the system inputs and outputs crossing the outer boundary are of the same quality regardless of the desalination technology used. As is shown in Fig. 1, the inputs to the combined system include the thermal energy flowing into the power plant $\dot{Q}_H$ at temperature T_H and the feedwater stream, at salinity y_f. Although either unburned fuel or solar radiation will be the input to the cogeneration plant, we simplify the analysis by removing the combustion or absorption step. The effect of adding in these steps is considered in Section 3.4.

The heat input stream, $\dot{Q}_H$, is composed of the thermal energy, $\dot{Q}_{pp}$,

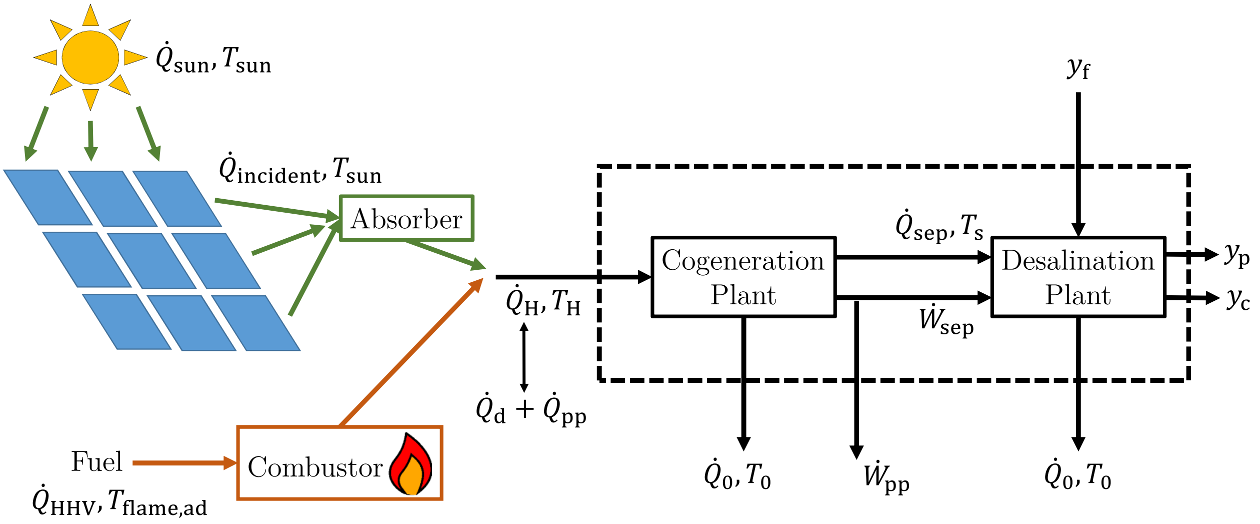

Fig. 1. Diagram of a generalized cogeneration-desalination system, where incoming heat is generated by either a solar collector and absorber or a fossil fuel combustor.

used to generate electricity to be sent to the grid, and the additional thermal energy input into the plant to power the desalination plant, $\dot{Q}_{\mathrm{d}}$, which is what we are interested in. The cogeneration plant rejects thermal energy $\dot{Q}_0$ to the environment at the dead state, or ambient temperature T_0, and produces electrical work that is sent to the grid, $\dot{W}_{\mathrm{pp}}$. The cogeneration plant also produces electrical work $\dot{W}_{\mathrm{sep}}$ and thermal energy $\dot{Q}_{\mathrm{sep}}$ at temperature T_{sep} that are used to power the desalination plant. The desalination plant takes in these energy inputs, along with the feedwater y_{f}, and produces product water y_{p} at some concentration less than the feedwater, and some concentrate (or brine) y_{c} at some concentration greater than the feedwater. The energy and exergy associated with the additional input into the system required to drive the desalination system, $\dot{Q}_{\mathrm{d}}$ and $\dot{\Xi}_{\mathrm{d}}$, respectively, are the terms that will be used to compare systems.

3.2. Power plant efficiency

The first law efficiency of a power plant is the ratio of electrical energy output to the thermal energy input:

$$\eta^{I} \equiv \frac{\dot{W}_{\mathrm{pp}}}{\dot{Q}_{\mathrm{H}}} \tag{2}$$

The exergetic efficiency, or second law efficiency, of a power plant that converts a thermal energy input into some electricity is the ratio of the exergy output of the real system to the exergy output of a thermodynamically reversible system:

$$\eta^{II} \equiv \frac{\dot{\Xi}_{\mathrm{out}}}{\dot{\Xi}_{\mathrm{out,rev}}} \tag{3}$$

Considering a simple power plant, the exergetic efficiency is the fraction of the maximum possible work achieved by the real cycle, where the maximum possible work output is determined by the Carnot efficiency η_{C}^{I}, and $\eta_{\mathrm{C}}^{I} = \dot{W}_{\mathrm{rev}}/\dot{Q}_{\mathrm{H}}$:

$$\eta_{\mathrm{pp}}^{II} = \frac{\dot{\Xi}_{\mathrm{pp}}}{\dot{\Xi}_{\mathrm{rev}}} = \frac{\dot{W}_{\mathrm{pp}}}{\dot{W}_{\mathrm{rev}}} = \left(\frac{\dot{W}_{\mathrm{pp}}}{\dot{Q}_{\mathrm{H}}}\right)\cdot\left(\frac{\dot{Q}_{\mathrm{H}}}{\dot{W}_{\mathrm{rev}}}\right) = \frac{\eta^{I}}{\eta_{\mathrm{C}}^{I}} = \frac{\eta^{I}}{(1 - T_0/T_{\mathrm{H}})} \tag{4}$$

For the case of a cogeneration power plant with steam extraction, we choose to define first law efficiency of the power plant in a similar manner as Eq. (2):

$$\eta_{\mathrm{pp}}^{I} = \frac{\dot{W}_{\mathrm{pp}} + \dot{W}_{\mathrm{sep}}}{\dot{Q}_{\mathrm{H}}} \tag{5}$$

where $\dot{W}_{\mathrm{sep}}$ is the electrical energy used for the chemical separation (in this case within a desalination plant), not to be confused with the thermodynamic least work of separation. This definition treats thermal energy diverted to the desalination plant in the same way as energy rejected to the environment. By defining first law efficiency in this manner, any desalination system that extracts steam from the power plant will necessarily reduce the first law efficiency of the power plant.

For the case with steam extraction, the second law efficiency definition changes, because the exergy diverted from the power plant is not exergy that can be converted into electricity. With steam extraction, the maximum possible work generated by a reversible system would be $\dot{\Xi}_{\mathrm{H}} - \dot{\Xi}_{\mathrm{sep,thermal}}$. The resulting second law efficiency is:

$$\begin{aligned} \eta_{\mathrm{pp}}^{II} &= \frac{\dot{\Xi}_{\mathrm{pp}} + \dot{\Xi}_{\mathrm{sep,electr}}}{\dot{\Xi}_{\mathrm{rev}}} = \frac{\dot{W}_{\mathrm{pp}} + \dot{W}_{\mathrm{sep,electr}}}{\dot{\Xi}_{\mathrm{H}} - \dot{\Xi}_{\mathrm{sep,thermal}}} \\ &= \frac{\dot{W}_{\mathrm{pp}} + \dot{W}_{\mathrm{sep}}}{\dot{Q}_{\mathrm{H}}(1 - T_0/T_{\mathrm{H}}) - \dot{Q}_{\mathrm{sep}}(1 - T_0/T_{\mathrm{s}})} \end{aligned} \tag{6}$$

Unlike first law efficiency, second law efficiency does not necessarily have to decrease when steam is extracted from the power plant, even when the system is operating at fixed power production. Because the exergy of the extracted steam is not counted towards the maximum work that can be generated by a reversible system, the second law efficiency of the power plant can increase if the power that was lost to steam extraction is made up by power produced in a turbine section prior to the steam extraction point that is more efficient than sections downstream.

3.3. Desalination plant efficiency

The exergetic separation efficiency of a desalination plant *by itself* can be defined as the ratio of minimum least work of separation, $\dot{W}_{\mathrm{least}}^{\mathrm{min}}$, to the exergy input into the plant, $\dot{\Xi}_{\mathrm{sep}}$.

$$\eta_{\mathrm{sep}} \equiv \frac{\dot{W}_{\mathrm{least}}^{\mathrm{min}}}{\dot{\Xi}_{\mathrm{sep}}} \tag{7}$$

$\dot{W}_{\mathrm{least}}^{\mathrm{min}}$ is the thermodynamic least work of separation in the limit as the freshwater recovery ratio goes to zero [22], as if the desalination process has no dissipation of useful work. If we consider the exergetic efficiency *with respect to primary energy*, we must replace the exergy input to the plant with the post-combustion fuel exergy, $\dot{\Xi}_{\mathrm{d}}$.

Many desalination plants, such as MED or MSF, use low temperature steam heat, $\dot{Q}_{\mathrm{sep}}$ at some temperature T_{s}, where $T_0 < T_{\mathrm{s}} < T_{\mathrm{H}}$, along with electricity, $\dot{W}_{\mathrm{sep}}$, as inputs. The exergy input to the plant *by itself* is:

$$\dot{\Xi}_{\mathrm{in}} = \dot{\Xi}_{\mathrm{W,sep}} + \dot{\Xi}_{\mathrm{Q,sep}} = \dot{W}_{\mathrm{sep}} + \dot{Q}_{\mathrm{sep}}\left(1 - \frac{T_0}{T_{\mathrm{s}}}\right) \tag{8}$$

The separation efficiency of the plant *by itself* is:

$$\eta_{\mathrm{sep}} \equiv \frac{\dot{W}_{\mathrm{least}}^{\mathrm{min}}}{\dot{\Xi}_{\mathrm{in}}} = \frac{\dot{W}_{\mathrm{least}}^{\mathrm{min}}}{\dot{W}_{\mathrm{sep}} + \dot{Q}_{\mathrm{sep}}(1 - T_0/T_{\mathrm{s}})} \tag{9}$$

Mistry et al. [22] provided second law efficiency for several model desalination plants, and Tow et al. [23] have compiled values of η_{sep} (based on finite water recovery) for a spectrum of real plants. The above formulation is appropriate for heat transfer by steam condensation at a fixed temperature, T_{s}; however, it needs adjustment for other cases in which steam is used at more than one condition or other mass flows occur. For a case with mass flow in and out, $\dot{m}_i$, and a dead state $(\cdot)_0$, $\dot{\Xi}_{\mathrm{in}}$ should be calculated as:

$$\dot{\Xi}_{\mathrm{in}} = \dot{\Xi}_{\mathrm{W,sep}} + \dot{\Xi}_{\mathrm{Q,sep}} + \sum_{i} \dot{m}_i[(h - h_0) - T_0(s - s_0)] \tag{10}$$

3.4. Combined system efficiency

To express the separation efficiency of the combined system with respect to post-combustion primary energy, we determine the additional post-combustion fuel energy and exergy ($\dot{Q}_{\mathrm{d}}$ and $\dot{\Xi}_{\mathrm{d}}$) needed to generate the heat and work *inputs* ($\dot{\Xi}_{\mathrm{Q,sep}}$ and $\dot{\Xi}_{\mathrm{W,sep}}$) to the plant.

The most difficult part of this analysis is accounting for the change in performance of a power plant from some baseline condition, where no thermal energy is diverted to the desalination plant and the system is optimized for power production, to a condition with steam extraction, where thermal energy is diverted from the power plant, resulting in a power plant efficiency change. In this analysis, we will assume that any change from the baseline condition is attributable to the desalination plant, and that change will be reflected in the calculation of the desalination plant's energy requirement.

In other words, we first consider a power plant without a desalination system, using fuel energy $\dot{Q}_{\rm pp}$ and sending power $\dot{W}_{\rm pp}$ to the grid. This system is optimized for electrical power production, and this hypothetical system is considered our baseline. When the desalination system is added, we assume the power plant still produces the same amount of power for the grid as in the baseline condition, as well as any additional thermal and electrical energy required for the desalination system. Any difference between the baseline fuel requirement $\dot{Q}_{\rm pp}$ and the fuel requirement for the system with the desalination plant $\dot{Q}_{\rm H}$ is attributable to desalination plant and falls under the term $\dot{Q}_{\rm d}$.

3.4.1. Method I - varying power plant efficiency

If we know the amount of power sent to the grid, $\dot{W}_{\rm pp}$, the power plant first law efficiency for a baseline system without steam extraction, $\eta_{\rm b}^{I}$, and the power plant first law efficiency for a system with steam extraction, $\eta_{\rm e}^{I}$, an exact calculation for the desired values of $\dot{Q}_{\rm d}$ and $\dot{\Xi}_{\rm d}$ can be performed. The first law efficiency is defined for both systems using Eq. (5). We also note that $\eta_{\rm b}^{I}$ should be the same for any power plant producing only electricity without steam extraction, whether that be a power plant with no desalination system or a combined water and power plant using RO.

For the baseline case with no heat extraction, the power plant efficiency can be written as:

$$\eta_{\rm b}^{I} \equiv \frac{\dot{W}_{\rm pp}}{\dot{Q}_{\rm pp}} \tag{11}$$

For the case with heat extraction ($\dot{Q}_{\rm sep}$), the power plant efficiency follows from Eq. (5):

$$\eta_{\rm e}^{I} \equiv \frac{\dot{W}_{\rm pp} + \dot{W}_{\rm sep}}{\dot{Q}_{\rm pp} + \dot{Q}_{\rm d}} \tag{12}$$

Combining and rearranging these two equations to solve for $\dot{Q}_{\rm d}$:

$$\dot{Q}_{\rm d} = \dot{W}_{\rm pp}\left(\frac{1}{\eta_{\rm e}^{I}} - \frac{1}{\eta_{\rm b}^{I}}\right) + \frac{\dot{W}_{\rm sep}}{\eta_{\rm e}^{I}} \tag{13}$$

This equation can also be written in terms of the primary exergy added to the desalination plant:

$$\dot{\Xi}_{\rm d} = \dot{Q}_{\rm d}\left(1 - \frac{T_0}{T_{\rm H}}\right) = \left[\dot{W}_{\rm pp}\left(\frac{1}{\eta_{\rm e}^{I}} - \frac{1}{\eta_{\rm b}^{I}}\right) + \frac{\dot{W}_{\rm sep}}{\eta_{\rm e}^{I}}\right]\left(1 - \frac{T_0}{T_{\rm H}}\right) \tag{14}$$

Finally, the overall second law efficiency of the entire cogeneration and desalination operation with respect to primary energy can be calculated as:

$$\eta_{\rm sep,primary} \equiv \frac{\dot{W}_{\rm least}^{\rm min}}{\dot{\Xi}_{\rm d}} = \frac{\dot{W}_{\rm least}^{\rm min}}{\dot{Q}_{\rm d}\left(1 - \frac{T_0}{T_{\rm H}}\right)} = \frac{\dot{W}_{\rm least}^{\rm min}}{\left[\dot{W}_{\rm pp}\left(\frac{1}{\eta_{\rm e}^{I}} - \frac{1}{\eta_{\rm b}^{I}}\right) + \frac{\dot{W}_{\rm sep}}{\eta_{\rm e}^{I}}\right]\left(1 - \frac{T_0}{T_{\rm H}}\right)} \tag{15}$$

Interestingly, the heat of separation utilized by the desalination plant, $\dot{Q}_{\rm sep}$, does not appear directly in these equations. The first term of Eq. (13) accounts for the additional fuel energy that needs to be added to the system to maintain the power output to the grid in spite of the decreasing first law efficiency. The second term accounts for the fuel energy added to the system to generate the electricity required by the desalination plant. Because of the way η^{I} has been defined, the first term accounts for both $\dot{Q}_{\rm sep}$ and the change in thermal energy rejected to the environment, $\dot{Q}_0$. Because both $\dot{Q}_{\rm sep}$ and the change in $\dot{Q}_0$ are due to the extraction of steam from the power plant, we attribute the first term of Eq. (13) to the thermal portion of any desalination plant involving both heat and work.

When there are no heat inputs into the desalination plant, as is the case for a reverse osmosis system, the equations are simplified. The power plant efficiency does not change when comparing a power plant driving an RO plant with a power plant with no desalination system at all, as both power plants have been optimized for electricity production. The $\eta_{\rm e}^{I}$ and $\eta_{\rm b}^{I}$ terms are equal, and the $\dot{W}_{\rm pp}$ term drops out of Eqs. (13)–(15).

These equations directly give the additional energy that must be added to the system when a desalination plant is integrated with a cogeneration system. If all terms required to solve Eq. (13) are known, including the power plant first law efficiency and desalination system electrical energy consumption, this method is recommended for determining the additional energy required by the desalination system.

3.4.2. Method II - fixed power plant efficiency

If knowledge of the desalination system's impact on the power plant efficiency is not available, an estimate of primary energy for desalination is still possible. If the exergy used to make electrical power is much larger than the total thermal exergy used by the desalination system, then the thermal exergy term can be neglected from the denominator of Eq. (6), and the power plant second law efficiency can be regarded as constant regardless of the desalination plant's operating parameters or the amount of steam extracted. Under the assumption of constant second law efficiency, we can estimate the primary energy consumption of the desalination plant.

For desalination technologies that have some thermal energy input (which in this case is all systems except for RO), we assume that all additional high temperature primary energy passes through the power plant before any is diverted at low temperature to the desalination plant (i.e., we assume that high temperature heat is not simply degraded to low temperature as it might be if, e.g., we burned fuel to directly boil off a pot of seawater).

Because energy is conserved as it travels through the power plant, one may think that the high-temperature post-combustion fuel *energy*$\dot{Q}_{\rm d}$ that must be added to produce the low-temperature energy $\dot{Q}_{\rm sep}$ is simply $\dot{Q}_{\rm sep}$. However, the associated high temperature *exergy* input to the power plant is $\dot{Q}_{\rm sep}(1 - T_0/T_{\rm H})$, whereas the exergy of the steam extracted for desalination is much lower: $\dot{Q}_{\rm sep}(1 - T_0/T_{\rm s})$. The exergy difference reflects the fact that $\dot{Q}_{\rm sep}$ is what remains from a larger quantity of high temperature thermal energy, much of which was converted to work by the power plant turbines. The power plant necessarily rejects low temperature heat as it produces work. The difference in coproduction is that some of the rejected heat is taken at a temperature $T_{\rm s}$ greater than T_0. This potentially represents a power loss for the power plant.

The outgoing exergy of the $\dot{Q}_{\rm sep}$ stream is not converted to electric power, and so it represents a potential reduction in the electrical generation of the plant. Because we assume that the power plant second law efficiency is constant regardless of the extraction of the $\dot{Q}_{\rm sep}$ stream, the reduction in power generation because of the steam extraction stream is $\eta_{\rm pp}^{II}\dot{Q}_{\rm sep}(1 - T_0/T_{\rm s})$. To maintain the power production at some desired level, additional fuel had to be added to the power plant to make up for the exergy extracted for desalination and its potential reduction in power generation. The *additional* fuel energy, $\dot{Q}_{\rm d,thermal}$ that had to be added to offset the power loss associated with exergy input to the desalination plant can be found by equating it to the power loss from extracting $\dot{Q}_{\rm sep}$ for desalination [7]:

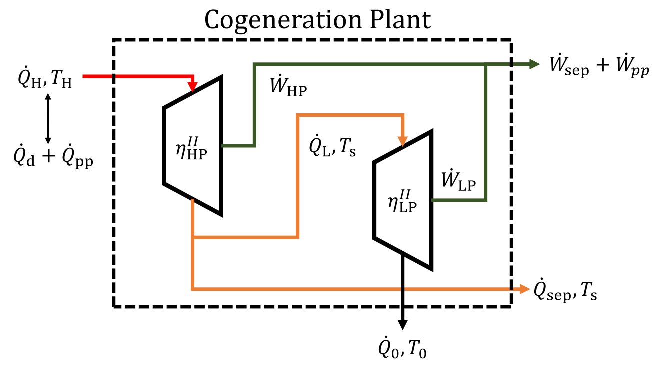

Fig. 2. Diagram of a generalized cogeneration plant, with high pressure turbine with efficiency η^{II}_{HP} and low pressure turbine with efficiency η^{II}_{LP}.

$$\eta^{II}_{\mathrm{pp}} \dot{Q}_{\mathrm{d,thermal}}(1 - T_0/T_{\mathrm{H}}) = \eta^{II}_{\mathrm{pp}} \dot{Q}_{\mathrm{sep}}(1 - T_0/T_{\mathrm{s}}) \tag{16}$$

Thus, the additional required primary energy is[1]:

$$\dot{Q}_{\mathrm{d,thermal}} = \dot{Q}_{\mathrm{sep}} \frac{(1 - T_0/T_{\mathrm{s}})}{(1 - T_0/T_{\mathrm{H}})} \tag{17}$$

Adding the primary energy required to produce $\dot{W}_{\mathrm{sep}}$, which is found by rearranging Eq. (4), gives:

$$\dot{Q}_{\mathrm{d}} = \frac{\dot{W}_{\mathrm{sep}}}{\eta^{II}_{\mathrm{pp}}(1 - T_0/T_{\mathrm{H}})} + \dot{Q}_{\mathrm{sep}} \frac{(1 - T_0/T_{\mathrm{s}})}{(1 - T_0/T_{\mathrm{H}})} \tag{18}$$

Likewise, the primary, or fuel, exergy requirement for the desalination plant is:

$$\dot{\Xi}_{\mathrm{d}} = \dot{\Xi}_{\mathrm{d,electr}} + \dot{\Xi}_{\mathrm{d,thermal}} = \frac{\dot{W}_{\mathrm{sep}}}{\eta^{II}_{\mathrm{pp}}} + \dot{Q}_{\mathrm{sep}}(1 - T_0/T_{\mathrm{s}}) \tag{19}$$

Finally, the second law efficiency of the thermal plant with respect to primary exergy is:

$$\eta_{\mathrm{sep,primary}} \equiv \frac{\dot{W}^{\mathrm{min}}_{\mathrm{least}}}{\dot{\Xi}_{\mathrm{desal,primary}}} = \frac{\dot{W}^{\mathrm{min}}_{\mathrm{least}}}{\dot{W}_{\mathrm{sep}}/\eta^{II}_{\mathrm{pp}} + \dot{Q}_{\mathrm{sep}}(1 - T_0/T_{\mathrm{s}})} \tag{20}$$

Modifications to $\dot{\Xi}_{\mathrm{d}}$ can be made (as shown in Eq. (10)) when flow occurs.

We can use this analysis in all cases where we can assume that the second law efficiency of the power plant does not change significantly with additional heat extraction. This includes cases where the exergy used by the desalination plant is on the same order as the exergy used to generate power. In order to make this assumption, the power plant must function in such a way that both turbines (high and low pressure) have a similar efficiency.

3.4.3. Limitations of method II

The reason that method II provides only an estimate is because power plant second law efficiency is assumed to remain constant because the exergy used to make electrical power is much larger than the total thermal exergy used by the desalination system. This assumption neglects the separation thermal exergy term from the denominator of Eq. (6) as if the small change in efficiency that may arise from the steam extraction stream has a negligible effect on the calculation of power loss due to the desalination plant. While this small change in efficiency may result in discrepancies that are small on the scale of the power plant, they may not be small on the scale of the desalination system, which itself is small compared to the power plant.

To clarify this statement using equations, let us consider a cogeneration plant. For a system with steam extraction, we can think of the power plant as incorporating two separate turbines, with second law efficiencies η^{II}_{HP} in the high pressure turbine, and η^{II}_{LP} in the low pressure turbine, as shown in Fig. 2. The high pressure turbine produces power $\dot{W}_{\mathrm{HP}}$ and the low pressure turbine produces power $\dot{W}_{\mathrm{LP}}$.

For this model, we can write second law efficiencies for the individual turbines:

$$\eta^{II}_{\mathrm{HP}} = \frac{\dot{W}_H}{(\dot{Q}_{\mathrm{pp}} + \dot{Q}_{\mathrm{d}})(1 - T_0/T_H) - (\dot{Q}_{\mathrm{LP}} + \dot{Q}_{\mathrm{sep}})(1 - T_0/T_s)} \tag{21}$$

$$\eta^{II}_{\mathrm{LP}} = \frac{\dot{W}_L}{\dot{Q}_{\mathrm{LP}}(1 - T_0/T_s) - \dot{Q}_0(1 - T_0/T_0)} = \frac{\dot{W}_L}{\dot{Q}_{\mathrm{LP}}(1 - T_0/T_s)} \tag{22}$$

If we combine the two equations, knowing that $\dot{W}_{pp} + \dot{W}_{sep} = \dot{W}_H + \dot{W}_L$:

$$\begin{aligned} &\dot{W}_{pp} + \dot{W}_{sep} \\ &\quad = \eta^{II}_{\mathrm{HP}} \dot{Q}_{\mathrm{pp}}(1 - T_0/T_H) + \eta^{II}_{\mathrm{HP}} \dot{Q}_{\mathrm{d}}(1 - T_0/T_H) + (\eta^{II}_{\mathrm{LP}} - \eta^{II}_{\mathrm{HP}})\dot{Q}_{\mathrm{LP,1}} \\ &\quad (1 - T_0/T_s) - \eta^{II}_{\mathrm{HP}} \dot{Q}_{\mathrm{sep}}(1 - T_0/T_s) \end{aligned} \tag{23}$$

and if we re-write for the case without any desalination plant, we get:

$$\dot{W}_{pp} = \eta^{II}_{\mathrm{HP}} \dot{Q}_{\mathrm{pp}}(1 - T_0/T_H) + (\eta^{II}_{\mathrm{LP}} - \eta^{II}_{\mathrm{HP}})\dot{Q}_{\mathrm{LP,0}}(1 - T_0/T_s) \tag{24}$$

where $\dot{Q}_{\mathrm{LP,0}}$ is the heat that goes to the low pressure turbine in the base case without desalination and $\dot{Q}_{\mathrm{LP,1}}$ is the heat that goes to the low pressure turbine in the case with steam extraction. Taking into account that $\dot{Q}_{\mathrm{pp}}$ and $\dot{W}_{\mathrm{pp}}$ are equal in Eqs. (23) and (24) when considering a particular power plant, we can subtract one equation from the other and rearrange, solving for our desired quantity $\dot{Q}_d$, giving us the equation:

$$\begin{aligned} &\dot{Q}_{\mathrm{d}} \\ &\quad = \frac{\dot{W}_{\mathrm{sep}}}{\eta^{II}_{\mathrm{HP}}(1 - T_0/T_{\mathrm{H}})} + \dot{Q}_{\mathrm{sep}} \frac{(1 - T_0/T_{\mathrm{s}})}{(1 - T_0/T_{\mathrm{H}})} + (\dot{Q}_{\mathrm{LP,1}} - \dot{Q}_{\mathrm{LP,0}}) \frac{(1 - T_0/T_{\mathrm{s}})}{(1 - T_0/T_{\mathrm{H}})} \\ &\left(\frac{\eta^{II}_{\mathrm{LP}} - \eta^{II}_{\mathrm{HP}}}{\eta^{II}_{\mathrm{HP}}} \right) \end{aligned} \tag{25}$$

Notably, the first two terms are similar to what we found in Eq. (18) but with a different second law efficiency. If the bulk of the energy is generated in the high pressure turbine, then we would expect the $(\dot{Q}_{\mathrm{LP,1}} - \dot{Q}_{\mathrm{LP,0}})$ term to be on the order of $\dot{Q}_{\mathrm{sep}}$. If the low and high pressure turbines have a similar second law efficiency, then the third term drops out, and we can use the analysis of the previous section to get an accurate estimate of $\dot{Q}_{\mathrm{d}}$. However, if there is a significant difference between the high and low pressure turbine efficiencies, the third term could be large enough to cause significant errors in the calculation of $\dot{Q}_{\mathrm{d}}$.

While method II will give an estimate for $\dot{Q}_{\mathrm{d}}$, the authors do not encourage using method II to compare various desalination methods, especially when the resulting $\dot{Q}_{\mathrm{d}}$ values for different systems are very similar, or when considering desalination plants that use thermal energy at different temperatures and pressures. Doing so will cause a larger error in the third term of Eq. (25), potentially leading to incorrect conclusions if method II is used to compare desalination plants.

If the second law efficiency of the overall system decreases when steam extraction is added, then the result of using method II is a lower-bound estimate on the primary energy that must be added to the system to account for the desalination system. By performing the analysis under the assumption of an unchanging power plant second law efficiency, we are neglecting the negative effects of the steam extraction on the power plant performance, leading to an underestimate of $\dot{Q}_{\mathrm{d}}$. This can be useful when comparing a thermal technology to RO, as we can

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[1] We may consider the rest of the energy $\dot{Q}_{\mathrm{sep}}$ as if it were heat that must be discharged from the electricity production process. The analysis of the additional energy and exergy has been previously considered by El-Sayed and Silver [7] and by Mistry and Lienhard (2013) [10]. Other analysis can be found in those papers. The key idea in those works is that the entropy generated in the power plant can be written in proportion to $(1 - \eta^{II}_{\mathrm{pp}})$, but the result is the same as above.

Table 1

Annual average fixed environmental and operating conditions for desalination systems.

Variable	Value	Units
Desalination plant capacity	100,000	m^3/day
Intake water salinity	44	g/kg
Intake water temperature	33	°C

compare the lower bound of $\dot{Q}_d$ for thermal systems to actual values of $\dot{Q}_d$ for RO, giving us an understanding of the limit of how good thermal systems can be relative to RO, when power plant effects are neglected.

However, if η^{II}_{HP} is greater than η^{II}_{LP}, then the bound we calculate is actually an upper bound on the primary energy required by the desalination system. In this case, the low pressure turbine is less efficient than the high pressure turbine, and removing exergy from the low pressure turbine via steam extraction will shift more electricity to be generated in the high pressure turbine, increasing the power plant second law efficiency. Because of this discrepancy, it is important to have an understanding of the inner workings of the cogeneration plant if the results of method II are to be used for anything other than a rough estimate of $\dot{Q}_d$.

3.4.4. Note on combustor or collector efficiency

If we had included the losses in the combustor or solar collector and absorber, the losses in these components would equally affect the heat and work terms in Eq. (19) or Eq. (13), because the losses occur before the power generation process [10]. These losses can be accounted for by dividing $\dot{Q}_d$ or $\dot{\Xi}_d$ by the second law efficiency of the components that convert the system's fuel (fossil fuels or solar radiation) into the thermal input into the power plant ($\dot{Q}_H$). The inclusion of these components will affect the second law efficiency of the system, $\eta_{sep,primary}$, and would allow for a calculation of additional fuel or radiation required by the cogeneration plant to power the desalination plant. However, for the remainder of this analysis, we will exclude these components for simplicity, focusing on the thermal energy required to power the desalination plant, $\dot{Q}_d$.

4. Determination of combined system operating parameters

For each of the 48 unique systems we analyze here, we have calculated the performance of a combined cogeneration-desalination plant. The environmental and operating conditions, which are based on average conditions encountered in desalination plants in the GCC region and which are commonly applicable for all the technology alternatives considered in this study, are listed in Tables 1 and 2.

The operating parameters for each desalination plant and power plant combination are determined using data from real plants already in operation or from numbers quoted in the process of bidding for new projects. Thermoflow software is used to determine the energy requirements from these operating parameters. Additional data and calculations can be found in the supporting information. As noted before, some of the quoted performance characteristics, especially those for FO and MD, have not been proven at large scale yet and should be regarded as optimistic estimates.

Because real desalination plants are designed to minimize the cost of water without regard for recovery ratio, not all desalination plants are operating at the same recovery ratio. We consider this study to be a comparison of primary energy requirements for cost-optimized power and water production systems. Recovery ratio differences would be important if we were calculating the second law efficiency as a function of the least work at finite recovery. However, because we are calculating second law efficiency with respect to minimum least work at zero recovery, varying recovery ratios will not affect the interpretation of the results from a thermodynamic perspective. This approach treats all product water as if we are blind to the process that produced it and the recovery ratio. This makes sense when looking at cost-optimized technologies, as the user generally prioritizes the cost of water when making decisions about technology selection. However, this approach may lead to other important aspects of desalination plant operation being ignored. When trying to compare the operating costs of various plants, it will be important to take varying recovery ratios into account when considering the costs of pretreatment, chemicals, pumps, etc.

In order to have a fair comparison between the technologies, we also have a fixed amount of power and water output from the combined water and power plant. In real plant development, the ratio of power output to water output, or power to water ratio (PWR), may not be fixed. This allows for plant designers to adjust this ratio to optimize the performance of the system. Some plants considered here may be able to operate more efficiently with a different power to water ratio.

Another complicating factor is that the criteria by which we have selected these systems (typical recovery values and operating parameters), is different than the basis of comparison (specific primary energy consumption). Additionally, the correlation between recovery ratio and energy requirement is different for each technology considered here. Generally, the correlation between recovery ratio and energy consumption is stronger for work-based technologies, like RO, and less strong for thermal or evaporative desalination technologies. The recovery ratios of each type of desalination plant are shown in Tables 3 and 4. Additional operational details for all desalination plants and power plants can be found in the appendices and supporting materials. We also note here that the recovery ratios for thermal processes do not take cooling water into account.

5. Results

Exergetic efficiency with respect to primary energy is evaluated based on Eq. (15) and plotted for all technology combinations analyzed in this study in Fig. 3. Results for specific primary energy consumption are shown in Fig. 4. Here, specific primary energy consumption is a measure of the amount of thermal energy that enters the cogeneration plant per cubic meter of water produced by the desalination system. The values reported in this section are not a measure of the incident solar energy or fuel chemical energy, but the energy that enters the cogeneration plant after absorption or combustion. Referring back to

Table 2

Operating conditions for combined cogeneration power plants. *Note that the CCGT plant is operated with fixed fuel input, resulting in a variable gross power production, while the other plants are operated with fixed gross power production.

	Combined Cycle Gas Turbine	Oil fired	Parabolic Trough CSP	Power Tower CSP
Fuel combustion or absorber temperature, T_H	1250 °C	1300 °C	450 °C	610 °C
First law efficiency range	56–59%	42–46%	37–41%	38–43%
Carnot efficiency	79.9%	80.5%	57.7%	65.3%
Second law efficiency	74–75%	55–57%	71–73%	64–66%
Gross power produced	823–868 MW*	660 MW	400 MW	400 MW

Table 3
Recovery ratio of desalination plants with only one section producing product water. Systems that have not been validated at large scale are noted with an asterisk.

Desalination System	RO	MED	MEDT	MSF	FO*	MD*	NF-MED	NF-MEDT	FO*-MSF
Recovery Ratio	40%	30%	30%	36%	35%	60%	35%	35%	40%

Table 4
Recovery ratio of hybrid desalination plants with multiple sections producing product water and overall net recovery ratio. Systems that have not been validated at large scale are noted with an asterisk.

Desalination System	Section	Section Recovery Ratio	Overall Recovery Ratio
RO-MED	RO	45%	33.8%
	MED	30%	
RO-MEDT	RO	45%	33.8%
	MEDT	30%	
RO-MSF	RO	45%	38.3%
	MSF	36%	
NF-RO-MED	RO	50%	38.8%
	MED	35%	
NF-RO-MEDT	RO	50%	38.8%
	MEDT	35%	
FO*-MED	FO*	35%	31.3%
	MED	30%	
RO-FO*	RO	40%	38.8%
	FO*	35%	

Section 3 and Fig. 1, specific primary energy consumption in this paper is calculated as

$$Q_{\text{spec}}^{\text{primary}} = \frac{\dot{Q}_{\text{d}}}{\dot{V}_{\text{product}}} \tag{26}$$

In order to include the losses caused by the combustor or solar collector and absorber and obtain a measure of incident solar radiation or chemical energy required per unit of water produced, see Section 3.4.4.

Under the operating conditions described in previous sections, RO is the most efficient desalination technology with respect to primary energy, and RO is about twice as efficient as MED for a CCGT power plant (20.6% 2nd law efficiency for RO compared to 11.3% for MED). Previous analyses of *stand-alone* desalination plants have found the difference between these two technologies to be much greater [22,24,25]. One reason that the difference is smaller on the basis of primary energy is that the conversion of high temperature thermal exergy into electricity destroys a significant amount of exergy. While the use of low-temperature steam extraction appears to favor thermal and evaporative systems, the benefits of using low specific exergy steam are fully offset by the high efficiency of RO in the desalination portion of the system.

Analyzing second law efficiency from the perspective of primary energy instead of at the desalination plant level provides a more

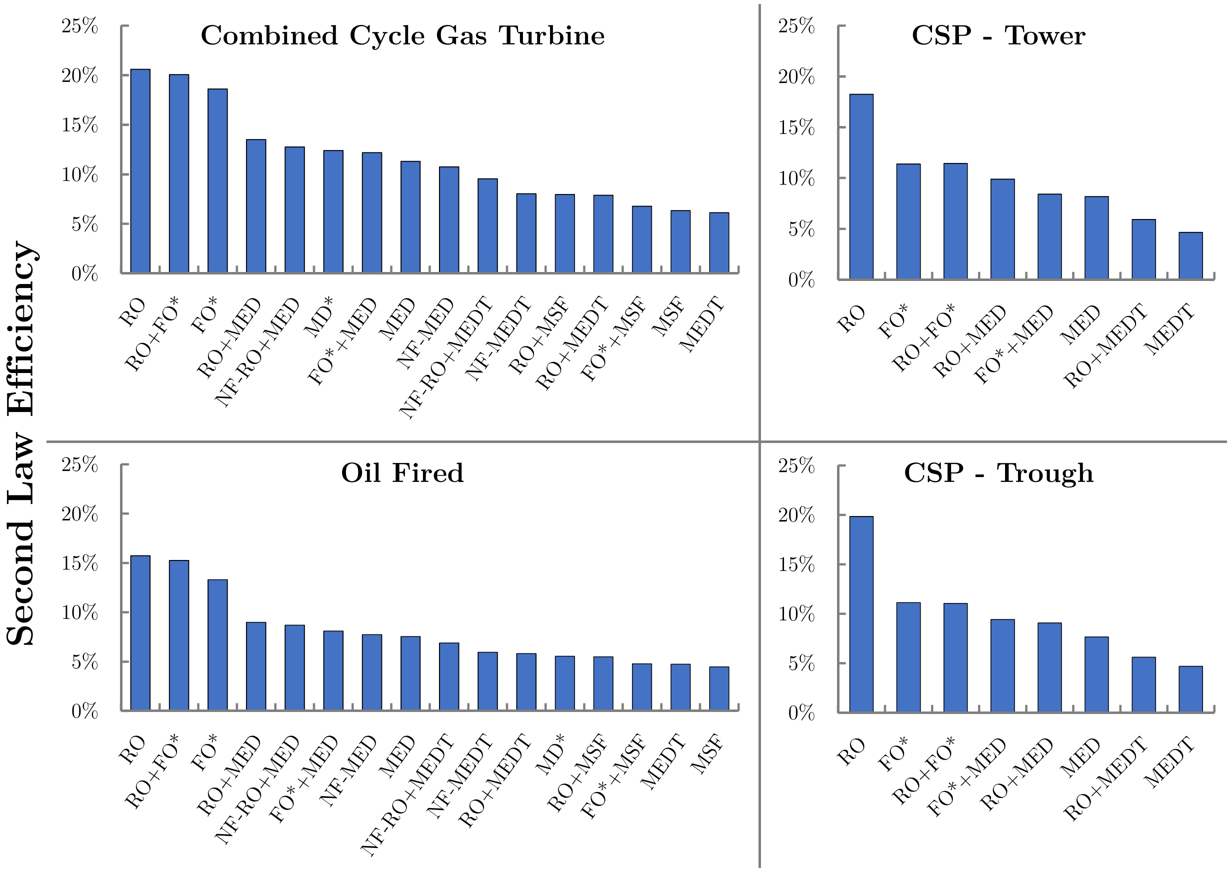

Fig. 3. Second law efficiency with respect to primary energy of various desalination technologies, by power plant type. Systems that have not been validated at scale are marked with an asterisk.

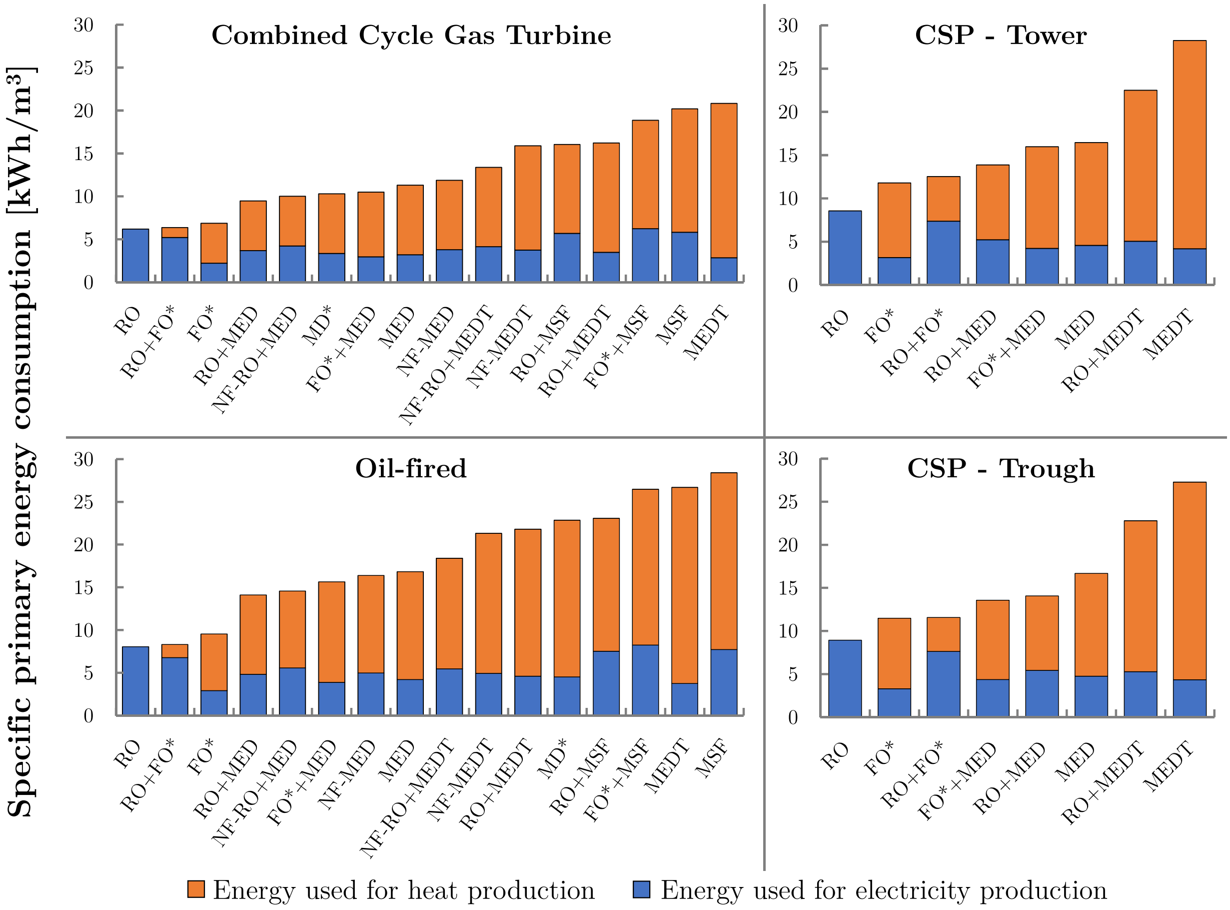

Fig. 4. Specific primary energy consumption of all technology combinations analyzed in this paper, by power plant type. Systems that have not been validated at large scale are marked with an asterisk. Primary energy is considered to be the post-combustion or post-absorption thermal energy entering the power plant.

accurate picture and does not unfairly advantage electrically driven desalination plants, a point that also was made in the work of Mistry and Lienhard [10]. Further implications of using primary energy instead of energy at the plant level extend to comparisons of MVC and MED. When analyzing stand-alone desalination plants, stand-alone MVC outperformed stand-alone MED in terms of energy consumption in two studies that looked at both technologies [22,24]. However, assuming an electrical energy consumption of 7–12 kWh/m^3 for MVC (which is in line with previous studies [22,24]) and using Eqs. (18) and (20), we estimate a range of 11.8–20.3 kWh/m^3 of primary energy consumption and a second law efficiency of 10.8 to 6.3% when considering cogeneration with a CCGT power plant. As a result, MVC is surpassed by MED in terms of second law efficiency under these conditions, providing a different result than the stand-alone system analysis.

Another striking result of this analysis is that FO emerges as the second best technology, closely approaching RO and far-outperforming MED. The FO process considered in this study uses a novel draw solution that releases pure liquid water by phase separation upon heating to below the boiling point, and allows for operation using reduced amounts of low-quality heat. Specifically, the draw solution is an ethylene oxide-propylene oxide copolymer solution from Trevi Systems Inc. [26]. As a result, no evaporation is involved in the draw regeneration step and the heating energy can be effectively recovered from the draw solution and the pure water stream using heat exchangers. If the high performance that has been projected for FO can be attained in practice for large scale systems (a GOR of nearly 21 has been estimated), FO would approach RO in terms of energy consumption. If the FO GOR is significantly lower in practice than in small-scale pilot tests, then FO will not approach RO.

It is also interesting to note that the performance of the MD system here is similar to that of MED since the variant of MD considered is a vacuum multi-effect membrane distillation process whose operating principle exactly mimics that of an MED device. That MD system has not yet been proven at scale, however.

5.1. *MED and MEDT*

MED-TVC performs worse in terms of primary energy than standard MED, even though MED-TVC has a higher GOR. This is due to the difference in specific exergy of the steam feeding the two desalination systems. Although MED-TVC requires less thermal energy, it requires steam at higher temperature and pressure, which is associated with a greater power loss. Standard MED uses steam with a lower temperature and lower exergetic value, reducing the power loss associated with extracting the steam from the turbine, and leading to better thermodynamic performance and less primary energy consumption.

This result highlights the fact that using GOR to compare desalination plants without considering the quality of the incoming steam can be misleading. This result is especially important considering that much

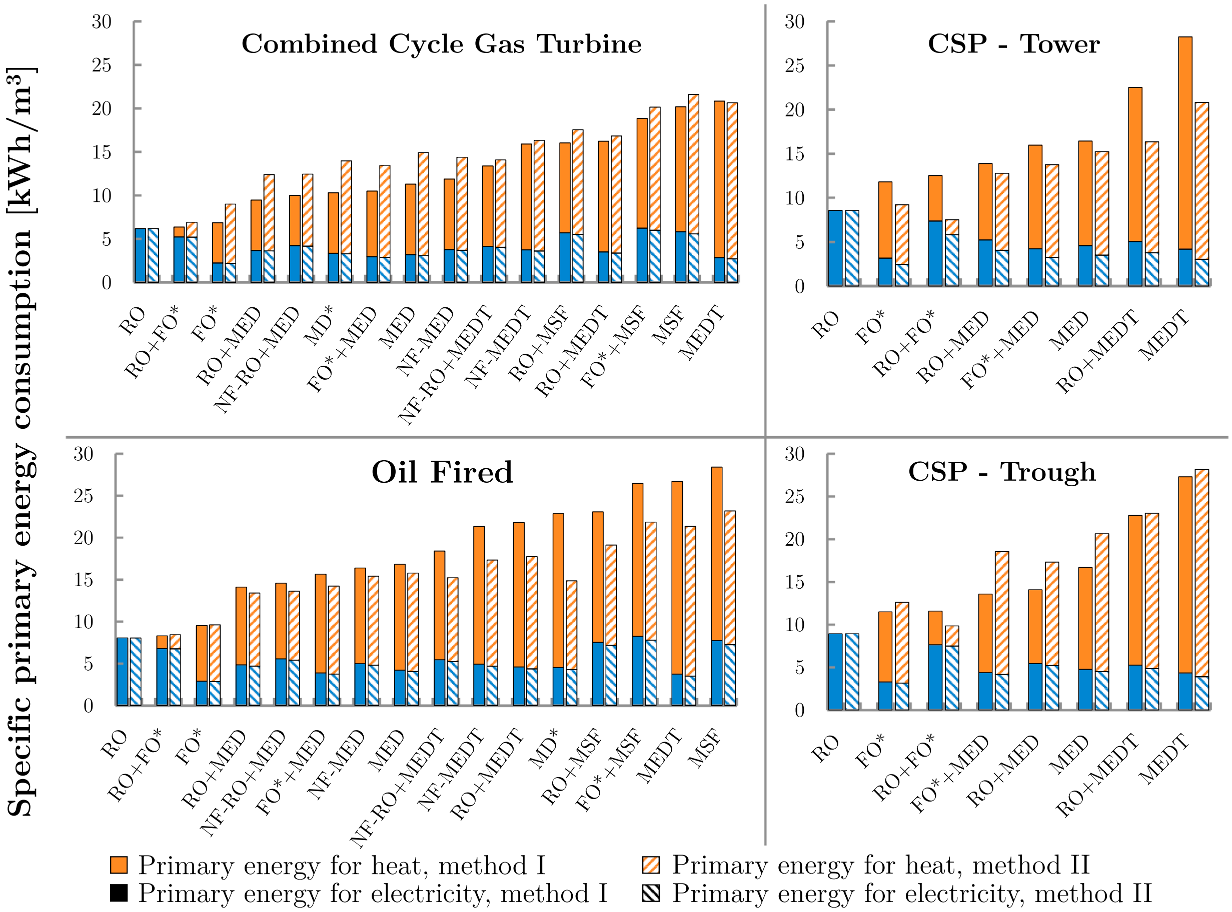

Fig. 5. Specific primary energy consumption of all technology combinations analyzed in this paper. Each technology is shown with its performance found using both methods of calculating primary energy consumption, as described in Section 3. Primary energy is considered to be the post-combustion or post-absorption thermal energy entering the power plant. Systems that have not been validated at large scale are noted with an asterisk.

of the research surrounding MED and MED-TVC today is focused on improving GOR [27,28], and some past research has concluded that MEDT is better than MED from a thermodynamic perspective because of the high GOR [29].

Other factors may encourage the use of MEDT, such as system size, operational benefits, or cost concerns. One practical concern is the volume of steam that must be transported at low pressures in MED, which is significantly larger than would be required for an equivalently sized MEDT plant. For large scale plants, the size of the ducting that would be required to operate MED plant using low pressure steam may be large enough to create cost barriers. In the future, utilizing alternative methods of transferring thermal energy from low pressure steam to the desalination plant, such as a hot water loop, may be employed to allow for further development of MED with low grade heat.

5.2. Discussion of methods

The results of all technology combinations for both methods described in Section 3 are shown in Fig. 5. As was discussed previously, we consider method I to provide accurate calculations of primary energy consumption, while method II is better suited for estimating the approximate primary energy consumption when not enough information about power plant first law efficiency is available. The calculated specific primary energy consumption for both method I and method II is shown in more detail in the supporting information.

As described in Section 3.4.3, the difference between the two methods arises because method II assumes a fixed second law efficiency. The fact that there is a significant difference in results from the two methods shows that this assumption is not valid for most cases. Additionally, the fact that method II sometimes provides an overestimate of primary energy consumption and sometimes provides an underestimate tells us that the effect of extracting steam from turbines is sometimes beneficial in terms of power plant second law efficiency and sometimes harmful. The only way to reliably predict if we would produce underestimates or overestimates would be to know the efficiencies of the turbine stages before and after the steam extraction (η_{HP}^{II} and η_{LP}^{II} from Section 3.4.3). Additionally, this error can be quite large, as we show discrepancies in primary energy consumption of up to 35% between the two methods. Due to the potential for large errors and difficulty in predicting the results we will get with method II, we do not recommend using method II for anything other than a first-order estimate, or as a tool for understanding system operation.

As was described in Section 3.4.3, the cases where method II provides an overestimate, such as all cases utilizing the CCGT plant, are cases where the steam extraction occurs in a part of the turbine that operates at lower efficiency than the rest of the power plant. The steam extraction causes the power plant second law efficiency to increase in reality, but because it is assumed to be constant in method II, the result is an overestimate of primary energy consumption. The opposite is true for the oil fired power plant, where method II results in a lower bound estimate in all cases.

Using the logic of method II, we would also assume that power

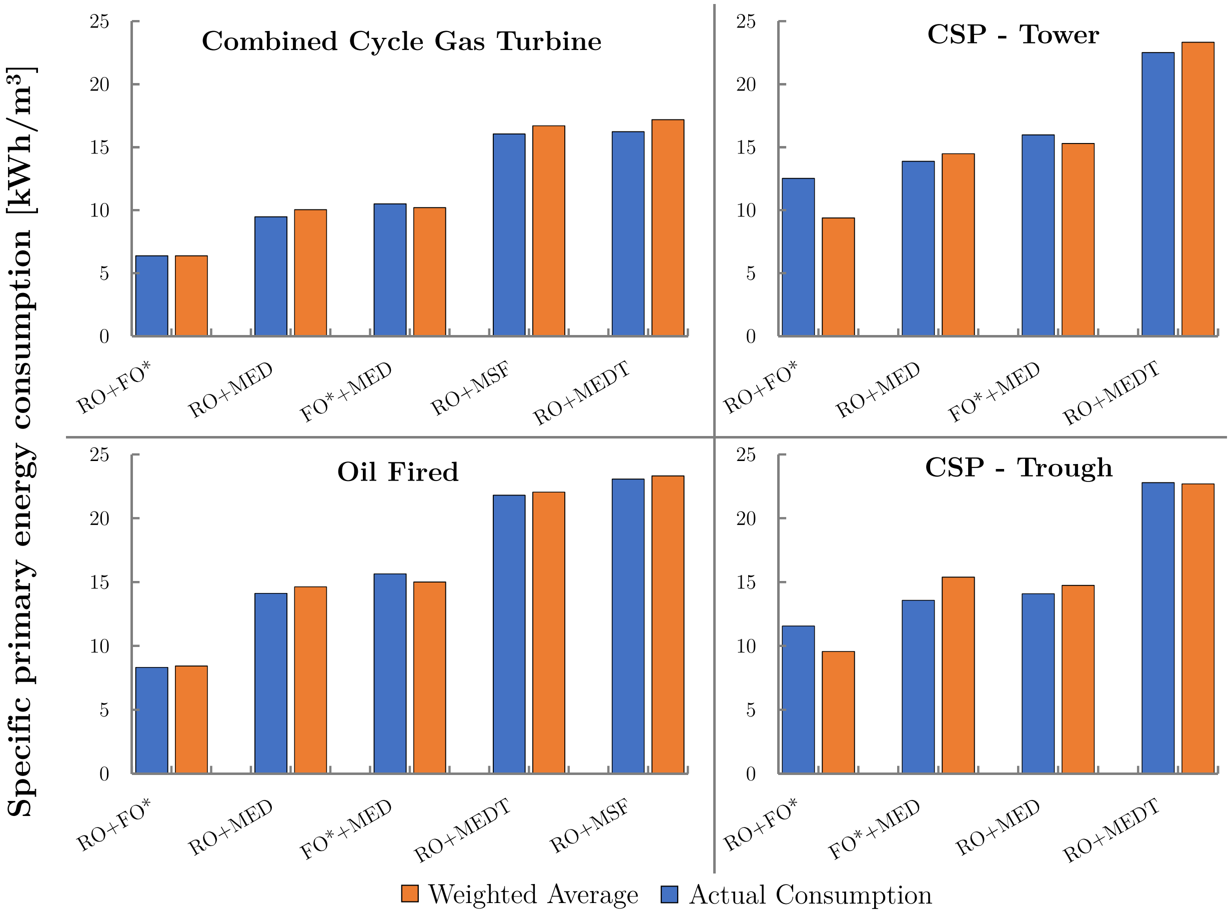

Fig. 6. Specific primary energy consumption of several technologies when hybridized with RO or FO. Primary energy is considered to be the post-combustion or post-absorption thermal energy entering the power plant. Systems that have not been validated at large scale are noted with an asterisk.

plants with low second law efficiency would tend to make thermal or evaporative desalination systems look better relative to RO. However, this does not happen when we evaluate all systems with method I. Under the assumption of constant power production, we instead find that what really matters is how power plant efficiency changes with heat extraction, not the absolute efficiency itself. This is illustrated in Eq. (18). Another way to state this is that if we first consider a power plant operating without desalination, we care about how the efficiency changes when some amount of steam is extracted at the desired temperature.

5.3. *Advantage of hybridization*

Another interesting finding from these results is that systems that hybridized with RO performed better than a simple weighted average of the two technologies for all but one system, while systems that hybridized with FO did not uniformly outperform the weighted average.[2] The primary energy consumption for hybridized systems is shown in Fig. 6. It is important to note here that the RO hybrids outperform their weighted average even when the recovery ratio of the hybridized RO portion increases above that of standard RO, and so we would expect that all RO hybrids would outperform their weighted average if compared on the basis of systems with equivalent recovery ratios.

The fact that RO hybrids outperform the weighted average of their components can be rationalized by the advantages described in Appendix A.3.1, including eliminating the 2nd pass in two-pass RO systems and increasing RO feed temperatures, which improves flow through the membrane. Although RO hybrids allow for some advantage over thermal technologies, a standard RO plant is still better from an energetic perspective. While there may be applications in which it makes sense to hybridize RO with some other technology due to operational constraints, reliability concerns, cost measures, or simple integration with existing plants, we do not expect any system which hybridizes RO with a thermal desalination technology to approach the primary energy efficiency of a standard seawater RO plant.

FO hybrids do not have the same performance benefits as RO hybrids. This is due to the fact that the FO hybrid configurations are essentially two separate systems operating in parallel. Because no measurable heat or mass is transported between the two systems being hybridized, and there are no other significant energetic benefits added by including another system (like eliminating a 2nd pass, as can be done with RO), the performance of FO hybrids aligns with the weighted average in most cases. The cases that do not align with the weighted average deviate for a number of reasons, including variable steam conditions (superheated or wet) even though extraction pressures are the same, multiple steam extraction and return points affecting system operation, and rounding errors.

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[2] The weighted average is calculated by multiplying the specific energy consumption of each non-hybridized technology component by the fraction of total product water provided by the respective technology component, and summing over all technology components. This weighed average is only useful as a comparison metric when both desalination technology components are producing product water. For example, the FO-MSF plant operates by having the FO plant dilute brine for the MSF plant, rather than producing pure water. Because each desalination system is not recovering pure water, comparing between the hybridized system and the weighted average of the components is irrelevant.

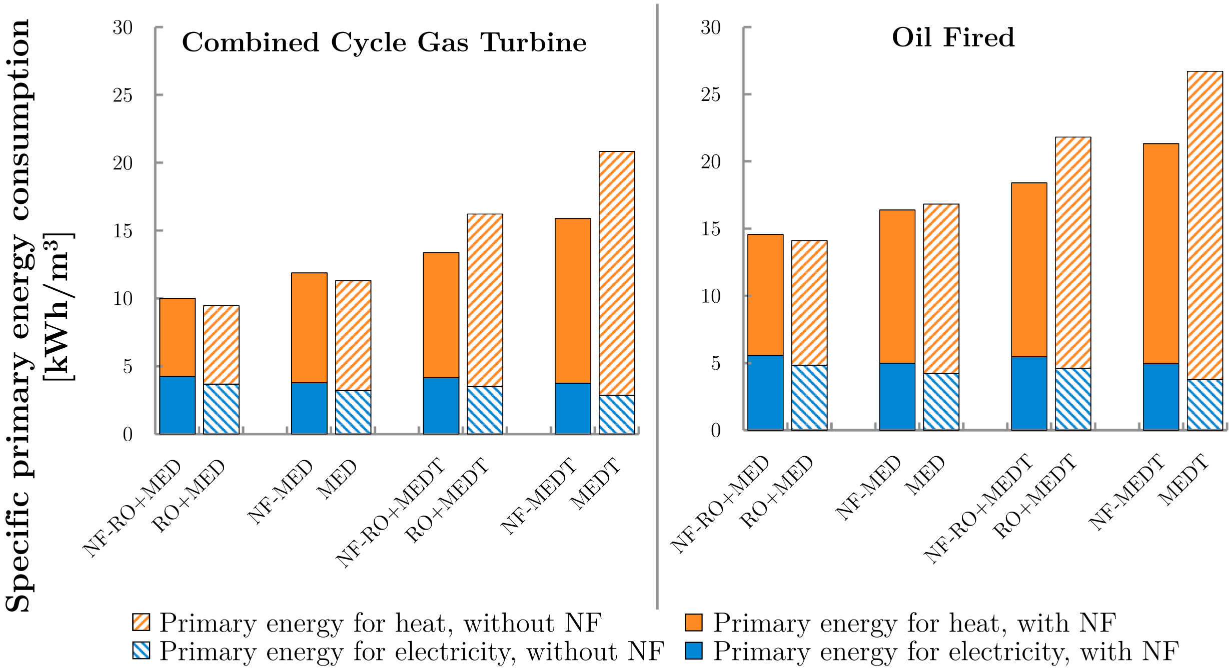

Fig. 7. Specific primary energy consumption of several desalination technologies with and without NF pretreatment. Primary energy is considered to be the post-combustion thermal energy entering the power plant.

5.4. NF pretreatment

NF pretreatment allows the efficiency of several thermal technologies to be increased by allowing the top brine temperature to be increased. The increased top brine temperature allows for greater efficiency in desalination systems, but also allows for higher recovery ratios, which tends to increase primary energy consumption. These effects are reflected in the specific primary energy consumption results shown in Fig. 7.

As with other comparisons in this study, the overall advantage of adding an NF module must be evaluated, accounting for the increased capex (membranes, pressure vessels, pumps etc.) and opex (membrane replacement, cleaning) of the NF system as well, while also taking into account recovery ratio changes.

5.5. Limitations

The present analysis answers questions about thermodynamic efficiency only, and a full cost analysis would provide a clearer picture about which technologies are best suited for various applications. Additionally, the data produced in this analysis is for a specific range of conditions, specifically for Arabian Gulf seawater conditions and utilizing equipment and contractors who have bid for plants in GCC states. Although this data can serve as a useful benchmarking tool for other locations and applications, the power plant and desalination plant operating conditions will also have to be explicitly considered in other cases. Additionally, a fixed power to water ratio is used to compare different desalination plants for each power plant case so that all comparisons are done on a fair basis, even though actual system designs may adjust this ratio to achieve optimal performance and maximize profit potential. Discussions of design optimization for cogeneration plants is available in the literature [30].

Desalination technologies may be compared on the basis of primary energy consumption for systems that share a common fuel source, but care should be taken not to compare systems with different fuel sources. In particular, if a given plant received heat and electricity from different primary energy sources, the present comparisons are invalid. While comparing on the basis of primary energy allows for the fair comparison of systems powered by heat, work, or some combination of the two, it does not allow for the comparison of fuel sources. In order to do this, a complete analysis including fuel costs and capital costs should be performed on a case-by-case-basis, for example, with an economics-based second law efficiency [31].

6. Conclusions

Considering the primary energy use of desalination systems paired with a cogeneration power plant allows for the fair comparison of the energy efficiency of desalination technologies. Although the relative efficiency of electricity-driven reverse osmosis is still greater than that of thermally-driven systems, such as multiple effect distillation and multi-stage flash, the gap between the technologies is reduced significantly when the comparison is done using primary energy consumption rather than at the desalination plant level. This difference results from taking into account the inefficiency in production of electricity. In terms of primary energy, the relative performance of some desalination systems is reordered compared to stand-alone plant analyses; for example, as a stand-alone system, mechanical vapor compression outperforms multiple effect distillation, but MVC has a lower second law efficiency than MED when the comparison is based on primary energy consumption.

Additional conclusions from this work are as follows:

- Although the gap between reverse osmosis and thermal technologies is lowered on a primary energy basis, reverse osmosis is still the most energy-efficient technology for seawater desalination in every single case examined in this study.
- The primary energy requirement for desalination is affected both by the power plant efficiency and the change in power plant efficiency that results from extracting steam. Depending upon how power plant efficiency changes with heat extraction, either thermal or electrical technologies can be favored.
- If forward osmosis technology can achieve high thermal energy efficiency at large scale, the energy efficiency gap between forward

osmosis and reverse osmosis is significantly reduced by considering primary energy consumption.
- The efficiency of many technologies can be improved by hybridizing with other desalination technologies to take advantage of operational benefits and to leverage the best aspects of each technology.
- While there may be applications in which it makes sense to hybridize reverse osmosis with some other technology, we do not expect any system which hybridizes reverse osmosis with a thermal desalination technology to approach the primary energy efficiency of a standard seawater reverse osmosis plant.
- Pretreating feedwater with nanofiltration can help to prevent fouling in many desalination systems and can allow for higher efficiency and higher temperature operation in thermal desalination systems.
- Assuming that steam extraction for desalination has a negligible effect on power plant second law efficiency can lead to inaccurate estimates of primary energy consumption; determining primary energy consumption by a first law energy balance is preferred.

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Appendix A. System configurations

As stated in Section 2, we examine five different core desalination technologies, along with various hybrids, constituting a total of 16 different desalination systems investigated. When combined with the various power plant options, 48 unique combinations are analyzed.

A.1. Mature technologies

Reverse osmosis (RO), multiple effect distillation (MED), and multi-stage flash (MSF) are technologies that are considered to be mature, in that they have been proven over a long period of time at large scale, and their performance is well understood by the desalination community. Although incremental improvements are constantly being developed and introduced, basic performance characteristics of these technologies are well known both in industry and in academia.

A.1.1. Reverse osmosis

RO is the most common and fastest growing technology for potable water production from seawater around the world [32]. RO separates fresh water from a pressurized saline solution using a semi-permeable, salt-rejecting membrane. No intentional heating or evaporation is involved in this separation. Of the energy required to desalinate with RO, the largest portion is used to pressurize the feedwater. The saline feedwater is pumped into a pressure vessel, where the pressurized salt water contacts the RO membrane. Since the applied hydraulic pressure is greater than the osmotic pressure differential across the membrane, a portion of the water passes through the membrane, while salt is rejected. The remaining feedwater increases in salt concentration and is discharged from the pressure vessel as brine. The concentrated brine passes through a mechanical energy recovery device (ERD) before being discharged into the sea. Depending on the cost of electricity, energy costs can account for up to 60% of the final product water costs, thus making highly efficient ERDs of vital importance. Several ERDs have been developed to recover the energy from SWRO brines, but isobaric pressure exchangers [33] and DWEER devices [34] are the most energy efficient devices in use today.

The fraction of incoming feedwater recovered as permeate, called the recovery ratio, varies from 40% to over 60% [35], depending on the salt content of the feedwater, hydraulic pressure, and type of membrane used. Recovery ratios for RO systems have increased over the years from lower values of around 25% to current values of up to 45% in the harsh Middle East seawater conditions [36].

Depending on the requirements for product water quality, RO processes can involve one or two passes through membranes. While most contaminants are effectively rejected by the RO membrane, RO's efficacy with respect to boron removal is relatively poor. In cases where this poses a problem and the boron concentration in the permeate stream is higher than WHO recommended limits, the permeate may be pressurized and passed through a second RO module for further purification. Such a design is referred to as two-pass RO. The selection of pretreatment technology for desalination in seawater reverse osmosis (SWRO) applications is also critical in achieving the desired plant performance and product quality. While the reverse osmosis section is undoubtedly the main energy consumer of an SWRO plant, pretreatment processes can account for a substantial fraction of the plant's total energy consumption, especially in the case of high-complexity treatment trains. More information regarding RO operation can be found in [12].

A.1.2. Multiple effect distillation

Multiple effect distillation (MED) is a commonly used evaporative technology for producing high quality distillate from seawater. The system is composed of a series of effects. Each effect in MED contains a horizontal tube bundle heat exchanger. Seawater is sprayed at the top of the tube bundle and flows down the outside of the tubes due to gravity. At the first effect, external steam is used to supply energy to the MED process. The heating steam is introduced inside the tubes where the steam condenses into distillate. The seawater outside the tubes receives the condensation heat (latent heat) and partially evaporates, creating vapor that can be passed to the inside of the tubes of the next effect. As the seawater flows down the tube bundle and loses water as vapor, the remaining seawater is concentrated, resulting in brine accumulating at the bottom of the cell. The vapor generated by seawater evaporation is at a lower temperature than the initial heating steam, but it can still be used as heating media for the next effect, where evaporation and condensation occur at a lower operating pressure. The decreasing pressure from one cell to the next also drives the flow of brine and distillate to each successive cell, where the brine will flash and release additional amounts of vapor at the lower pressure [14].

This cascade of condensing vapor into distillate and evaporating the solution to generate more vapor continues until the generated vapor is condensed in the last effect by transferring the heat in the condenser to the cooling water (seawater). A portion of the heated seawater exiting the final condenser tubes becomes the makeup water for evaporating effects while the remainder is discharged to the sea. Brine is collected from the last effect of the evaporator and discharged while the distillate is collected from the final condenser. To increase the gained output ratio (GOR) of the process, a portion of the vapor generated in an intermediate or last effect is recompressed in a thermal vapor compressor (TVC) and fed inside the tubes of the first effect to supply heating. This process is then referred to as MED-TVC or MEDT [15]. To avoid the contamination of distillate by the mixing of vapor produced from the evaporator and the power plant steam, which may contain hydrazine, an isolation heat exchanger called a steam transformer may be used.

A.1.3. Multi-stage flash

Multi-stage flash (MSF) desalination has proven to be the one of the most reliable desalination technologies for the Arabian Gulf region. MSF desalination is characterized by high capacity, reliability, and simple operation [13]. However, this desalination method requires more thermal and electrical energy than other desalination technologies. Consequently, more and more MSF plants are being replaced by other types of plants.

The MSF desalination process begins with preheated seawater being heated in a vessel called the brine heater. This is generally done by condensing steam on a bank of tubes that carry seawater, which passes through the vessel. The heated seawater flows into another vessel, called a flash chamber (FC), which generally consists of twenty or more stages, each maintained at a slightly lower pressure than the previous stage. The sudden introduction of the heated seawater into the low-pressure chamber causes a portion of the seawater to flash into steam. Generally, only a small percentage of the incoming water is converted to steam in each stage, since the heat of vaporization quickly cools the remaining seawater to the saturation temperature associated with the stage pressure. The steam generated by flashing is condensed on tubes of heat exchangers that run through each stage. The tubes are cooled by the incoming feedwater going to the brine heater. The incoming feedwater is in turn warmed, so that the amount of thermal energy required in the brine heater is reduced. The final brine is collected from the last stage of the flash chamber and the distillate is collected from the last stage of the flash chamber through the distillate channel.

A.2. Emerging technologies

We also examine two new, emerging technologies in this paper. These technologies have had their performance demonstrated at bench or pilot scale, but have not been implemented in large scale projects yet. The data for these technologies comes from projections, not data from the field, and as such the conclusions drawn about these technologies are more speculative. Results for these technologies should not be treated with the same confidence as other technologies.

A.2.1. Forward osmosis

Forward osmosis (FO) is a membrane separation process in which pure water from the feed solution passes through a semi-permeable membrane into a concentrated draw solution. In contrast to an RO system, where pressurized feedwater is separated into concentrated brine and permeate, an FO system does not pressurize the feedwater, instead allowing osmosis to draw water out of the feed and into the concentrated draw solution, resulting in two output streams: a concentrated brine and a dilute draw solution. The concentrated brine is disposed of back into the ocean. The diluted draw solution can be regenerated by a number of processes, resulting in the separation of the diluted draw solution into a pure product and a concentrated draw solution.

The spontaneous movement of water from the feed stream into the draw solution generates entropy and actually increases the minimum energy of separation for the system [37]. However, novel draw solutions may enable pure water recovery from the draw at high exergetic efficiency, potentially leading to primary energy requirements on par with RO. Even if the primary energy consumption of FO is higher, other practical advantages such as FO's often-stated fouling resistance under typical operating fluxes and low hydraulic pressure which results in reduced capital investment, could make FO an economical alternative to RO in some situations. Hence, FO is chosen as one of the key technologies in this study. Understanding the overall energetics of FO and comparing them to RO in a consistent way is essential, since a significantly higher energy cost for FO can render the other practical advantages of FO relatively useless. Research in FO remains active, especially with respect to novel draw solutions [38], fouling propensity [39], and efforts to understand how the hydraulic pressure level affects FO performance [40]. Further information on FO [16], its development [41], and future research directions [42] are available in the literature.

The system we consider in this analysis [26] uses four stages (pretreatment, forward osmosis with 10 inch TOYOBO hollow fiber membranes, regeneration with a coalescer, and NF post-treatment). The system regenerates the draw solution by supplying heat, and the draw solution becomes immiscible with water at elevated temperatures, enabling physical separation of the two streams. After separation, the water and draw solution are both hot, and the excess heat can be transferred to the cold diluted brine solution through heat exchangers, reducing the external heat input into the system. The recovered concentrated draw solution is reused in the FO process. The system produced 10 m^3/day, the product water had a concentration of approximately 180 ppm, and the system operated at a recovery ratio of 30%.

The FO system modeled in this work claims a remarkably high thermal energy efficiency (GOR $= 20$), which remains to be proven at large scale [26].

A.2.2. Membrane distillation

Membrane distillation is a compact thermal desalination process where pure water is produced by separating it out of solution through phase change. A microporous hydrophobic membrane prevents liquid feedwater carrying dissolved salts from passing through, while allowing vapor to pass. When heated salt water comes in contact with the membrane, pure vapor is collected on the other side, which can then be condensed to produce pure water. The feed stream temperature drops as vapor passes through the membrane, carrying energy with it. Several configurations of MD have been developed that utilize the latent heat of condensation from the condensing vapor to heat the feed stream, thereby recovering energy from the distillate and reducing the external energy requirement.The configuration and flow rates of MD have an essential influence on the energy efficiency of the technology [43,44].

In this manuscript, a multi-effect vacuum MD design commercialized by Memsys [45] is considered. This design resembles a forward-feed MED, where condensation of vapor from one effect is used to evaporate more water from the feed at a subsequent effect, at lower temperature. The stages operate at decreasing feed temperature levels, since the vacuum level on the vapor side of the membrane is increased with each operating stage. One advantage of MD relative to other large-scale established thermal-powered desalination processes is that it can be compact and readily scaled down to small sizes due to the hydrophobic membrane effectively separating the evaporating and condensing liquid interfaces without the need for large vapor volumes.

Like the FO systems considered, this MD system has a very high thermal energy efficiency (GOR $= 9$), which remains to be proven at an operating scale [45,46]. MD systems with GOR of over 7 have been demonstrated at small scale [47].

A.3. Hybrid configurations

These principal desalination technologies can be hybridized and combined with other desalination technologies and pretreatment methods to take advantage of the beneficial aspects of several technologies in a single system or overcome limitations that may hinder a single technology by itself.

A.3.1. RO hybrids

Desalination plants require significant amounts of energy as heat or electricity and significant amounts of equipment. Reverse osmosis plants typically require less primary energy than thermal distillation plants. However, the membrane replacement and the high-pressure pumps increase the RO system's capital cost significantly. Furthermore, the permeate stream in an RO plant is not free of salt, while the distillate stream produced by a thermal desalination plant is.

Therefore, hybrid systems combining thermal and membrane processes are being considered as potentially efficient options for coupling with a power plant. An optimized hybrid desalination option comprises an RO plant integrated with an MSF or MED plant, which has the advantages of a lower energy consumption than a standalone thermal plant, and improved water quality over a standalone RO plant due to blending of RO permeate and MSF or MED distillate. The system's recovery ratio can also be improved over standalone thermal plants, resulting in lower pretreatment costs than standalone thermal desalination plants.

Since the permeate from RO is blended with distillate from the thermal process, a hybrid arrangement allows for the elimination of a 2nd RO pass while still producing the required product water quality, thus resulting in potentially lower capital and operating costs. This includes meeting boron level requirements, even with relatively high seawater TDS, which can be a challenge for RO systems.

Combining thermal and membrane desalination plants at the same site allows for the use of common intake and outfall facilities which further reduces the capital costs and makes it easier to comply with environmental regulations. Post-treatment operating costs can also be reduced by extracting CO_2 from the thermal desalination plant vent.

In the areas surrounding the Arabian Gulf, distillate exits thermal desalination plants at a temperature close to 40 °C and needs to be further cooled to meet environmental regulations. The water produced from the reverse osmosis plant, however, will be at 35 °C or less. By blending the two system products, the final product water temperature will be reduced and an additional distillate cooler will not be required downstream of the thermal desalination plant.

During winter seasons, the preheated seawater leaving the heat reject section of the MSF distiller or the final condenser of the MED plant can be used as feedwater for RO plant. Increase of seawater feed temperature by one degree centigrade will increase the water production of SWRO by approximately 2–3% [48]. The optimal hybrid plant setup will change from case to case because of the large variation in the power demand between summer and winter, with the winter power demand sometimes being only 30% of the summer demand, while water demand remains stable throughout the year.

A.3.2. FO hybrids

Many thermal or evaporative desalination processes are limited by the formation of scale. The formation of scale from sparingly soluble salts limits the top brine temperature (TBT) in MSF plants to around 110 °C. The limited TBT limits the recovery ratio and drives up the steam consumption, increasing the specific energy consumption of the plant. One way to combat these negative effects is to reduce the concentration of scale-forming compounds in the recirculating brine. While a normal MSF plant uses seawater to make up for the evaporated steam, the MSF plant can instead be hybridized with FO in order to dilute the recycled brine and provide makeup water, while keeping scale-forming ions out of the MSF plant [49,50]. This is done by placing an FO system between the cooling water discharge, which is at low salinity as it exits the system, and the brine blowdown, which is at a much higher concentration. Osmosis draws nearly pure water from the cooling water into the recirculating brine stream, diluting and increasing the flow rate of the recirculating brine stream. By reducing the concentration of the recirculating brine stream and rejecting scale-forming ions with the membrane, opportunities are provided to either increase the output of the system or reduce the steam consumption. For the case examined here, for a plant of fixed output, the increase in TBT from 112 °C to 125 °C allows for an increase in recovery ratio of 4% and an increase in GOR of 1.8.

FO can also be hybridized with MED. By running an FO plant normally and passing the brine on to an MED plant to be further desalinated, the work is split up in an advantageous way. A membrane process like RO operates by applying enough pressure to compensate for the osmotic pressure of the feed stream. As a result, its energy consumption increases with increasing feed concentration. On the other hand, the TBT in a thermal process is relatively constant irrespective of the feed salinity. The specific energy consumption of a thermal process therefore is a stronger function of system design (such as number of stages) and only shows a weak decline with increasing feed salinity. Hence, hybrids may be designed to desalinate higher salinity brine using the thermal desalination process. One such hybrid of FO and MED is considered in study, where permeate is initially generated using FO, and the brine from FO is passed on to MED.

A.4. Nanofiltration pretreatment

A.4.1. NF-MED

Scale formation represents a major operational problem encountered in thermal desalination plants. In today's plants, to allow for a reasonable margin of safety, calcium scale deposition limits the TBT in MED distillers to 65 °C. Limited TBT and flashing range have a significant effect on per-unit of water capital and operational costs. In addition, scale deposits have a direct influence on the thermal units' performance; scaling affects the fouling factor, overall heat transfer coefficient, specific heat transfer area, and as a result, the cost of water.

In a system that hybridizes some other desalination process with NF, pretreated seawater will first be passed through the nanofiltration (NF) membrane. Using NF, sulfate ions are almost completely removed from seawater, and TBT can easily be increased above the present operational limits. NF pretreatment has a significant capability to lower the concentration of hard scale elements in seawater, especially Ca^{2+}, Mg^{2+}, $SO_4{}^{2-}$, and $HCO_3{}^{-}$. NF also offers, due to the loose membrane structure and greater porosity, higher fluxes than RO processes. When the NF permeate becomes the makeup water for an MED system, the NF permeate is acidified to reduce the pH from around 8.3 to 4.5 before being passed to the decarbonator. The makeup leaving the decarbonator is freed from carbon dioxide, and to some extent the associated air, and its pH will increase from 4.5 to around 5.6. The makeup blend is then passed to the vacuum deaerator to remove dissolved air and other gases, if required. The NF permeate with reduced TDS will then enter the MED section as feed makeup. Since the key hard scale elements are reduced substantially from the MED makeup feed, the

MED plant can operate at higher TBT. The brine reject from the MED plant can be further recycled in the evaporator, depending on the TBT and salinity limit, with or without blending with raw seawater or NF treated seawater. The brine from the NF plant is rejected back to the sea or mixed with the condenser cooling water to reduce the total seawater demand to the MED plant. This NF-MED configuration allows the MED unit to operate at a TBT of up to 125 °C. Hybridizing NF with MED is possible for both simple MED and MED with a MVC or TVC. The higher performance of hybrid MED plants with less consumption of steam, power and seawater allows for more compact MED plants.

A.4.2. NF-RO-MED

Advanced hybrid desalination integrates an NF-MED plant and an RO plant. This configuration complements all the process advantages given under NF-MED and RO-MED desalination plants above. The preheated seawater from the MED condenser is first passed through the pretreatment system. The pretreatment system is similar to that of an RO process, such as a one or two stage multi-media filter, depending on the seawater quality. The pretreated seawater will then pass through the NF membrane, reducing the key hard scale elements and the TDS. The NF permeate feed will then enter the 1st pass RO unit. The brine from the NF plant is enriched with bivalent ions, which could potentially be recovered. Otherwise, this brine is rejected back to the sea. Since TDS and the key hard scale elements are reduced substantially, the RO plant can operate at higher recovery (>50%). The brine reject from the RO plant is used as MED makeup water, with or without blending with raw seawater or NF treated seawater. As in the RO-MED hybrid system, the 2nd RO pass can be eliminated, resulting in lower capex and opex, though still producing the required permeate quality, even with relatively high seawater TDS. Permeate from the 1st RO pass can be directly blended with MED distillate, resulting in a product water that meets all specifications, including boron content and other elements. Additionally, in a hybridized NF-RO-MED plant, the production of the RO section of the plant is more stable throughout the year because of stable feedwater temperatures coming from the discharged cooling water from the MED plant.

A.5. Power plants

A.5.1. Oil fired power plant

The oil-fired power plant uses fuel oil to produce heat. Here, electrical energy is generated by converting the heat obtained by oil combustion. Oil is burned inside a boiler to generate steam at high temperature and pressure. In the boiler, cold water is converted into steam. This steam drives a steam turbine, which in turn powers generators that produce electricity. After doing its work in the turbine, the steam is drawn into a condenser, where cool water from a nearby source (such as an ocean, river, or lake) is pumped through a network of tubes running through the condenser. The amount of cooling water that must be circulated can range 75–200 m^3 of water per MWh of electricity produced [51]. The cooling water in the tubes converts the steam back into water that can be recycled back to the boiler to repeat the cycle. The cooling water is returned to its source without any contamination.

A.5.2. Combined cycle gas turbine

A basic gas turbine cogeneration system consists of a gas turbine cycle (compressor, combustion chamber and expander), a heat recovery system for steam production and steam turbine. Fuel is introduced into the combustion chamber of the gas turbine where combustion takes place with compressed air coming out from the compressor. Hot exhaust gases from the gas turbine are the “waste heat” sources for process heat production. The quantity and quality of process heat produced depend on the temperature of the hot exhaust gases entering the heat recovery system and the resulting temperature of the steam produced. Steam produced can be used either for process heat or electric power that is generated by a steam turbine.

A.5.3. Concentrated solar power

In concentrated solar power (CSP) plants, the sun’s rays are focused onto a collector, which heats a working fluid, which in turn drives a heat engine, such as a steam turbine. In parabolic trough CSP, long troughs of parabolic mirrors focus the sun’s rays onto collector tubes, which carry a working fluid which is heated as it passes through the tube. In a power tower CSP plant, large heliostats track the motion of the sun across the sky and reflect the sun’s rays onto a central collector, which heats a working fluid. Power tower-type CSP plants can achieve higher working temperatures than parabolic trough systems, leading to higher efficiencies. In order to operate at high temperatures while still being able to effectively move heat away from the collector, the working fluid is often molten salt. These plants are also well suited to store molten salt in reservoirs, allowing for dispatchable power production. In recent years the price of energy from both parabolic trough type and power tower type CSP has fallen drastically [52], resulting in increased interest in CSP, especially for use in water and power cogeneration schemes [53], prompting our inclusion of CSP in this analysis.

Appendix B. System diagrams

This appendix provides system diagrams for many of the systems described in Appendix A. Some systems are not shown because they are simple combinations of the illustrated systems.

Figs. B.1–B.12.

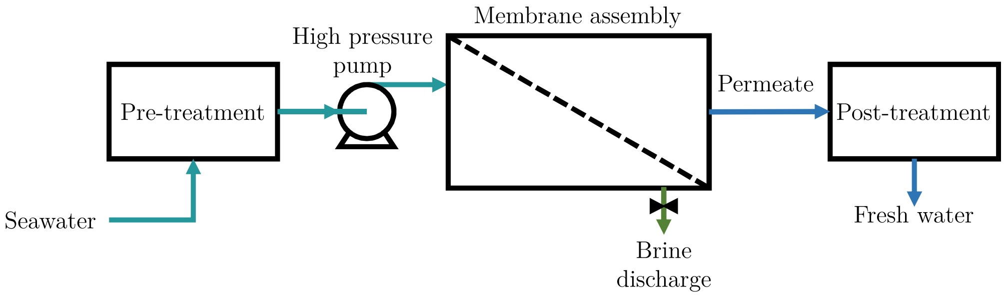

Fig. B.1. Diagram of standard single-pass reverse osmosis (RO).

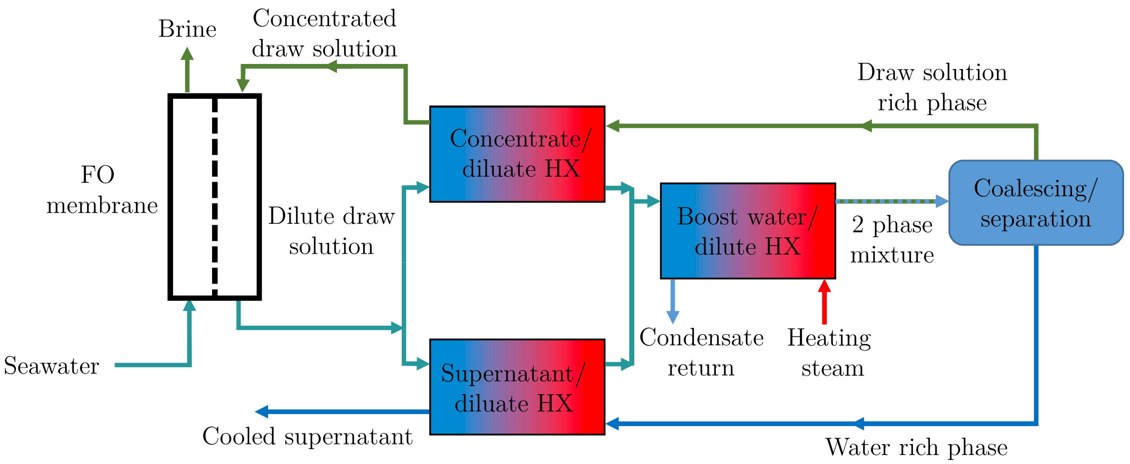

Fig. B.2. Diagram of forward osmosis (FO).

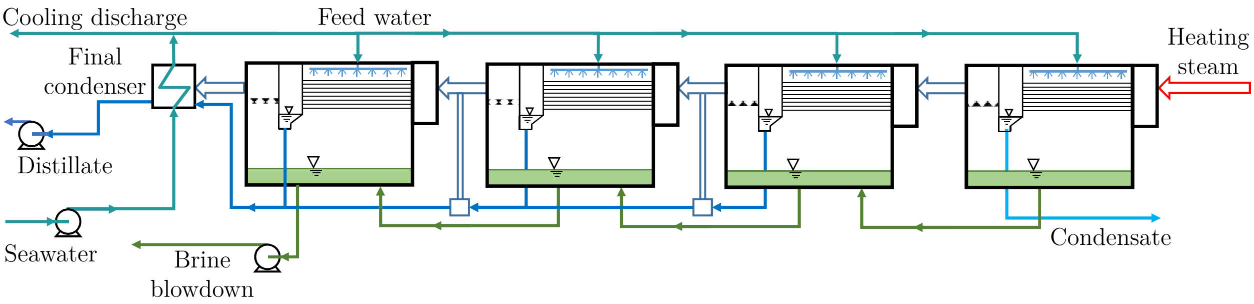

Fig. B.3. Diagram of multi-effect distillation (MED).

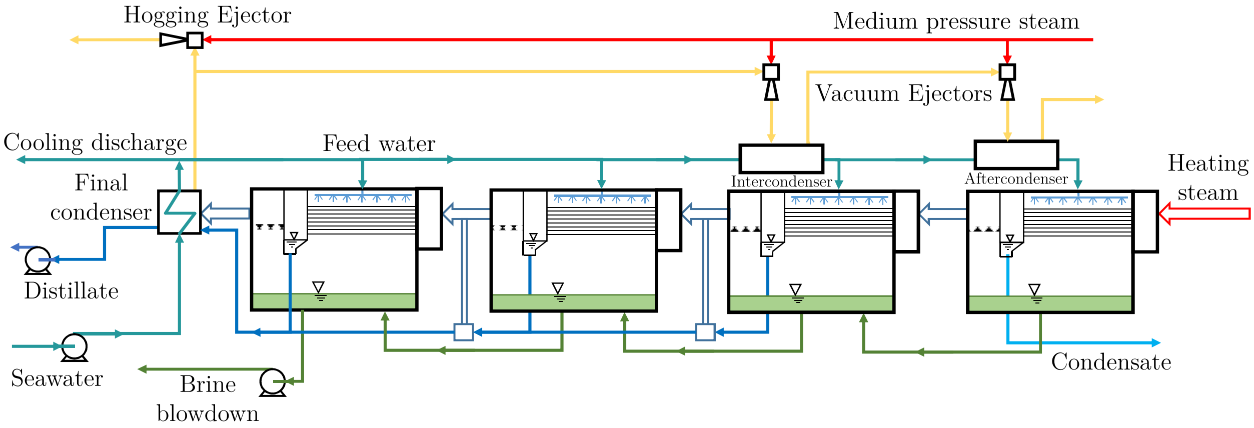

Fig. B.4. Diagram of multi-effect distillation with thermal vapor compression (MED-TVC).

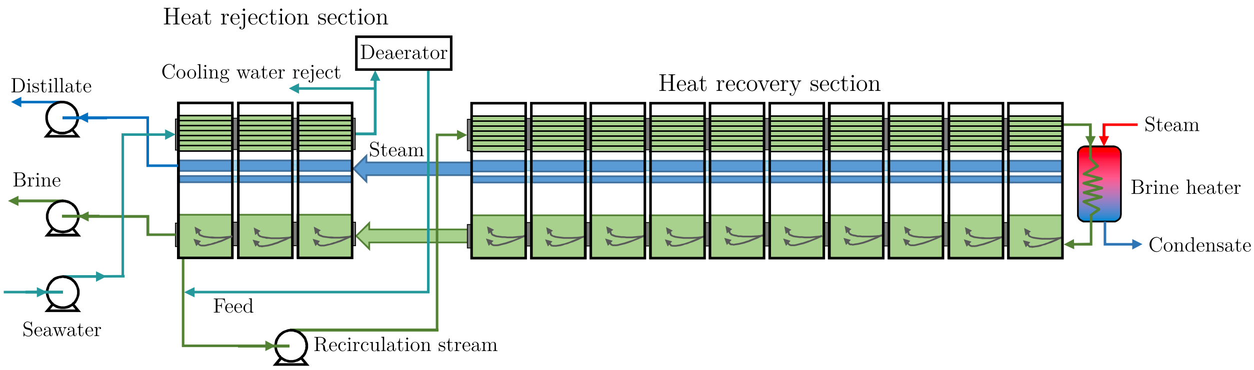

Fig. B.5. Diagram of multi-stage flash (MSF).

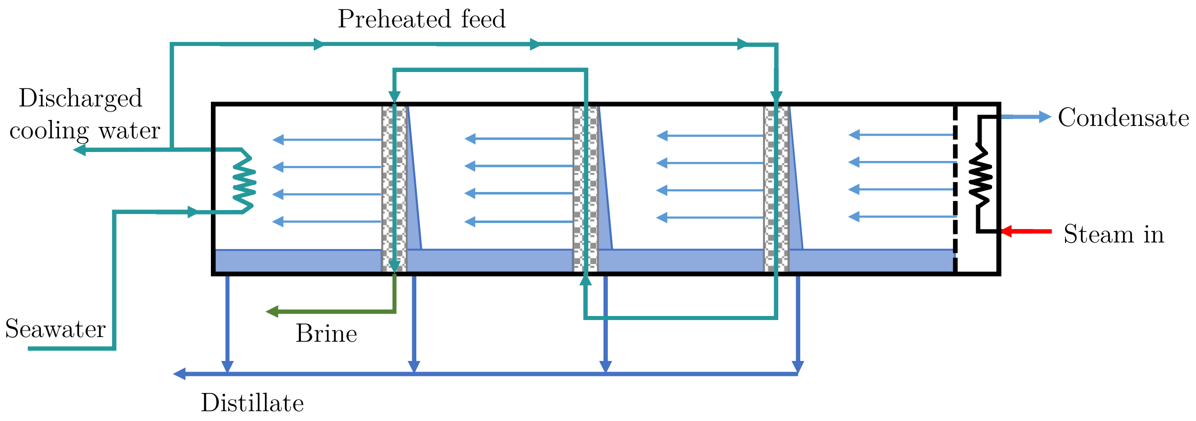

Fig. B.6. Diagram of membrane distillation (MD).

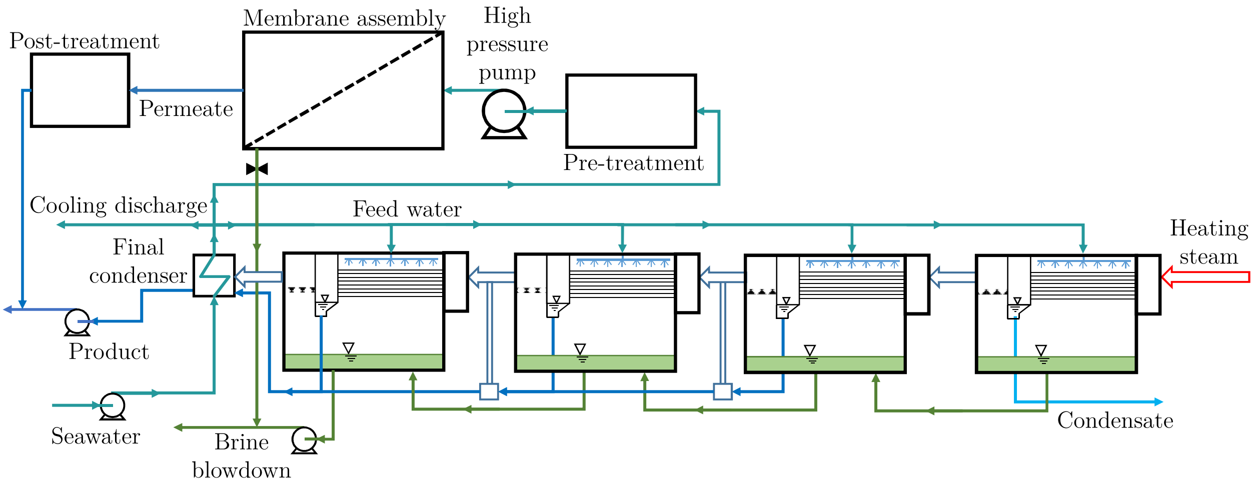

Fig. B.7. Diagram of RO-MED.

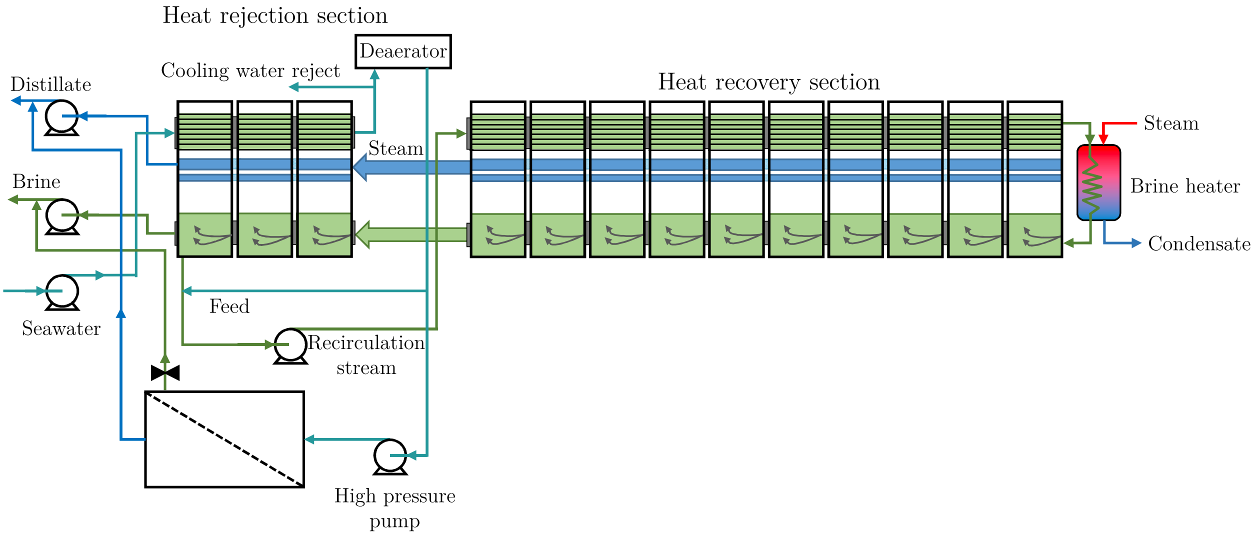

Fig. B.8. Diagram of RO-MSF.

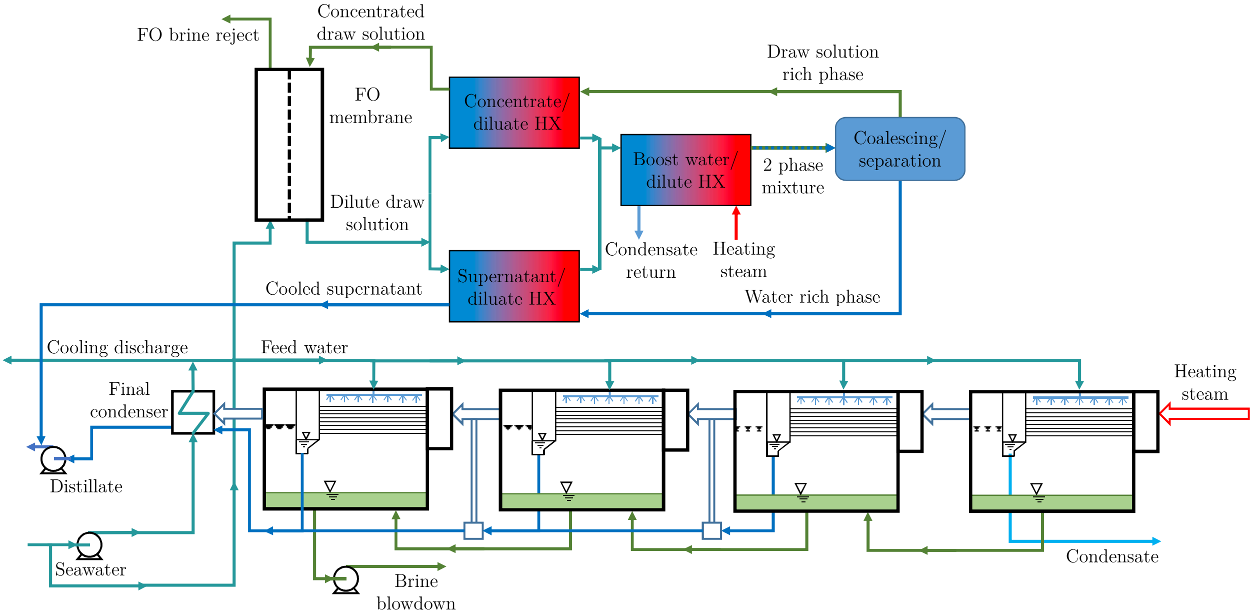

Fig. B.9. Diagram of FO-MED.

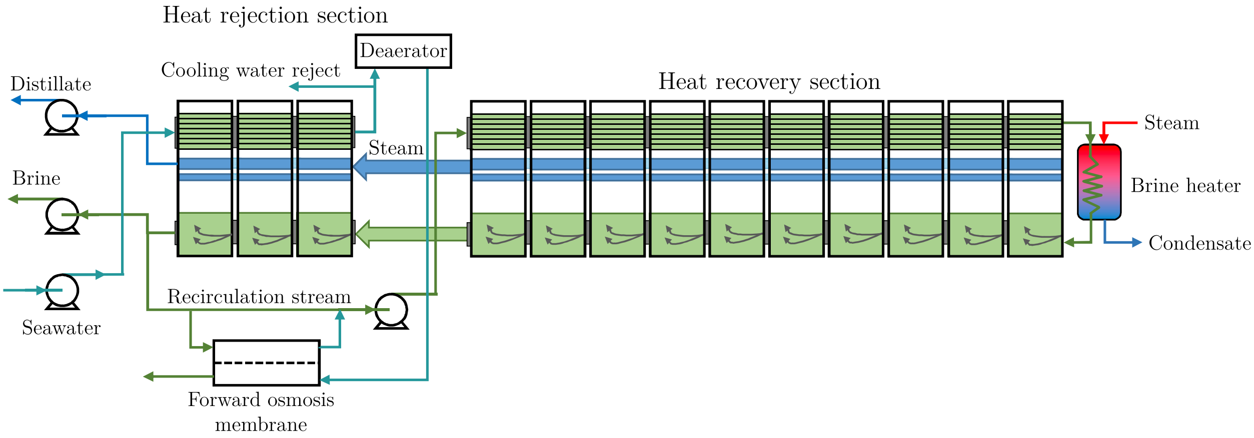

Fig. B.10. Diagram of FO-MSF.

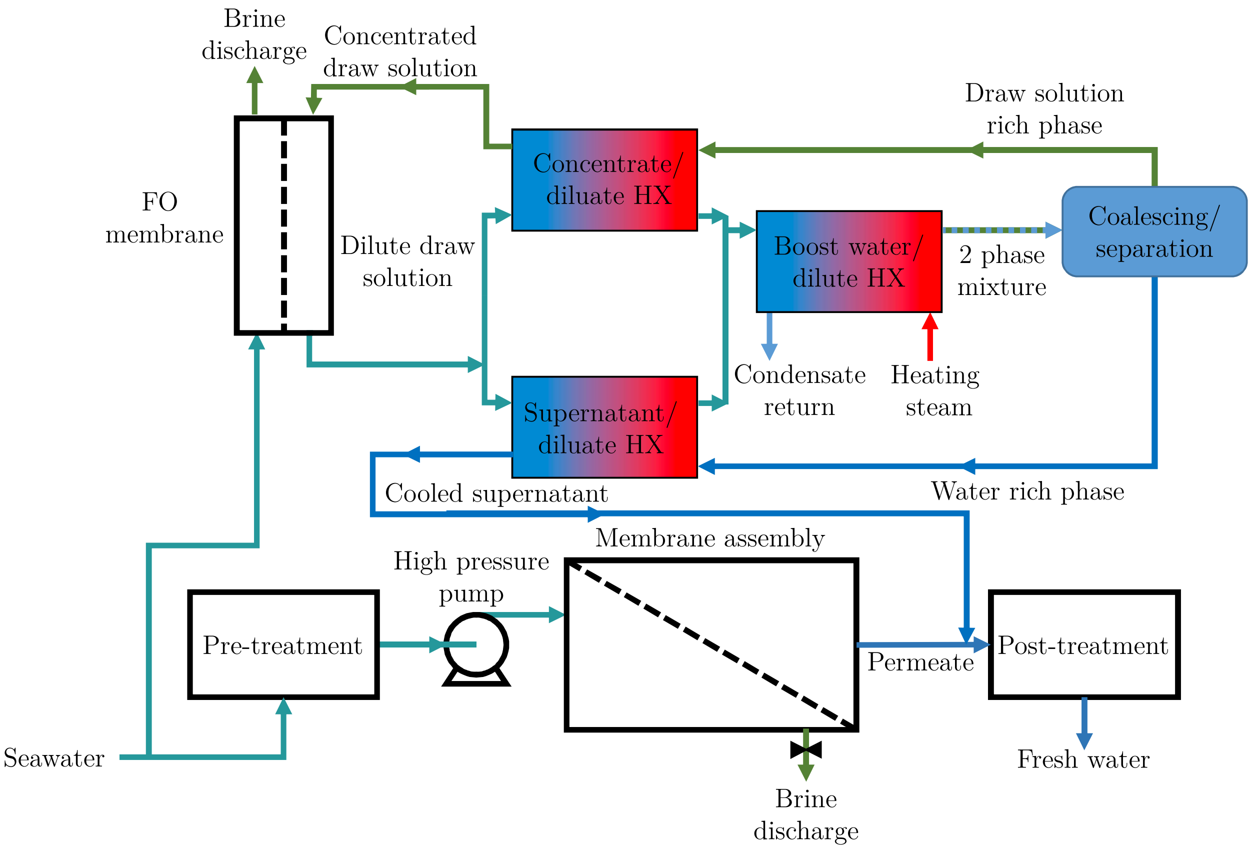

Fig. B.11. Diagram of FO-RO.

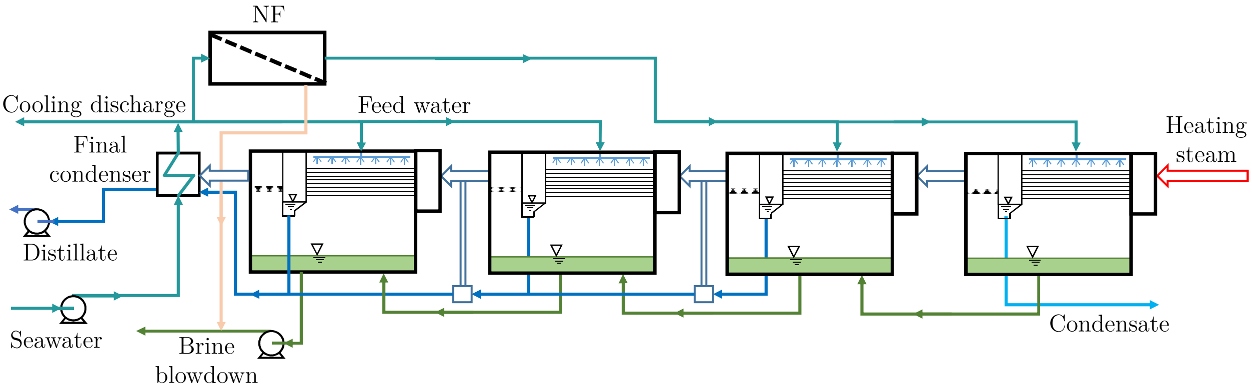

Fig. B.12. Diagram of NF-MED.

Appendix C. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.apenergy.2019.113319.

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