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# A review of hybrid desalination systems for co-production of power and water: analyses, methods, and considerations

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ABSTRACT

The production of freshwater from seawater is a growing necessity throughout the world. In arid areas with high temperature and salinity seawater, thermal desalination and power plants (dual-purpose/cogeneration plants) are often employed for the production of power and water. In other areas, reverse osmosis is commonly employed. However, both technologies are inherently challenged with economic and performance issues. As a response to these issues, hybrid desalination, that is, employing both thermal and mechanical desalination methods, has been increasingly utilized over thermal desalination plants alone. In this article, an overview of thermal desalination, seawater reverse osmosis (SWRO), and co-generation of power and water is presented, specifically with regards to the motivation for utilizing hybrid plants, for example, process limitations and areas of potential improvement. In addition, a review of the considerations for design and economics of hybrid desalination plants is presented, for example, existing system configurations, thermoeconomic analyses, and improvements of seawater pretreatment are discussed. Finally, studies for the optimization of hybrid desalination systems are reviewed. Specifically, the use of objective functions, continuous optimization methods, and optimal hardware configurations are discussed with respect to the key considerations of hybrid desalination plants.

*Keywords:* Hybridization; Optimization; Literature review; Thermal desalination; Seawater reverse osmosis; Nanofiltration

## 1. Introduction

Seawater desalination processes are highly energy intensive, and the need for freshwater procurement has been of growing importance over the past several decades. In the Middle East and other regions with water of high salinity (total dissolved solids (TDS) of ≈35,000–45,000 ppm) and high temperature (≈30–35°C during summer), thermal desalination methods, in particular multi-stage flash (MSF), have historically been favored. The energy consumption of thermal desalination methods is independent of the feedwater salinity to a first order. Typically, these regions also

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have difficult water pretreatment issues due to seasonal algae growth, and pretreatment in MSF is less critical since scaling in MSF is minimal.

These thermal desalination plants are usually integrated as a dual-purpose scheme (also called co-generation), that is, simultaneous production of power and water, which increases the thermal efficiency of the plant as compared to a standalone thermal desalination plant. However, high capital and maintenance costs are associated with the use of thermal desalination and issues, for example, mismatch in production ratio to meet electrical/water demand, exist when integrated as a dual-purpose plant. As a result, improvements to existing desalination technologies and novel integration schemes have been increasingly investigated.

Hybrid desalination systems, that is, the combination of thermal and mechanical desalination technologies, in addition to integration with electrical power production is a promising solution to the difficulties associated with conventional dual-purpose plants. The purpose of this article is to review investigations of hybrid desalination and dual-purpose integrations; specifically, studies relating to the analyses and methods used to optimize such systems will be reviewed. Because of the high investment and long-term maintenance costs involved in large scale dual-purpose plants, the optimization of potential hybrid schemes is of high importance. Further, both the concerns and potential advantages or ideas relating to hybrid desalination systems shall be reviewed within the context of existing literature.

As a precursor to the discussion on hybrid dual-purpose desalination systems, the desalination technologies typically suggested for hybrid integration shall be overviewed. The most popular industrial-scale desalination systems, that is, MSF, multi-effect distillation (MED) and seawater reverse osmosis (SWRO), shall be presented for the reason that MSF is the most popular technology utilized in dual-purpose schemes and MED and SWRO are the fastest growing technologies to be implemented in seawater desalination applications. The interest in hybridization has been increasing over the past decade, and the focus of this article shall be mainly on recent publications.

In this article, a dual-purpose plant shall refer to a system that produces both power and water. In most contexts, a dual-purpose plant refers to one utilizing thermal desalination because of the thermodynamic benefit of integration (to be summarized later). A hybrid desalination system shall refer to the combination of more than one desalination technology, typically thermal desalination combined with mechanical desalination. An example of a single-purpose hybrid desalination system is multi-stage flash with reverse osmosis and nanofiltration (NF–SWRO–MSF). The details of each technology and subsequent integration schemes will be summarized in the following sections. Finally, in the last section, conclusions from the literature review will be drawn as well as suggestions for where future work should focus on.

## 2. Overview of thermal desalination in large scale applications

Thermal desalination has been applied in large-scale production, especially in the Middle East and North African countries, since the mid-20th century. This is because this region has a lack of fresh water resources and requires large-scale desalination plants to meet the water demand of the increasing population and development. MSF is the dominating technology within thermal desalination with multiple installations in the countries of Gulf Cooperation Council (GCC), where the energy cost is low. Thermal desalination technologies produce high-quality product water with very low salinity, and the efficiency and production rate are not affected by the quality of feedwater (to a first order). As a result, the majority of large-scale desalination plants in the GCC countries use thermal desalination processes. About 77% of the total water production in this region is produced by thermal desalination processes [1].

MSF is more reliable and simpler in operation than other desalination processes. In the 1960's, the unit capacity of MSF plants was 500 $m^3$/day (0.1 MIGD), and later in the late 1970's, the capacity increased to 27,000–32,000 $m^3$/day (6–7 MIGD) [2]. Current MSF capacities have increased to 50,000–75,000 $m^3$/day (11–16.5 MIGD) [3]. This increase in unit capacity of MSF was achieved through improvements in construction materials and by newly designed and streamlined components, which includes tubing, demisters, venting systems, partitions, and pumping units. The MSF technology has excellent process reliability and the ability to continuously operate for durations of more than two years; this has encouraged the continued maintenance and updating of existing MSF plants. MSF requires minimal feedwater pre-treatment and has low potential of bio-fouling and scaling. However, MSF is highly energy intensive and requires large investment cost.

MED (also known as multi-effect evaporation, MEE or multi-effect boiling, MEB), is another thermal desalination process which has been used in large scale production. MED was the first proposed thermal desalination technology (before MSF), but due to severe scaling and fouling problems the plants experienced frequent shutdowns [4]. Presently, MED does not have large market share as compared to MSF, especially in GCC countries. However, MED has increasingly been installed in large-scale water production due to improvements in enhanced heat transfer surfaces and antiscalants. Furthermore, due to reduced pressure drop in pipes and ducts of the MED, the electrical power consumption for pumping in MED is claimed to be lower than MSF. The unit capacity of MED systems have significantly increased up to 45,000–68,000 $m^3$/day (10–15 MIGD) as compared to market introduction of 4,500 $m^3$/day (1 MIGD) [4].

### 2.1. Overview of the MED process

In the MED plant, seawater is desalinated by means of evaporation in a series of evaporators (effects); then the vapor is condensed to be collected as distillate. To increase the efficiency as compared to a single-effect process, the vapor formed in one effect is used to vaporize seawater in the next effect. This procedure is repeated from one effect to another with gradually decreasing temperature and pressure due to the decrease in the formed vapor saturation temperature. The process is driven by a heat source from steam that evaporates the seawater in the first effect. Fig. 1 shows a simplified schematic of a MED process. Each effect is composed of heat transfer tubes wherein vapor is condensed and seawater evaporates outside the tubes. The vapor formed outside the tubes is transferred to flow inside the tubes of the next effect to vaporize more seawater. The vapor inside the tubes is condensed and collected in the distillate line. The vapor at the last effect (lowest temperature) is condensed using cooling seawater. Part of the seawater which is preheated in the last condenser is fed to the effects and the remaining part is discharged back to the sea.

There are three main types of MED processes. The first type is the low-temperature MED process (Fig. 1) in which low pressure steam (typically less than 0.5 bar saturation pressure) is the main heating source. The second type is MED–TVC (thermal vapor compression) in which moderate pressure steam (2.5–3 bar) is used as motive steam of an ejector. The ejector entrains the vapor from the last effect (condenser) and mixes it with the motive steam to be compressed and introduced to the first effect for heating the seawater (Fig. 2). MED–TVC is mostly used in large scale co-generation plants. Table 1 summarizes the key features of MED–TVC plants, which are most used in large co-generation production. The third type is MED–MVC, which is very similar to MED–TVC but the vapor is compressed by a mechanical compressor (Fig. 3). MED–MVC eliminates the need for a steam supply since the compression process raises the temperature of the vapor. Therefore, this type is used when no steam is available. However, MVC requires compressor operation at extremely high speed and pressure ratios. There are also other types of MED that use different compression methods including absorption vapor compression, adsorption vapor compression, and chemical vapor compression. These types are not used in large scale desalination plants.

For MED (with or without TVC/MVC), there are different configurations for the flow arrangement of both the feed seawater and the vapor in each effect. These configurations are parallel (Fig. 1), forward (Fig. 4) and backward (Fig. 5). In the parallel-feed configuration, the feed seawater is sprayed in near equal amounts in each effect over the bank of tubes. In the forward-feed configuration, the feed seawater is pumped to the first (highest temperature) effect; then the brine and vapor flow in the same direction to the last effect (condenser). In the backward-feed configuration, the feed seawater enters the last (lowest temperature) effect; then the brine from that effect is pumped to the next effect (higher temperature) until reaching the first (highest temperature) effect. In the backward-feed configuration, vapor flows in the opposite direction of the feed flow.

The forward-feed configuration could operate at higher top brine temperatures (TBTs) as compared to

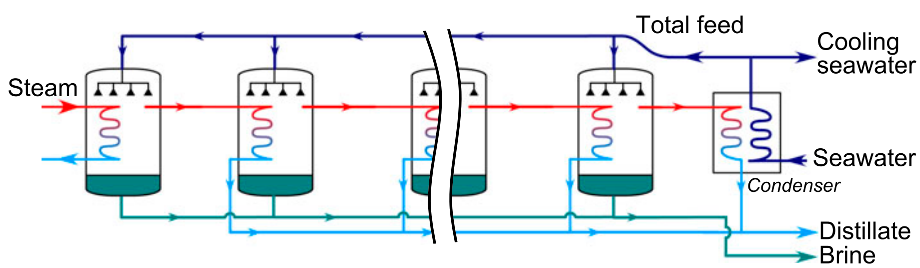


Fig. 1. Schematic of MED process.

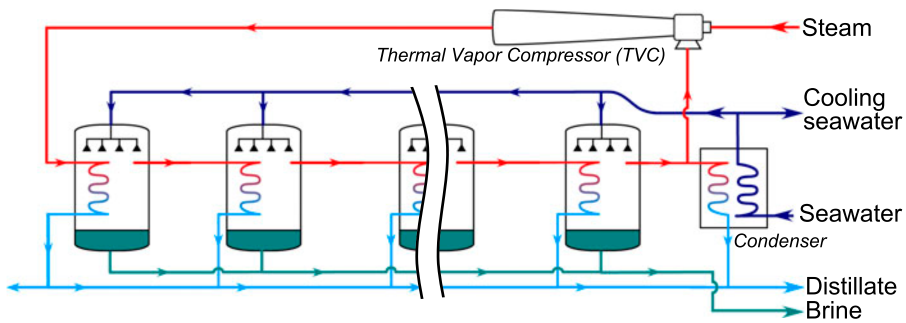


Fig. 2. Schematic of MED–TVC process.

parallel or backward-feed since the salt concentration at the highest brine temperatures is minimal [5]. However, from a thermodynamic point of view, the forward configuration has a large temperature difference between the heating steam in the first effect and feed seawater which increases the irreversibility. From this aspect, the backward configuration performs better, but the major disadvantage of the backward system is the high pumping power as compared to other configurations required to pump the feed seawater to the higher pressure effects. The other disadvantage of this system is that the brine with the highest concentration is subjected to the highest temperature which easily allows the brine to exceed the solubility limits of seawater salt constituents. Moreover, analysis of the heat transfer surface areas shows that more total area is required with backward feed than the forward feed due to the difference in effect temperature profiles [6]. Because of these disadvantages, the backward feed configuration is inappropriate for seawater desalination [7].

### 2.2. *Overview of the MSF process*

MSF desalination is the most common thermal desalination process employed in large scale cogeneration plants. In this process, seawater is evaporated at subatmospheric pressure by reducing the pressure in a flashing chamber. The flashing method reduces scale formation significantly as compared with evaporation on tubes or a hot surface. The MSF process, shown in Fig. 7, consists of three major sections: the brine heater, the heat recovery section, and the heat rejection section. In the brine heater, steam from the power plant is used to heat preheated seawater to the TBT. The heat recovery section consists of a series of flashing chambers in which the hot brine is allowed to flow freely and evaporate through reducing pressure. Flashing occurs in each stage, where a small amount of vapor is generated and is used to preheat the feed seawater flowing in the tubes at the top of the chamber. The feed seawater is preheated, and the generated vapor is condensed and collected in a tray. This type is called the once through MSF. Another type which is commonly used is the brine recirculation (Fig. 6). In this method, the hot cooling seawater is mixed with the brine pool in the last flashing stage. Then the feed is taken from this pool to be preheated in the previous stages. This method controls the feed seawater temperature to the flashing stages, especially when the intake seawater has large temperature variations. The key features and operating parameters of MSF plant are given in Table 2.

Table 1
Main features of MED–TVC plant [8]

| | |
|---|---|
| Seawater salinity | 30,000–47,000 ppm |
| TBT | 63–75°C |
| Steam supply | 2.5–3 bar |
| Steam consumption | 15.8 tons/MIGD |
| GOR | 12–15 |
| Capital cost | 4.5–9.0 US$ MM per MIGD |
| Capital cost—intake/outfall | 0.1–2.0 US$ MM per MIGD |
| Chemicals cost | 40,000 US$/yr per MIGD |
| Labor cost | 40,000 US$/yr per MIGD |

The flashing process is a simple process where the inlet brine stream flashes off because the saturation pressure of the incoming brine is higher than the stage pressure. MSF produces high quality fresh water (salinity $\leqslant$10 ppm) from feed of high salinity seawater. MSF has low potential for scale formation since the evaporation of seawater occurs from the bulk of water by flashing instead of evaporation on a hot surface. This feature is the main reason why MSF has been the popular and primary technology for desalination of seawater for several decades. However, the MSF process has many limitations. The TBT is limited to 90–120°C [9] due to the precipitation of salts at higher temperatures.

The velocity of flashed vapor should be maintained below 6 m/s [10] to limit entrainment of brine droplets in the vapor stream. This is done by

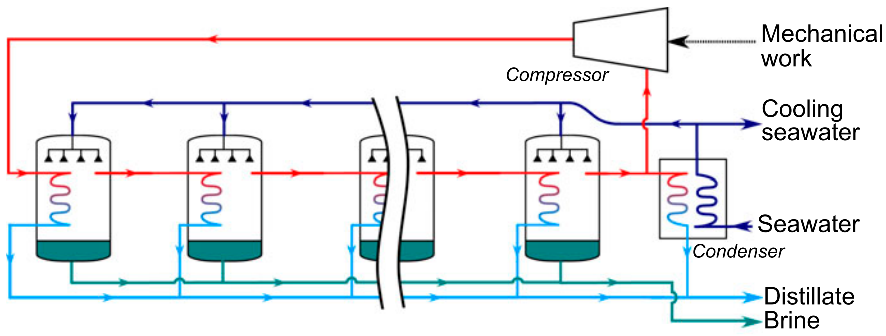


Fig. 3. Schematic of MED–MVC process.

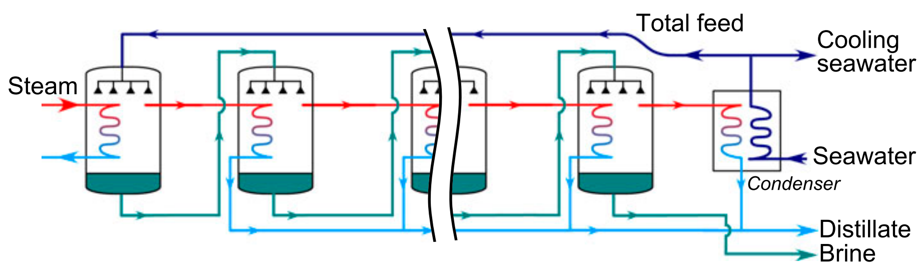


Fig. 4. Forward MED configuration.

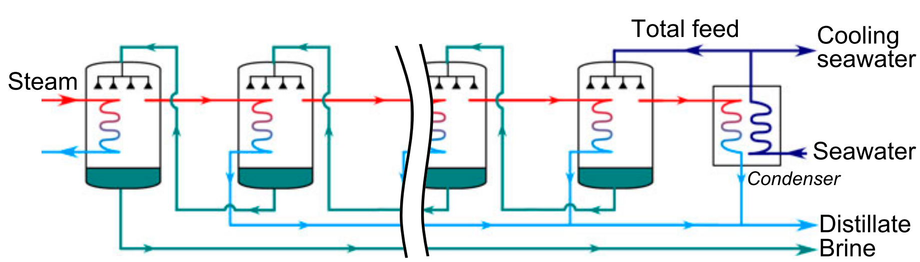


Fig. 5. Backward MED configuration.

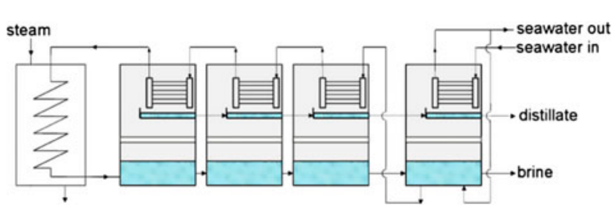


Fig. 6. MSF process with brine recirculation.

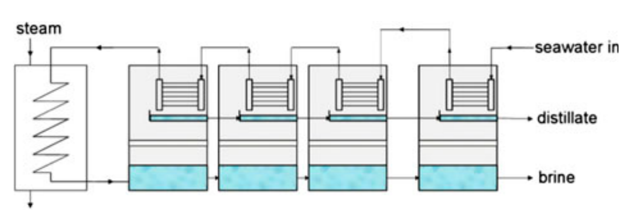


Fig. 7. MSF process with once through cooling.

appropriate design of the flashing chamber geometry (width and length) which results in high volume and construction cost. The MSF plants cannot be operated below 70–80% [11] of the design capacity for the reason that the flashing process will not be efficient.

### *2.3. Electrical energy consumption in thermal desalination*

Although the separation process in thermal desalination is driven by a heat source, that is, thermal power, the electrical power required is still significant. Electrical energy is required for the high pressure

Table 2
Main features of MSF plant [8]

| | |
|---|---|
| Seawater salinity | 30,000–47,000 ppm |
| TBT | 100–112°C |
| Steam supply | 2.5–3 bar |
| Steam consumption | 23.7 tons/MIGD |
| GOR | 8 |
| Capital cost | 5.5–10 US$ MM per MIGD |
| Capital cost—intake/outfall | 0.1–2.0 US$ MM per MIGD |
| Chemicals cost | 40,000 US$/yr per MIGD |
| Labor cost | 40,000 US$/yr per MIGD |

pumps of the feed, the brine recycling, the brine blowdown, the seawater intake, the distillate, and other auxiliary pumps. In MSF, pressure drops in the flashing chambers contribute substantially to the pumping necessary. The pumping energy in MSF is higher than that of MED, especially with the brine recirculation configuration. This difference is because the amount of the circulated brine is much more than the amount of the feed.

In the literature, authors have most often used constant electrical energy consumption values per unit volume of water produced (kWh/m$^3$) as an assumption in numerical modeling and optimization. Some published values are taken from industrial installations, for example [12,13]. However, to the authors knowledge, there are no published models for electrical energy consumption that capture the dependence on design and part load. The use of an electrical energy consumption model by the characterization of MSF or MED pressure drops, and thus the required pumping would allow for models which could reflect part loading of systems. These models are necessary for a system level model used

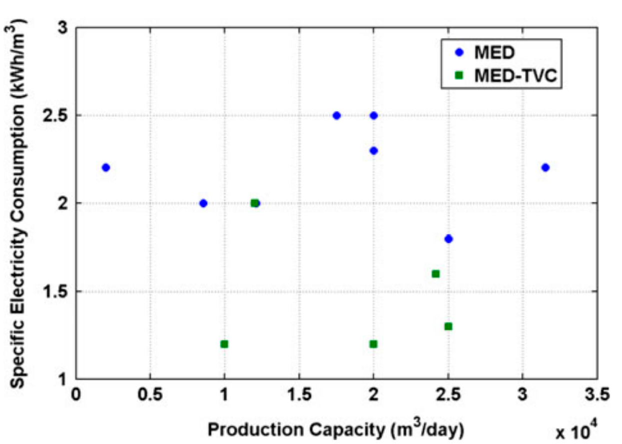


Fig. 8. Reported values of MED and MED–TVC electrical consumption.

for optimization of design and operation, especially when considering varying loads. Further, a model should accurately reflect the variation of electrical energy consumption with unit capacities. Currently, most constant electrical consumption values utilized in thermal desalination models do not appear to scale with the unit capacities. Fig. 8 shows reported specific electricity consumption for MED and MED–TVC [12–23]. As shown in Fig. 8, the range of reported values in MED systems varies from 1.2 to 2.5 kWh/m$^3$ for unit capacities of 1,992–31,499 m$^3$/day and have no notable correlation with respect to production capacity. In the GCC countries, the specific electrical energy consumption range is reported as 2.5–4.5 kWh/m$^3$ of product water [15–17,24–26]. It is important to note that the estimated values of electrical energy consumption make a large difference in thermal desalination perhaps being competitive to SWRO, whose electricity consumption is typically reported as 3–4 kWh/m$^3$ [27].

### 2.4. Common models to describe thermal desalination

Modeling of the thermal desalination processes is well established in literature [3,6,12,28–39]. The governing equations of the mathematical models are most often energy balance, mass balance, and heat transfer equations. There are some empirical correlations and short cut techniques summarized in [7], which are useful to provide quick estimates of process parameters, that is, performance ratio, condenser heat transfer area, and flow rates of various streams. However, detailed analyses are required for accurate thermo-economical calculation, feasibility studies [40] and numerical optimization.

The following are the key assumptions that are frequently used to model MSF and MED processes: (i) the plant is working in steady-state operation at the design point; (ii) heat losses to the surroundings are negligible; (iii) the distillate product is salt free and (iv) equal temperature difference on each stage.

In addition to these assumptions, empirical correlations are used to calculate the overall heat transfer coefficients in the evaporators and condensers which depend on flow rate and temperature of the condensing vapor, flow rate and temperature of the brine inside the condenser tubes, physical properties of the condensing vapor and the brine, the tube material, diameter, and wall thickness, the fouling resistance, and the percentage of non-condensable gases. Some models consider other effects such as boiling point elevation, non-equilibrium allowance, and demister losses. The solution of the energy and mass balance equations define the temperature, flow rate, and salinity profiles across the stages. It is important to note that these equations are non-linear and coupled [41,42].

## 3. Overview of SWRO

SWRO is the most popular membrane-based desalination method, and a fast growing seawater desalination technology. The membranes used in SWRO have high permeability for water and low permeability for dissolved substances. Feedwater in SWRO is pressurized such that the pressure difference across the membrane is higher than the osmotic pressure difference between the feedwater (significant) and the permeate water (negligible). As a result, the feedwater pressure can be as high as 85 bar. The performance of SWRO (e.g., recovery ratio and power consumption) depends on parameters such as the feed pressure, TDS of the feedwater, membrane characteristics (e.g., salt rejection and material), membrane fouling and concentration polarization [43]. Membrane fouling, that is, the accumulation of foreign materials on the active surface of the membrane, increases the energy requirement of SWRO significantly. Similarly, concentration polarization, that is, creation of a boundary layer at the membrane surface, increases the osmotic pressure near the membrane surface, and consequently the energy consumption of the separation process. More on SWRO can be found in [44]; herein, the focus is on SWRO in the context of hybrid desalination and cogeneration schemes and more specifically on limitations (process and mechanical), energy consumption, and system configuration.

### *3.1. Limitations of SWRO*

The permeate flow rate in SWRO can be enhanced via a number of methods such as increasing feedwater pressure and temperature. However, a number of mechanical and process constraints need to be considered. For instance, preheating feedwater to SWRO enhances salt passage [45,46] and likely membrane degradation. As such, membrane manufacturers recommend a maximum feedwater temperature. Such constraints must be taken into account in synthesizing the hybrid desalination system, where multiple feedwater arrangements are possible. There are also mechanical constraints associated with SWRO. The vessel containing the membranes has a pressure rating which puts a limit on the feedwater pressure. A key performance limitation of SWRO is the inability of a single-stage SWRO to meet a maximum allowable boron concentration in the product water [47,48]. As such, SWRO plants employ additional steps to increase boron reject, such as pH adjustment of feedwater, and blending of SWRO permeate with other sources. However, in most cases a multi-stage SWRO has been implemented [47,48] where an increased boron reject and the overall recovery ratio has been achieved at a significant added capital cost. A key advantage of a hybrid desalination system is the opportunity to blend the product water from a low-cost, single-stage SWRO with relatively low product quality with the high-quality permeate flow from an energy-intensive thermal desalination method.

### *3.2. SWRO systems configuration*

System configuration in SWRO has effect on performance and economics of the plant. A key design decision is whether to build a single or multi-stage system. Single-stage SWRO has a lower capital cost, but yields a lower recovery ratio and a faster membrane degradation. A single-stage SWRO also requires more frequent membrane cleaning, which can be a costly process depending on feedwater quality. A key motivation in use of multi-stage SWRO has been the need to meet stringent permeate water quality, and in many cases a minimum desired boron reject that is not achievable in a single-stage SWRO, for example the Ashkelon plant [47,48]. A multi-stage SWRO, however, has a higher overall specific electricity requirement [49]. Other configuration considerations include the use of pressure recovery devices (pressure exchangers or Pelton wheels), the permeability of the membranes, or the use of partial pass configurations with permeate blending [50]. Recent advances in membrane technology resulting in a reduced cost and energy efficient membranes with high salt rejection are the reason that most new SWRO plant are single stage [49,51].

## 4. Overview of co-generation for power and water

Co-generation is the simultaneous production of electrical energy and thermal energy in one power plant. It has been used in many industrial applications including chemical industries, paper mills, food processing, and district heating. Seawater thermal desalination processes (MSF and MED) are most often combined with power generation in large scale dual-purpose co-generation plants. The combined efficiency of a dual-purpose plant is higher than the efficiency if the production of electricity and water is carried out separately, that is, fuel consumption is reduced as compared to utilizing separate boilers for the production of steam for a power cycle and thermal desalination. The design of co-generation plants is an important subject due to the difficulties in satisfying the dynamic variation of both the electrical load and water demand with economically effective plant operation. For example, during off-peak hours or when the power demand is changing, it is essential to provide an auxiliary boiler to provide additional fuel to keep water production at a constant level. This additional fuel results in the increase in water costs significantly, and the electricity and water production process can become unprofitable [52].

### 4.1. Steam supply design

Large thermal desalination plants are most often coupled with power plants. The steam required for the thermal desalination process can be extracted from the steam turbine in several ways. In general, the steam temperature required to heat the feed seawater in the brine heater, that is, the minimum approach temperature (pinch) in the brine heaters, should be 5–7°C higher than the TBT [6]. There are many commercially available configurations that provide both electrical power and the steam for the thermal desalination process. These configurations are as follows (shown in Fig. 9) [53–55]: (i) steam cycle with back-pressure steam turbines (BP-ST) where the exhaust steam from the steam turbine is used in the desalination process where it condenses and returns back to the steam cycle; (ii) steam cycle with extraction/condensing steam turbines (EC-ST) where the steam for the desalination process is extracted from the steam turbine at the appropriate pressures (and temperatures) needed for the desalination process; (iii) gas cycle with gas turbines connected to heat recovery steam generators (with or without supplementary firing) which use energy from the exhaust gases to generate steam for the desalination process (GT-HRSG); (iv) combined gas and steam cycle where a heat recovery steam generator (with or without supplementary firing) is used to produce steam at medium or high pressure that is supplied to a back-pressure steam turbine discharging into the thermal desalination plant (CC-BP); (v) combined gas and steam cycle that is similar to the previous one except that an extraction/condensing steam turbine is used (CC-EC).

In all of these configurations, some high-pressure steam is required to activate a thermocompressor (steam ejector) to purge the system during start-up and to remove non-condensable gases [56]. The temperature and pressure of the steam required for the desalination process differs according to the desalination process. Table 3 shows the typical temperature and pressure ranges as well as the TBT for MSF, MED–TVC, and MED [13,57]. Each of the above-

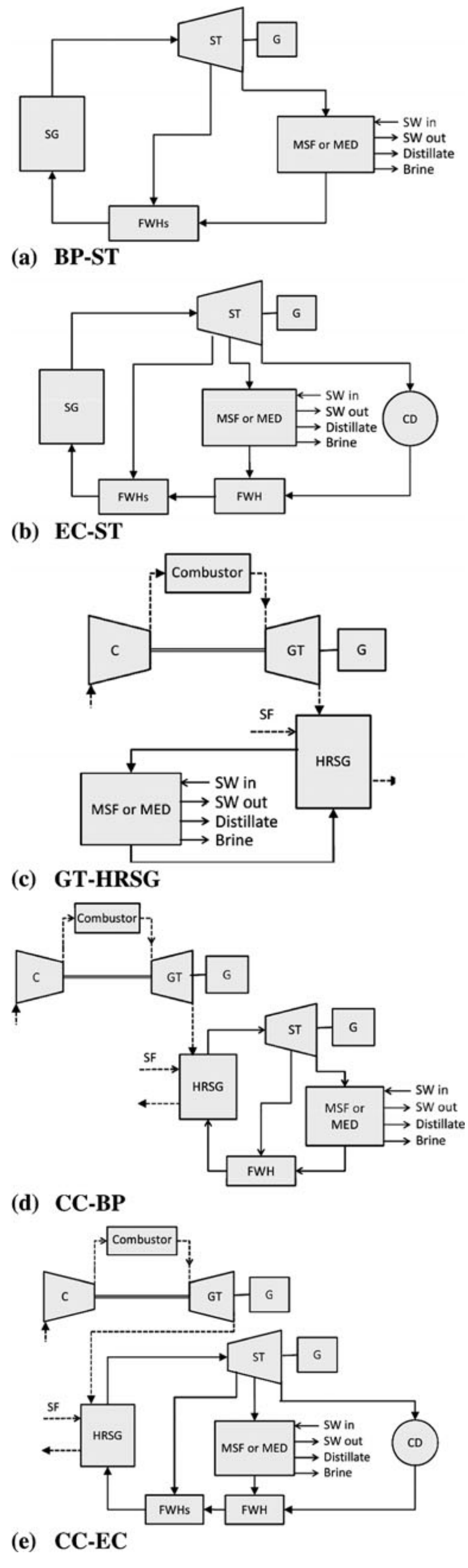


Fig. 9. Types of configurations for dual-purpose plants (explanation of abbreviations in Abbreviations).

Table 3
Typical steam conditions for thermal desalination plants [13,57]

| Process | Steam temperature (°C) | Steam pressure (kPa) | TBT (°C) |
|---|---|---|---|
| MSF | 100–130 | 250–350 | 90–120 |
| MED–TVC | 120–150 | 250–350 | 70–80 |
| LT–MED | 70–90 | 20–40 | 60–80 |

mentioned dual-purpose configurations has its own performance characteristics regarding the part load operation, efficiency, and power-to-water ratio [53].

### 4.2. Power-to-water ratio

A key parameter for dual-purpose plants is the power to water ratio (PWR), which is the ratio of the power produced to the fresh water produced. Spiegler and El-Sayed [58] cite a range of 50–500 kJ/kg for the PWR of dual-purpose plants. In the GCC countries, the rated PWR for the majority of the dual-purpose plants is between 115 and 230 kJ/kg [58]. The rated PWR is chosen based on the power and water demand of the customer region, that is, the amount of power and water produced must meet the demand of approximately the same population size. Between 1980 and 2010, the variation for all co-generation plants in Saudi Arabia was ±20%, mostly due to variation in power and water demand from year to year. However, the ability of a dual-purpose plant to meet a desired PWR is dependent on the power cycle design as well as part-load and supplementary firing characteristics.

Obviously, in extracting steam from an extraction turbine or using steam from a back pressure turbine for a thermal desalination process, the power produced by the turbine is reduced as compared to a power cycle without thermal desalination integration. This reduction increases with increased extraction pressure and amount of steam extracted. However, simultaneously, the amount of water produced increases. Consequently, the combination of these two effects determines the instantaneous PWR of a dual-purpose cycle.

## 5. Scaling and fouling in desalination

Scaling and fouling in both thermal desalination and SWRO are of major concern in the design and operation of such systems. The performance of desalination technologies is limited by the precipitation of salts and impurities present in seawater. Uncontrolled scaling and fouling leads to failure and plant shutdowns. Therefore, small improvements in scaling and fouling treatments, for example seawater additives and scaling inhibitors, can drastically improve process reliability and economics. The following sections present a short overview on scaling/fouling concerns in SWRO and thermal desalination. These phenomena are very relevant to optimization of hybrid desalination because they impose constraints that affect both the structural, design and operational degrees of freedom.

### 5.1. Scaling in thermal desalination

Scale is the formation of seawater salt deposits on process surfaces. Scale forms when a given salt exceeds its saturation limit, which depends on both temperature and concentration. Salts of particular concern in seawater desalination are calcium carbonate ($CaCO_3$), magnesium hydroxide ($Mg(OH)_2$), and calcium sulfate ($CaSO_4$). The solubility of these salts decreases with increasing temperature and concentration, thus limiting the operating range of thermal desalination. Scale formed on heat transfer surfaces reduces their effectiveness and increases the necessary pumping power.

As a result of these solubility problems, thermal desalination operation is limited to a TBT and a maximum brine concentration of effects/stages to avoid violation of solubility limits. Seawater pretreatment additives are utilized to increase the TBT and thus decrease the specific power consumption of the process. Common MSF additives are polyphosphate additives, high temperature additives, and acid treatment methods; these increase the maximum TBT to approximately 90, 100, and 120°C, respectively [59]. However, the effectiveness of scale control is dependent on many factors, for example, dosing rates (especially under varying seawater conditions) [60,61].

In addition to the scale formation, it is important to mention that the presence of dissolved non-condensable gases in process water is a serious problem in thermal desalination [62]. Even low concentrations can significantly reduce the overall heat transfer coefficient and hence the performance of desalination evaporators. In addition, $CO_2$ dissolves in the condensate and lowers its pH which with the presence of $O_2$, may cause corrosion of the condenser tubes. The release of $CO_2$ from the evaporation process considerably influences concentrations of the carbonate ions and thus plays an important role in scale formation. Furthermore, in MSF, the accumulation of non-condensable gases may disturb the brine flow through the flash chambers. Therefore, a deaerator and a decarbonator is installed to avoid the accumulation of non-condensable gases in thermal desalination systems.

### 5.2. Scaling and fouling in SWRO

In SWRO, membrane fouling, membrane scaling, and concentration polarization affect the performance and cost significantly. Membrane fouling, that is, the accumulation of foreign materials on the active surface of the membrane, increases the energy requirement of SWRO significantly. Similarly, concentration polarization, that is, creation of a boundary layer at the membrane surface, increases the osmotic pressure near the membrane surface, and consequently the energy consumption of the separation process. Membrane scaling of $CaSO_4$ and other salts reduces permeate flux and can reduce the lifetime of the membranes [63].

The silt density index (SDI) is an empirical parameter used by SWRO plant operators as an indicator of the quality of a feedwater to foul membranes [43,64]. SDI is also referred to as the fouling index in membrane industry. A typical maximum allowable SDI for feedwater in SWRO is five.

Fouling in SWRO is minimized through pretreatment of the feedwater and periodic membrane cleaning. To minimize consumption of chemicals and maximize plant availability, it is desired to minimize the frequency of membrane cleaning. As such, care is taken in designing efficient and cost effective pre-treatment processes for SWRO. Feedwater pretreatment in SWRO is a combination of media filtration (removal of colloidal particles), microfiltration (removal of suspended solids), and ultrafiltration (UF) (removal of organics). SDI's as low as one can be achieved with a well designed and properly maintained microfiltration or UF system, while traditional pretreatments (mainly media filtration) can only achieve a SDI near five [43]. Recently NF has been suggested as a promising pretreatment not only for SWRO, but also for pretreating the feedwater to a hybrid SWRO/MSF desalination plant [65–71].

## 6. Considerations for hybrid desalination systems

Hybridization of thermal and mechanical desalination technologies integrated with power plants is a proposed improvement over the standard dual-purpose plant. Several potential integration schemes of brine or permeate flow between MSF or MED and SWRO have been envisioned. The benefits of hybridization, as discussed by Awerbuch et al. [72,73] include reduction in capital costs through eliminating the need for second-stage SWRO and a decrease in required heat transfer area in thermal desalination. Other benefits [72,73] are improvement of overall performance by load shaving of electrical production under time-varying demands, potential for reduced pretreatment, and the increase TBT in thermal desalination systems, which will be discussed within the context of current literature in the coming sections.

The current literature typically focuses on aspects of research which would make hybrid desalination feasible for more widespread industrial scale implementation. Specifically, these include (i) how thermal and mechanical desalination technologies are combined and their subsequent merits; (ii) the importance of thermoeconomic analyses; and (iii) use of NF for pretreatment in hybrid desalination systems. These points will be discussed in the following sections.

### 6.1. Configurations of hybrid systems

A main advantage of hybrid desalination systems lies in the flexibility of connectivity between thermal and mechanical desalination; these options for connectivity lead to integration which can minimize the disadvantages and maximize the advantages associated with each technology. Further, it can reduce capital costs for fixed production of water as compared to a dual-purpose plant utilizing thermal desalination alone by sharing some necessary installations between technologies such as intake/outfall facilities and portions of the pre- or post-treatment systems [72].

There are many possibilities for routing of brine and permeate between thermal desalination and reverse osmosis in a hybrid plant, and subsequently, the integration of thermal desalination with a power plant can also vary. Two general routing schemes are commonly employed in the literature, namely, parallel [14,21,74–77] or series configuration [78–82]. Shown in Fig. 10 are simple examples of parallel and series configurations; other more complicated integrations have been employed in open literature.

In the parallel configuration, shown in Fig. 10(a), intake feed is split between thermal desalination and SWRO, and then permeate and brine streams are blended at the outlet. Operation of the desalination modules is primarily independent, and the relative production capacities of each module is the most important design consideration. The independence of operation in parallel configuration can be advantageous, in that these systems can be easily adjusted to respond to variation in the demand of power and

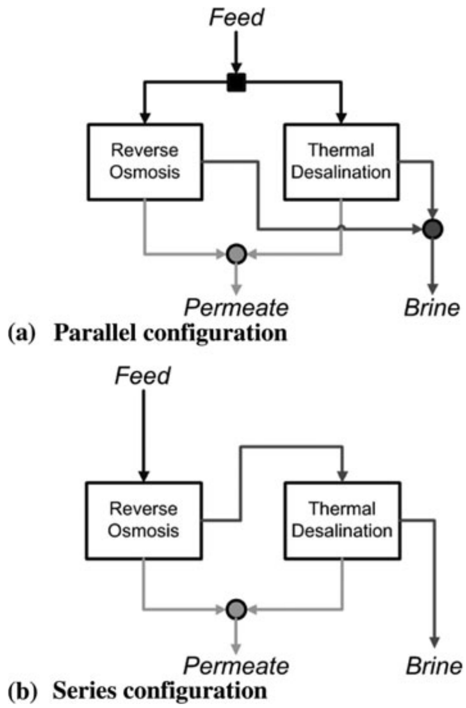


Fig. 10. Examples of hybrid configurations.

water, that is, the performance of thermal desalination and SWRO do not depend on each other and thus can be independently adjusted for given plant conditions.

In choosing a ratio of production between thermal desalination and SWRO, the blended permeate concentration should be taken into account. Over operation life, the salt passage of SWRO increases due to membrane degradation; in a standalone SWRO system, the membranes would need to be replaced once the permeate is above acceptable drinking quality, that is, a TDS above 500 ppm [44]. These replacements incur high maintenance costs over the total lifetime of the plant. In contrast, the permeate obtained through thermal desalination methods is a constant, near-zero TDS. Therefore, the low TDS permeate of thermal desalination can be blended with SWRO permeate to extend the usable lifetime of the membranes and reduce maintenance costs. It is important to note that the target recovery ratio for the SWRO system contributes to SWRO membranes degradation, since higher recoveries imply higher feedwater pump pressures which limit membrane lifetime [44]. Therefore, the SWRO recovery for these systems is critical to consider.

Series configuration can involve many integration strategies involving either permeate or brine connections between thermal and mechanical desalination technologies. For example, Cardona et al. [78] propose that the brine of reverse osmosis could be fed to the inlet of either MSF or MED, as shown in Fig. 10(b). Cardona et al. proffer this scheme as an alternative to using a second stage of SWRO. As mentioned in Section 3, a second stage of SWRO is typically employed to increase the recovery of water to values as high as 85% and therefore reduces the amount of feedwater to be pretreated. Cardona et al. claim that it is desirable to use thermal desalination, so as to reduce the electrical energy consumption that is associated with the high feedwater pressure necessary in a second stage of SWRO. Similarly to the parallel configuration, blending of the thermal desalination and SWRO permeate can be employed and thus reduce maintenance costs. It is important to note that the trade-off between electricity consumed by SWRO and the lost work of the power plant turbine to provide steam for thermal desalination is essential to consider. Further, as aforementioned, the electrical work for pumps in MSF or MED is significant. Therefore, while this particular scheme is beneficial in some ways, the energetic and economic benefits cited by Cardona et al. may not be as substantial once a detailed analysis for given plant conditions is performed.

El-Sayed et al. [80] experimentally investigate another simple series configuration scheme. As shown in Fig. 11, the pilot-scale plant (20 $m^3$/day) studied preheats the SWRO feed through the heat rejection section of an existing MSF plant. El-Sayed et al. specifically investigate the SWRO performance gains, the product flow rate and the specific energy consumption. The results of the study are compared to a standalone SWRO system. It is reported that a feedwater temperature range of 15–33˚C can reflect an average product flow rate gain of 42–48%. Also, it is asserted that this can amount to a 45% decrease in specific energy consumption for SWRO.

El-Sayed et al. [79] investigate the effects of SWRO feed temperature experimentally using a similar configuration as in [80] (Fig. 11). In these experiments, a larger SWRO test rig (300 $m^3$/day) than [80] is used. After testing both spiral wound and hollow fiber membranes, it is found that only a 2.2% average increase in permeate recovery per degree Celsius

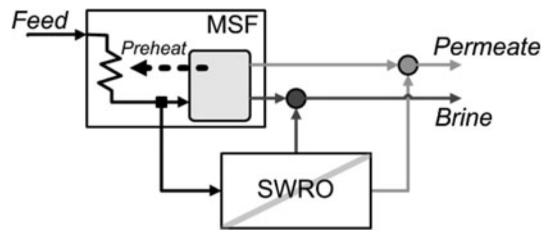


Fig. 11. MSF/SWRO hybrid experimental plant, El-Sayed et al. [80].

increase in feedwater temperature is achieved. Furthermore, both show an approximately 25% decrease in specific energy consumption, which is less than the decrease reported by the pilot scale testing in Ref. [80]. Because there is variation of results with respect to experiment scale for this hybrid scheme, it is unclear whether an industrial-scale implementation would see similar performance.

An advantage of this scheme (Fig. 11) is that existing MSF or MED plants could be retrofit to integrate SWRO without major changes in the existing plant. However, SWRO membranes are limited to a maximum operating temperature to avoid membrane degradation (typically ≈45˚C [43]); in climates where summer seawater temperatures can reach >35˚C, this scheme as it is, is not necessarily practical. Further, an increase in membrane temperature also increases salt passage, and the resulting quality of SWRO permeate should be considered. In this series configuration, the performance of MSF and SWRO is not independent as it is in the parallel scheme and so responding tochanges in plant conditions could be more complicated.

The parallel and series hybrid configuration schemes presented herein are rather simple; investigations regarding more complex configurations will be discussed in coming sections. While these simple configurations may be relatively easy to implement in terms of minimizing the complexity of stream connections, these configurations are not optimized to maximize all potential improvements available through hybridization, for example, overall reduction in costs, reduced scaling and fouling in both thermal desalination and SWRO, and increased energetic performance. Further, depending on the location of plant installation and other design constraints, it is not immediately clear whether parallel or series configuration is the most appropriate scheme. Therefore, systematic strategies for developing and implementing novel configurations to fully utilize the potential of the hybridized desalination concept should be employed. While more complex configurations could exploit possible improvements, it is important to note that there are limits to the practicality of such schemes, for example, increasing complexity has economic and operational disadvantages with regards to system construction and maintenance.

### 6.2. Thermoeconomic analyses

The installation of seawater desalination systems are highly cost intensive. Since hybridized desalination systems are promising in reducing the costs of production, many authors have conducted studies with detailed economic analyses. Mainly, these analyses quantify the total annualized cost (TAC) of water for a given system design.

The TAC includes both capital and operating expenses, of which the operating expenses are calculated based on an availability of the plant, that is, the number of days the plant is expected to operate. The TAC is highly dependent on the specific conditions of an installation. Common economic factors considered in thermoeconomic models are: (i) power and water demand and their time dependence [16,83–86]; (ii) fuel prices [87,88]; (iii) capital and maintenance costs of equipment [89,90]; (iv) interest rate and tax structures [91,92]. The citations in the list above indicate articles in which the relevant economic factor is a main focus of the authors. [83–86,88,90] study systems without hybridization, but their analysis is relevant to the economic factors to be considered for a hybridized dual-purpose plant. It is important to note that many authors present an analysis method and calculate a TAC of water with the caveat that their solution could be substantially different had other parameter values been considered in their calculations, for example, fuel prices, seawater temperatures, and capital costs of equipment [21,26,89,93,94].

Hybridized desalination plants coupled to power production are advantageous in responding to the time-varying demands of power and water. In many locations, the demand for water is relatively constant throughout the year, but the demand for electricity is high in the summer and low in the winter. Traditional dual-purpose plants employing a power cycle and thermal desalination system suffer from a mismatch in power and water production during winter months [54], that is, to satisfy winter water demands, more electricity than needed is generated so that steam can be provided to the thermal desalination system. Steam could be provided directly from an auxiliary boiler; however, the thermodynamic advantage of the dual-purpose production is lost, and the cost of producing water subsequently becomes high. The benefit of hybridization in this regard, that is, integrating SWRO, is that the SWRO system can essentially levelize the demand between power and water through its utilization of surplus electricity [95]. However, uncertainties in demand make the optimal integration of SWRO with the overall system economically complex.

Recent work by Ghobeity and Mitsos [83] finds that it is economically advantageous to design an optimal schedule for SWRO production when considering hourly variation in electricity prices including reducing production and even completely shutting down the SWRO system while electricity prices peak midday. Further, it is found that an oversized system with respect to a fixed water output per day could be economically favorable when there are high-energy prices and/or high fluctuations in hourly electricity price. These concepts could be expanded to consider not only the SWRO system but also an entire hybrid system including thermal desalination and power production.

Almulla et al. [16] investigate the seasonal variation of electricity demand as opposed to hourly. In this article, a hybrid CC–MSF–SWRO system is considered with the possibility of energy storage in a spinning reserve; alternatives in the time-varying operation of SWRO are explored, that is, coupling the spinning reserve to SWRO operation for six months of the year, all year, or not at all or by only using plant surplus power. This study is conducted within the context of an existing plant in the United Arab Emirates, and it is concluded that using spinning power reserve for six months of the year is the cheapest integration scheme. The best time-dependent integration scheme is not immediately evident in cases such as these and therefore, as is shown in Refs. [16,83], detailed economic analysis and optimization applied to hybrid system should be further explored.

The optimal design of a plant also depends on the region of installation due to available fuel prices, feedwater quality, etc. For example, the work presented by Cali et al. [87] considers the design of hybrid MSF and SWRO systems in locations where fuel prices are relatively high, unlike regions of the Middle East where primary energy sources are abundant; [87] assume that the cost of using low sulfur fuel oil is 0.02 and 0.2 €/kg, in OPEC and non-OPEC countries, respectively. Cail et al. determine that economies of scale is an important factor in making hybrid systems economical in regions with high fuel prices. However, [87] does not offer optimization analysis for determining alternative hybrid configurations which minimize production costs in markets with high fuel prices. This type of analysis may be useful for non-OPEC regions which have high temperature, difficult seawater and subsequently cannot exclusively use SWRO, for example, the Mediterranean.

Economic analyses often reveal the economic disadvantages of a technology; in the context of hybridized desalination systems, analyses can quantify the economic trade-offs of utilizing both thermal and mechanical desalination. For example, Refs. [34,96] recognize that MSF generally imparts high capital costs and is sensitive to the cost of producing steam with regards to fuel prices and steam quality. On the other hand, SWRO can be utilized to reduce this sensitivity via balancing of capital costs and production during varying loads. These conclusions clearly show that there is an optimal allocation of water production between thermal desalination and SWRO in a hybrid system which will minimize TAC. Therefore, it is of paramount importance that detailed thermoeconomic modeling frameworks, such as those in Refs. [91,92], are developed for use in optimization of hybrid desalination systems.

### *6.3. Pretreatment improvement through NF*

A major goal in the hybridization of thermal and mechanical desalination technologies is to reduce the pretreatment burden of influent feedwater as compared to standalone desalination systems. As discussed in Section 5, scaling and fouling in both thermal and mechanical desalination can greatly impede system performance through reduced hardware life causing frequent shutdowns or large expenses for equipment replacement. Pretreatment of feedwater is subsequently necessary but requires auxiliary equipment and recurring operational expenditures for pretreatment chemicals such as scale inhibitors and acid dosing. The integration of NF in hybrid systems, however, is a promising solution for addressing scaling and fouling issues.

NF is a membrane filtration technology with a filtering ability between UF and reverse osmosis. NF preferentially removes divalent ions from feedwater, thereby reducing the content of dissolved salts such as $CaSO_4$ and $CaCO_3$ [97]. As discussed herein, the solubility of salts is a function of both temperature and concentration, and these particular ions limit the performance of thermal desalination primarily through a maximum TBT and recovery ratio and reverse osmosis through a maximum recovery ratio. Besides the removal of low-solubility salts to improve system reliability, NF is also advantageous in that it can reduce the overall TDS of the feedwater [98].

The effectiveness of NF for reducing the potential for scaling and fouling is experimentally investigated in a series of articles by the Saline Water Conversion Corporation (SWCC) of Saudi Arabia [65–71,99]. Although most experiments are conducted at a pilot plant scale, key findings show superior performance for NF–SWRO, NF–MSF, NF–SWRO–MED–TVC, and NF–SWRO–MSF systems as compared to standalone MED–TVC, MSF or SWRO systems. For example, [69] achieves an operation period of over 1,600 h for an NF–MSF system with NF make-up and 270 h with NF–SWRO reject at a temperature of 120˚C without the addition of antiscalant chemicals. [68] investigates a NF–SWRO–MSF system operating in series; SWRO recovery is reported as 45% at an operating pressure of 60 bar, and MSF is successfully operated up to a temperature of 130˚C with an 9% increase in recovery over standalone MSF operation at 120˚C.

Similar experimental results are shown by Awerbuch [100]. Through a series of demonstration trials of a NF–MSF system, Awerbuch reports successful operation at a maximum TBT of 118˚C and a 24% increase in plant output over a standalone MSF plant. A study conducted by Al-Rawajfeh [101] models the potential of sulfate scaling in NF–MSF and NF–SWRO–MSF systems. Al-Rawajfeh finds that with 100% of feedwater pretreated by NF in the NF–MSF system, no antiscalants would be needed for TBTs up to 175˚C and for only 30% NF make-up, a TBT of 135˚C could be reached.

From the above studies, NF is clearly beneficial for hybrid desalination system performance. However, few studies have been conducted which examine the most effective way to integrate NF and/or quantify the maximum achievable performance and economic improvement of an overall system. Studies regarding optimal integration of NF have focused on maximum water recovery, which implies overall increase in production for the same capacity of equipment and minimal water to pretreat, that is, reduction in operational expenses.

In [102–104], Turek et al. discuss the merits of hybrid UF–NF–SWRO–MSF or MED-crystallization schemes. Turek et al. claim that such systems can reach overall recoveries up to 80% and substantially reduce the cost of water production. The cost of water which Turek et al. calculate relies on producing commodity salts through the crystallization process and brings the price below the best standalone SWRO systems. However, Turek et al. do not offer a rigorous economic model for their estimates of water costs which incorporate the addition of NF to hybridization nor is optimization of configuration performed.

In a two-part study by Abdullatef et al. [105,106], the optimal configuration of NF modules for maximum membrane life and water recovery, with a goal of over 80%, is studied. In these articles, the configuration of NF is not considered in relation to either thermal desalination or SWRO. Rather, the optimal number of elements within a stage and the choice of one NF stage or two is experimentally investigated. While Abdullatef et al. demonstrate the ability to reach NF recoveries above 80%, systematic modeling and optimization techniques are not utilized.

The result of the above studies show that the performance and configuration optimization of the individual NF module is important, but also that its interaction with coupled desalination technologies must also be considered. Rigorous optimization analyses which include detailed performance metrics and economic models will be necessary to truly characterize the maximum benefit of NF integration in hybrid desalination systems.

## 7. Optimization methods

As shown herein, hybrid co-generation plants offer benefits over traditional dual-purpose plants. However, it is clear that there is much to be investigated in regards to the optimal design and performance of such systems. Because desalination systems require such high investments for each project, it is not practical to experimentally test every potential system improvement. Further, testing performance at a laboratory-scale is not entirely useful since the performance of desalination systems is strongly scale dependent. Therefore, the use of systematic optimization methods to develop and quantify optimal performance criteria is critical for the understanding and practical implementation of dual-purpose hybrid desalination systems.

The following discussion is a survey of the literature which employs methods for optimizing hybrid and dual-purpose systems. Specifically, the following sections examine (i) the choice of objective function(s); (ii) which methods are used to optimize operational performance, that is, the selection of continuous optimization methods; (iii) how to choose the best hardware and subsequently its connectivity, that is, the merits of fixed vs. flexible configuration frameworks. In regards to the considerations discussed in the previous section, systematic use of optimization methods will address issues and improve upon benefits of hybridized desalination systems.

### *7.1. Objective functions utilized*

The choice of an objective function for optimization has a substantial impact on the optimal operating parameters of a system. An objective function is a mathematical formulation of what is desired to be maximized or minimized to obtain an "optimal" system. Within the context of hybrid desalination systems, economic considerations are usually of paramount importance when designing a system. Because of this fact, minimizing the cost of water in some form is a common objective function defined for optimization studies. The minimization of TAC of water has been employed by several authors [81,90,107–110].

Thermoeconomic optimization, which weighs the impact of exergy destruction through cost-based component models, has also been used to approach the dual-purpose and hybrid optimal design problem

[18,21,52,84,111]. In this case, the objective function quantifies the cost of exergy destruction expressed in terms of the cost of water or other parameters. For example, Rensonnet et al. [21] study the differences between minimizing electricity cost vs. water cost vs. the total combined cost within the context of a hybrid plant of power-MSF/MED–SWRO. Rensonnet et al. [21] conclude that optimizing for the total combined cost of electricity and water is most appropriate because of the strong interdependence between the two systems. As expected, this result implies that for given electricity/water demands, a specific PWR must be met in an optimal (most economical) fashion by the plant, and for certain time varying loading cases, the optimal condition may be to produce either no power or no water.

Because of the different objective functions, some authors have proposed multi-objective optimization (MOO) for dual-purpose and hybrid systems [89,112]. By employing MOO, the trade-offs between competing criteria can be quantified. For example, Abdulrahim and Alasfour [89] compare the maximization of distillate production and gain ratio and the minimization of product cost and exergy destruction as objectives in hybrid MSF–SWRO systems. In this study, it is found that the most influential trade-offs lie between minimization of cost and exergy destruction. Vince et al. [112] develop a general framework for MSF–SWRO systems and uses MOO to minimize the TAC of water and the water resource consumption, that is, the water drawn from a water source per cubic meter of water desalinated. In this study, less expensive solutions compete against solutions with less environmental impact. Although the results of these articles which employ MOO seem to result in expected generalizations of system trade-offs, MOO can be advantageous when it is used to separate the specific areas of a system which could affect the decision making process as a system designer. For example, the trade-off in capital cost vs. the operating cost could be beneficial to quantify when considering long term vs. short term investments in a desalination plant.

### 7.2. Continuous optimization methods

In order to determine the optimal performance criteria for a given objective function and fixed system flowsheet, continuous optimization methods are employed by many authors. The common methods used are single parameter parametric studies or multivariable nonlinear programming (NLP) techniques such as local gradient based methods, for example, variants of Newton's method, non-gradient based methods, for example, evolutionary algorithms, and deterministic global optimization methods. These methods are deemed continuous because they consider continuous variables, for example, operating temperatures, pressures, flow rates, and PWR, to achieve an optimal solution.

Single parameter parametric studies are typically the easiest to implement since they require merely a system model and the ability to evaluate its mathematical functions. Single parameter parametric studies can identify an optimal value of the varied variable for fixed values of the other variables. However, single parameter parametric studies do not systematically and simultaneously provide a deterministic optimal solution, that is, the absolute best objective value cannot be guaranteed, without cumbersome analysis which becomes computationally inefficient. In general, single parameter parametric studies best offer trade-offs between operating parameters in trying to satisfy an objective function. Authors who have employed single parameter parametric studies within the context of hybrid and dual-purpose systems to quantify sensitivities among several performance criteria such as heat transfer areas, power plant extraction flow rates and temperatures, and costs of fuel or pre/post treatment chemicals, include [20,34,75,76,88,91,96].

Parametric studies have also been used to evaluate location-specific feasibility of hybrid system integration to improve performance of existing plants [16,113] or to address a particular concern of the region's water demands [13,77,114]. For example, the result of [77] shows that a hybrid co-generating GT–MED–SWRO plant would most likely be cheaper than their currently installed freshwater transport scheme, given economic considerations specific to Spain. In these types of analyses, the optimal design of a system is not necessarily the most important consideration because the analysis need only show that an installation could be feasible, that is, profitable given a set of location and/or plant-retrofit constraints. Once feasibility is shown, more detailed analysis for optimizing a system would be conducted. Therefore, single parameter parametric studies can be suitable for a relatively simple review of the feasibility of a proposed installation.

In the above examples of location specific feasibility, the capital costs of equipment, fuel prices, demand, etc. vary with location of installation. The implementation of single parameter parametric studies in these cases makes the proposed optimal solution very specific to a particular system installation. In contrast, parametric optimization could be employed to create a general framework assuming unknown prices or other values for parts of a design. Parametric optimization returns the optimal solution as a function of unknown parameters; however, it is assumed that these unknown parameters would be known at time of installation. For example, a hybrid MSF–SWRO plant could be generally optimized as a function of fuel price. Then, when the installation location is chosen, the fuel price would subsequently be known, and the particular optimal solution for the hybrid system would be calculated based on the solution of the general parametric optimization. Additionally, parametric optimization can be used to capture uncertainty associated with the technology performance and identify optimal resource allocation for the advancement of the technology [115,116]. For example, for a fixed investment in a hybrid desalination plant, parametric optimization could be employed to determine whether improvement in anti-fouling measures in MED or the permeability of SWRO would garner a greater performance gain for the overall plant.

Parametric studies seem to be most useful in identifying general trends in desalination systems but do not establish a systematic approach to finding an optimal solution for a general set of performance criteria. In contrast, continuous optimization methods involving NLP are more appropriate to systematically solve for optimal performance. However, these methods have not been employed as commonly as parametric studies within the context of hybrid or dual-purpose desalination systems. [81,90,110,111] use NLP gradient based methods to solve hybrid or dual-purpose optimization problems. In these studies, a framework is developed to describe the operating constraints of the system. Common constraints include maximum brine concentrations, maximum temperatures able to be seen by SWRO membranes, and temperature limitations in the thermal desalination section. This framework is more rigorous than a single parameter parametric study because all non-fixed variables within a system are simultaneously considered to find an optimal solution. Further, the framework more easily allows for flexibility among different design conditions which are common in desalination and co-generation applications, for example, location-dependent fuel prices, availability of resources, and differences in water composition and temperatures.

It is important to note that the use of a local solver such as in [111] does not necessarily guarantee that the best solution has been found. In complex systems such as hybrid and dual-purpose desalination, introducing thermophysical property correlations and other non-convex functions within a system model means that many suboptimal local minima may exist.

Some authors use evolutionary algorithms, that is, genetic algorithms (GA), to solve hybrid and dual-purpose NLP optimization problems. Ansari et al. [18] use a genetic algorithm within the context of thermoeconomic optimization of MED–TVC coupled to a nuclear reactor. Abdulrahim and Alasfour [89] use a genetic algorithm to quantify differences in MOO objective values of a MSF–SWRO hybrid system. GA can provide solutions to an optimization problem without needing to evaluate the gradients of system model functions. However, like local gradient-based optimization methods, GA does not guarantee that a global solution has been found at finite termination due to an inherent lack of convergence criteria within this method. Therefore, deterministic global NLP methods, such as used in [83], which account for non-convexity are necessary to guarantee that the global optimal solution has been found. The use of deterministic global optimization approaches are likely intractable for optimization of the design and operation of the concepts discussed herein due to the large size of the models. In such case, the use of heuristic global optimization can be considered, such as is used in [117].

### *7.3. Fixed vs. flexible hardware configurations for optimization*

When minimizing the cost of a system or achieve another objective such as was described in Section 7.1, continuous operating variables are not the only consideration which could affect the optimal solution. The types of desalination or power technologies employed and their subsequent connections inform the possible range of optimal operating parameters. Further, the optimization of combinations of several different configurations could lead to novel system flowsheets and provide a substantially better optimal solution than if only one configuration had been optimized for optimal performance.

Authors weigh the connectivity and hardware trade-offs of hybrid and dual-purpose desalination systems using two main methods. The most common is to propose several fixed configurations, solve them to optimal performance via an NLP method, and then compare results. This method could identify the better configuration between two options, but when several different flowsheets are proposed, the analysis becomes extremely cumbersome and computationally inefficient. In addition, the method does not guarantee that a better configuration does not exist and is limited to combinations conceived by the designer. This method will be referred to as manual configuration optimization. The second method is to create a superstructure and then use mixed integer nonlinear programming (MINLP) to solve the optimization problem. This method and its merits will be described in further detail in the latter half of this section.

A disadvantage of using manual configuration optimization is that when several possible flowsheets are considered, extensive comparisons of performance between each possibility must be calculated and the interdependence of possible configuration and hardware choices may not be immediately evident. For example, Helal et al. [34,107,118] present model development, optimization results, and sensitivity analysis of hybrid a MSF–SWRO system. The objective minimizes the specific cost of product water among nine different hardware integration schemes with fixed MSF and SWRO output. Two of the configurations consider standalone systems of which one is MSF with brine recirculation and the other is two-stage SWRO. The seven other hybridized schemes combine SWRO brine to MSF make-up and SWRO feed preheat through the heat rejection section in several different ways; these configurations were originally proposed in [119].

Helal et al. come to general conclusions regarding process economics and thermal performance, but questions arise as to the methodological effectiveness of comparing among the nine configurations considered. Of the hybrid MSF–SWRO configurations, another topology could possibly be devised which exhibits improved performance over those envisioned. Also the large extent of sensitivity parameters explored in Ref. [34] shows that the interactions among variables are highly complex and dependent on the hardware configuration.

While Helal et al. use the fixed-configurations comparisons among MSF–SWRO connectivity, Mussati et al. [120] uses a similar analysis for determining the best power plant integration for a dual-purpose system. Mussati et al. use five power plant configurations coupled to MSF: EC-ST, BP-ST, CC-BP, a CC-EC, and GT-HRSG. Mussati et al. use the power plant configurations to compare PWR ratio against water costs for the different configurations and finds that a lower PWR generally means a lower specific cost of water.

The examples of manual configuration optimization described above provide substantial direction to hardware trade-offs for fixed operating conditions. However, the method does not provide a systematic and flexible framework for finding an optimal solution. Further, hybrid and dual-purpose systems are thermodynamically and subsequently economically complex with many interdependent interactions. Superstructure development and its application to solving an MINLP problem provides this framework.

A superstructure is a tool typically used by the chemical process industry which helps the system designer think about the ways that considered technologies could be connected on a flowsheet [121]. Essentially, it is the set of all possible flowsheets that could be envisioned. The superstructure provides a flexible framework and allows for a systematic consideration of hardware and connectivity possibilities. Subsequently, MINLP is used to mathematically represent a superstructure and to optimize the flowsheet. MINLP simultaneously optimizes integer and continuous variables. Integer variables are used to capture possible choices between hardware or flowhsheet routings, for example, the choice of whether or not to include a second stage for reverse osmosis, the possibility of blending brine with thermal desalination inlet feed, the number of stages or effects within a thermal desalination system, the type of power plant extraction for providing heat to thermal desalination, or even at which time periods to shut-off the plant [83]. The level of detail of system representation within a superstructure can vary, and the complexity of the superstructure has a direct impact on the relative difficulty of solving the corresponding MINLP problem.

Within the context of hybrid and/or dual-purpose configurations, [74,85,93,112,122–124] use superstructures and subsequently MINLP for optimization. In the existing literature, integer variable choices are considered either within the water production section or the power block, but not as an overall system MINLP optimization of both power and water section configurations. Superstructures proposed by [74] and [93] treat the water production section as a black-box, but include integer choices for the power plant hardware configuration. In the case of [93], the superstructure allows the selection of an air re-heater exchanger, heat recovery generators, burners, gas turbine, and a low-pressure turbine within the power plant but keeps the MSF plant configuration fixed with brine recirculation. Conversely, the superstructure proposed by [123] considers several possible permeate and brine blending strategies between MSF and SWRO, but does not provide integration options for the power plant. The superstructure proposed by [112] depicts a black-box version of a hybrid desalination system, where the separation between permeate and brine occurs as a "process unit". The optimizer then chooses between SWRO or MSF for each process unit.

Very recently, in Ref. [124] an automatic method to build the superstructure was used. First, all possible connectivities are enumerated. Then, based on physical and logical constraints, the set of connections in the superstructure is decreased. The advantage of this method is to ensure no valid connections are missed when large numbers of components are considered.

The current literature does not provide the solution of a MINLP problem for desalination/power systems which simultaneously consider power and water production integer variables. Superstructures considering both should be developed to consider water and power configurations and choices of hardware which are strongly coupled to the performance and overall production. For example, when thermal desalination is integrated with power production, the type of extraction from the power production section informs a trade-off between potential electrical work and water production. In cases where power or water load will vary with a high frequency, EC-ST may be preferable to a BP-ST since the quality of heat can be varied. However, if the water production section can include both thermal desalination and SWRO, SWRO could be used to provide an electrical demand when the nominal electricity demand is low and the water demand is high. Therefore, in this case, the optimal choice of both power and water production hardware for minimal TAC is not obvious since there are many possible trade-offs between configuration and operation, that is, MINLP would be a favorable method to use for the solution of this problem.

## 8. Conclusion

Thermal desalination and SWRO suffer from thermodynamic, reliability, and economic challenges, for example, scaling/fouling and high operational and capital costs. Further, most often these desalination systems are combined in co-generation (dual-purpose) plants which produce both power and water and have additional concerns, for example, power/water demand following. Hybrid desalination plants, which combine thermal and mechanical desalination technologies, have been utilized to help address these challenges. However, there are many opportunities to improve these complex hybrid systems so that they maximize benefits as compared to using thermal desalination or seawater reverse osmosis alone, for example, improved hardware integration between thermal desalination and reverse osmosis, reduced operational/capital costs, and reduced pretreatment burdens (especially when NF is utilized).

Upon reviewing available literature on the design and optimization of hybrid desalination systems, it is concluded that numerical optimization should be employed to maximize the benefits possible by hybridized seawater desalination systems. The models used must be improved upon, to account for effects such as the electricity consumption in thermal desalination methods and for fouling and scaling. Pilot scale experimental hybrid plants and parametric studies of plant performance provide some insight into operation improvements and limitations as compared to traditional dual-purpose plants alone, for example, increased TBTs of thermal desalination, and proof of hybrid concepts through feasibility studies. However, these analyses do not efficiently weigh the many design variables of hybrid systems, for example, hardware configurations, feed/brine blending, and power-to-water ratios under varying loads. Numerical optimization more appropriately addresses these design decisions and could possibly elucidate new hybrid concepts. However, the choice of objective functions, detailed mathematical models, and continuous versus. structural optimization should be considered to optimally address the economic, reliability, and thermodynamic questions surrounding hybrid co-generation systems for the production of power and water.

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## List of Abbreviations

| | |
|---|---|
| BP | Back pressure steam turbine |
| C | Compressor |
| CC | Combined cycle |
| CD | Condenser |
| EC | Extraction/condensing steam turbine |
| FWH | Feed water heater |
| G | Electrical generator |
| GA | Genetic algorithm |
| GCC | Gulf Cooperation Council |
| GT | Gas turbine |
| HRSG | Heat recovery steam generator |
| MEB | Multi-effect boiling, also known as multi-effect distillation |
| MED | Multi-effect distillation |
| MEE | Multi-effect evaporation, also known as multi-effect distillation |
| MINLP | Mixed integer nonlinear programming |
| MOO | Multi-objective optimization |
| MSF | Multi-stage flash |

| | |
|---|---|
| MVC | Mechanical vapor compression |
| NF | Nanofiltration |
| NLP | Nonlinear programming |
| PR | Performance ratio |
| PWR | Power-to-water ratio |
| SDI | Silt density index |
| SF | Supplementary firing |
| SG | Steam generator |
| ST | Steam turbine |
| SWRO | Seawater reverse osmosis |
| TAC | Total annualized cost |
| TBT | Top brine temperature |
| TDS | Total dissolved solids |
| TVC | Thermal vapor compression |
| UF | Ultrafiltration |

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