A Comparison of Desalination Technologies on the Basis of Primary Energy Consumption

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ABSTRACT

The primary energy consumption of a spectrum of desalination systems is assessed using operating information for real plants configured for coproduction of electricity and water. The energy efficiency of desalination plants is often rated using metrics such as electrical energy consumption per unit of water produced (SEC), water produced per unit of thermal energy consumed (GOR), or exergy use relative to the limit set by the second law of thermodynamics (η^{II}). Comparisons of desalination technologies using these metrics can be inaccurate if energy inputs to the desalination plant are not distinguished between electrical work input and heat input using exergetic methods. Further, the cost of electrical exergy and thermal exergy at a given temperature may be quite different. When both the heat and work inputs are drawn from a common primary energy source, as in electricity-water coproduction systems, work and heat can be compared and combined by tracing them to primary energy use. In the present study, we use an exergetic framework to compare 48 different configurations of electricity production and desalination, including cases with pretreatment and hybridized systems, based on performance figures from real and quoted desalination systems operating in the GCC region. The results show that, while reverse osmosis is 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 can help to reduce energy requirements. Further, the differences are affected by the thermodynamic efficiency of the power plant itself. Conclusions with regard to hybrid systems are more ambiguous.

Keywords: exergy, thermodynamics, primary energy, efficiency, hybridization

I. INTRODUCTION

As global population increases, and standards of living rise, global freshwater demand will continue to increase. One way to augment natural water supplies is seawater desalination, which has proven to be a dependable source of fresh water for locations near the oceans.

One of the biggest barriers to implementing desalination capacity is the amount of energy required to desalinate seawater. From the laws of thermodynamics, the minimum amount of energy that is required to create a cubic meter of fresh water from seawater at a concentration of 35 g/kg is approximately 1 kWh/m^3 at a recovery ratio of 50% [1]. Even if this limit could be approached, the energy consumption of desalination would still be significantly higher than that of treating freshwater when it is available [2]. Because of the intrinsically high energy costs of seawater desalination, many studies have compared different desalination systems on the basis of energy consumption [1,3–4].

In cases where desalination plants use the same source and grade of energy, several metrics have been used for comparison, including specific energy consumption (SEC), second law efficiency (η^{II}), and gained output ratio (GOR). GOR is defined as the ratio of enthalpy of vaporization for a given amount of water to the actual amount of heat that was used by the system to produce said water:

$$GOR = \frac{\dot{m}_p h_{fg}}{\dot{Q}_H} \qquad \text{Eq. 1}$$

These metrics are very useful when comparing two plants that use the same technology. However, different desalination technologies rarely operate with the same energy inputs. Because some technologies are powered by heat, and others by electricity, and because one joule of heat does not have the same exergetic or financial value as one joule of energy in the form of electricity [5–6], it can be difficult to establish a fair basis of comparison. Directly comparing thermal energy with electrical energy consumption (or comparing thermal energy consumption of plants using two different grades of steam) has no thermodynamic value.

A better approach is to identify a common input used for all desalination plants. One such metric is the cost of energy [$\$_{energy}/m^3$]. Another, which we will consider in this paper, is the primary energy consumption. Many seawater desalination plants operate along with power plants in water-power coproduction schemes. These combined systems take in some primary energy such as natural gas, oil, or solar radiation to produce electricity in the power plant, and if necessary, steam for the desalination plant. In this paper, we consider coproduction facilities for water and power, and we ask how much additional fuel must be consumed in order to desalinate water. This results in a metric called specific primary energy consumption (SPEC), which is defined in Section 2. This approach can also be extended to compare primary exergy.

Primary energy and primary exergy analyses have been known to be important for decades [4,7–9], and have been applied to numerous desalination technologies and configurations. The novelty in the present work is to apply primary energy analysis to a large number of desalination plants using realistic data from the field, or as quoted for projects, to evaluate desalination plant efficiency. Operating conditions and performance data from a variety of power plants and desalination plants both quoted and in operation in the GCC region are used in this analysis. We note that comparisons should not be made across different power plant types because the primary energy inputs to each power plant are different.

Another benefit of using primary energy as the basis of comparison is that it allows for the comparison of technologies that require more than one type of input. This approach allows for both the thermal and electrical energy for technologies such as MED to be accounted for, and also allows for the comparison of hybrid technologies, which may be able to take advantage of operational efficiencies to perform better than the sum of their parts [10].

In this paper, we consider five core desalination technologies, three of which we consider to be mature (RO, MSF, MED), and two of which we consider to be emerging technologies (MD, FO). We also consider hybrid systems that combine pairs of these technologies, as well as the impact of NF pretreatment on primary energy consumption. Each technology or technology combination is paired with one of four power plant options. These options include a combined cycle gas turbine (CCGT) power plant, an oil-fired Rankine power plant, and both power-tower and parabolic trough type concentrating solar power plants. Overall, 48 unique combinations are examined.

II. METHODS

The goal of this analysis is to determine the primary energy required to power desalination plants of different types. There are two different ways to derive this value, both of which we will show here.

2.1 Method I - First law analysis

In this method of calculating primary energy consumption, we first consider a power plant by itself, without any desalination systems. This hypothetical power plant is referred to as the baseline power plant, and it operates with some baseline first law efficiency, η_I^b, takes in some primary energy[1], $\dot{Q}_{pp}$, and produces some amount of power to be sent to the grid, $\dot{W}_{pp}$. We would like to determine how much additional primary energy is consumed when a desalination plant is added to the baseline power plant. We call this quantity the desalination primary energy, $\dot{Q}_d$. This additional primary energy allows for the power plant to cover the electrical needs of the desalination plant, $\dot{W}_{sep}$. Additionally, in thermal desalination systems, some amount of steam is extracted at temperature T_s to provide thermal energy $\dot{Q}_{sep}$ to perform the chemical separation in the desalination plant. The extraction of steam from the power plant will reduce the first law efficiency from the baseline efficiency, η_I^b, to some new first law efficiency, which we will call the extraction first law efficiency, η_I^e. We note here that the first law efficiency for the power plant will not change when the desalination plant connected to the power plant is powered only by electricity, as is the case for reverse osmosis (RO). In this case, the energy input and power output scale linearly while maintaining the baseline efficiency. A diagram showing a generalized water and power coproduction system is shown in Figure 1. Taking the first law efficiency to be defined as the total electrical work output divided by the total primary energy input:

$$\eta_I = \frac{\dot{W}_{pp}+\dot{W}_{sep}}{\dot{Q}_d+\dot{Q}_{pp}} \qquad \text{Eq. 2}$$

[1] Here, primary energy is taken to be the thermal energy entering the power plant. For fossil fuel plants, this is taken to be the post-combustion energy, and for solar thermal power plants, primary energy is taken to be the thermal energy that is taken in by the solar absorber. This simplifies calculations somewhat. In order to determine primary energy consumption or primary energy efficiency where primary energy is taken as the solar radiation itself or the heating value of the fuel, the results can be multiplied or divided by a "fuel conversion efficiency" [11].

the additional primary energy required to be added into the power plant to power the desalination system can be determined from combining the equations for first law efficiency for the baseline and steam extraction cases:

$$\dot{Q}_d = \dot{W}_{pp}\left(\frac{1}{\eta_e^I} - \frac{1}{\eta_b^I}\right) + \frac{\dot{W}_{sep}}{\eta_e^I} \quad \text{Eq. 3}$$

This quantity can simply be divided by volumetric flow rate of product water to determine the specific primary energy consumption (SPEC).

$$SPEC = \dot{Q}_d/\dot{V}_{product} \quad \text{Eq. 4}$$

We can compare desalination plants on the basis of this desalination primary energy or SPEC, provided we are comparing using the same energy source (e.g. we can compare cogeneration systems powered by natural gas to others powered by natural gas, but not natural gas systems to solar powered systems).

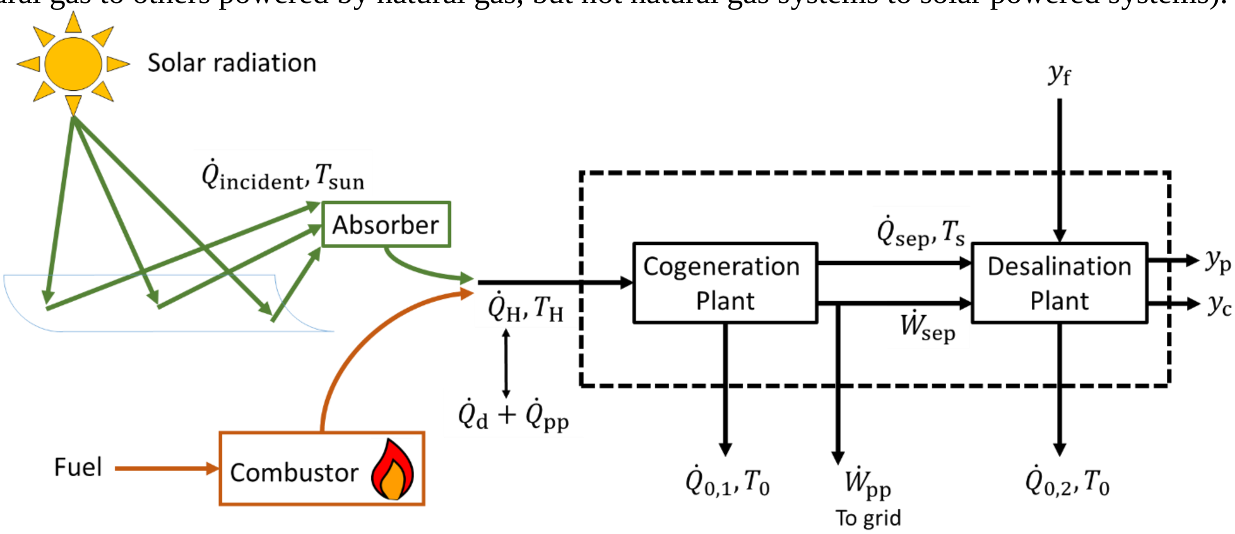

Figure 1. A diagram of a generalized water and power co-production system, with primary energy from fossil fuels or solar thermal power.

We can also manipulate Equation 3 to find the primary exergy consumption and the cogeneration system's overall combined second law efficiency with respect to the least work of separation in the desalination plant, shown in Equations 5 and 6, respectively. Here, $\dot{W}_{min,least}$ is the minimum thermodynamic least work of separation, taken in the limit as the recovery ratio of the system approaches zero [1].

$$\dot{\Xi}_d = \dot{Q}_d\left(1 - \frac{T_0}{T_H}\right) = \left(1 - \frac{T_0}{T_H}\right)\left[\dot{W}_{pp}\left(\frac{1}{\eta_e^I} - \frac{1}{\eta_b^I}\right) + \frac{\dot{W}_{sep}}{\eta_e^I}\right] \quad \text{Eq. 5}$$

$$\eta_{II,sep,primary} = \frac{\dot{W}_{min,least}}{\dot{\Xi}_d} = \frac{\dot{W}_{min,least}}{\left(1-\frac{T_0}{T_H}\right)\left[\dot{W}_{pp}\left(\frac{1}{\eta_e^I}-\frac{1}{\eta_b^I}\right)+\frac{\dot{W}_{sep}}{\eta_e^I}\right]} \quad \text{Eq. 6}$$

Although the heat of separation, $\dot{Q}_{sep}$, does not appear explicitly in any of Equations 2-6, it is embodied in Equation 3. The first term of Equation 3 can be thought of as the change in thermal energy rejected by the power plant, producing baseline power $\dot{W}_{pp}$, when the operation shifts from a power plant without steam extraction to one with steam extraction. The second term accounts for the additional primary energy needed to make electricity for the desalination plant, along with the energy rejected in the process of making additional power $\dot{W}_{sep}$. The total rejected energy includes both energy rejected to the environment, $\dot{Q}_{0,1}$, and the thermal energy sent as steam to the desalination plant, $\dot{Q}_{sep}$.

While this method works well and uses simple equations to arrive at a useful solution, all terms in Equations 2-6 may not be known, especially the varying first law efficiencies. In this case, we may be able to utilize a second method.

2.2 Method II – Second law analysis

The second method makes several assumptions to arrive at the primary energy consumption of the desalination plant. If the amount of exergy that is consumed by the desalination system is much smaller than the amount of exergy used by the power plant, then the second law efficiency of the power plant can be assumed to remain constant, with or without steam extraction. In this case, the primary energy for the electrical portion of the plant can be easily found from the definition of the power plant's second law efficiency.

$$\dot{Q}_{d,electric} = \frac{\dot{W}_{sep}}{\eta_{pp}^{II}(1-T_0/T_H)} \quad \text{Eq. 7}$$

Calculating the primary used to generate thermal energy for the desalination plant is not as straightforward. The additional primary energy that enters the system passes through the power plant before being diverted to the desalination plant at some temperature $T_s > T_0$. One may incorrectly assume that because energy is conserved, the high temperature heat required to be added to the system $\dot{Q}_{d,thermal}$ is equal to the low temperature heat needed to run the desalination plant $\dot{Q}_{sep}$. However, when we consider the exergy of the high and low temperature heat streams, we see that $\dot{Q}_{d,thermal}(1 - T_0/T_H) > \dot{Q}_{sep}(1 - T_0/T_s)$. The high temperature energy is not simply degraded within the power plant before being extracted for desalination purposes. The remaining exergy at low temperature is what is left after some amount of the high temperature exergy has been used to generate power within the power plant.

A better way to think about this problem is in terms of *power loss*. The amount of power that could have been produced by the steam extracted for desalination is $\dot{Q}_{sep}(1 - T_0/T_s)\eta_{pp}^{II}$. Because we assume that the power plant operates at a fixed power output, this power loss is compensated for by adding in more high temperature heat. The amount of high temperature primary energy that must be added to the system to compensate for the steam extraction is then

$$\dot{Q}_{d,thermal}(1 - T_0/T_H)\eta_{pp}^{II} = \dot{Q}_{sep}(1 - T_0/T_s)\eta_{pp}^{II} \quad \text{Eq. 8}$$

This can be rearranged and then combined with Equation 6 to find the total additional primary energy required to power the desalination system:

$$\dot{Q}_d = \frac{\dot{W}_{sep}}{\eta_{pp}^{II}(1-T_0/T_H)} + \dot{Q}_{sep}\frac{(1-T_0/T_s)}{(1-T_0/T_H)} \quad \text{Eq. 9}$$

This equation can also be extended to determine primary exergy consumption and second law efficiency with respect to primary energy, as in Equations 5 and 6. Equation 9 is likely easier to use when examining many different desalination plants than Equation 3 because of the fact that the second law efficiency is constant. However, there is potential for inaccurate results when using Equation 9 due to the fixed second law efficiency assumption.

We can think about the power generation section of the power plant as being broken into a number of smaller turbines, each of which has its own steam inlet, outlet, power output, and second law efficiency, as shown in Figure 2. Because each turbine has different operating conditions, we would expect each to have a different second law efficiency. The difference in calculated power loss when using the system average second law efficiency (assumed to be constant) and the actual second law efficiency of the stage steam was extracted from may be small compared to the power plant's overall primary energy input. However, because the desalination plant has already been assumed to be much smaller than the power plant, this discrepancy may be large enough to cause errors in desalination primary energy calculations.

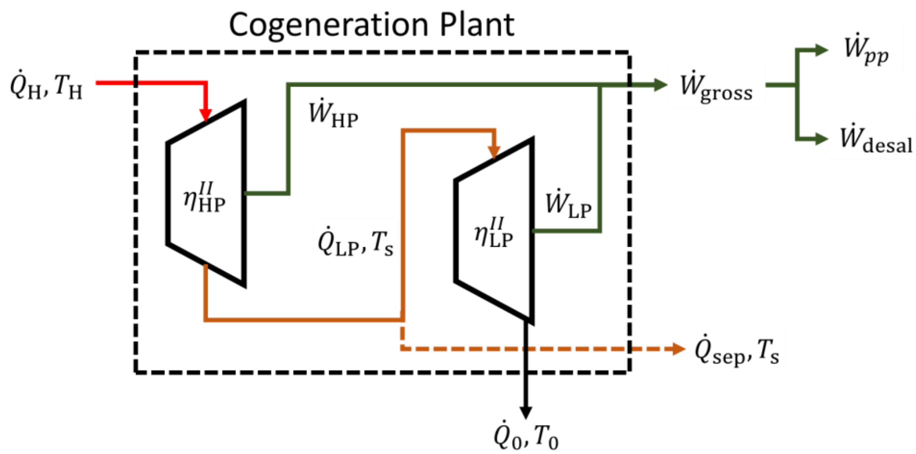

Figure 2. Hypothetical cogeneration plant with two internal stages and steam extraction.

The effects of using the second method are shown and discussed further in Sections 4 and 5.

III. SYSTEM CONFIGURATIONS

We consider 48 total unique systems in this analysis, composed of five core desalination systems, three of which we have considered to be mature, and two of which we have considered to be emerging. These desalination technologies are considered alone, as hybrids with other technologies, and with NF pretreatment. Each technology may be powered by one of four different power plant options. The operating parameters and environmental conditions are all derived from data from real plants or from quoted performance characteristics from real project bids [11].

3.1 Mature Technologies

The three mature desalination technologies, which have been proven and had their performance documented at large scale, include RO, MED, and MSF. The baseline RO system considered in this analysis is a two-pass system with a DWEER-type energy recovery device. When the system is hybridized with other technologies or pretreated with nanofiltration, it is possible to move to a single-pass system, reducing the energy required for the RO section of the system.

The MED system considered in this paper is a standard horizontal tube bundle MED system [12]. In order to increase the GOR of MED systems, steam can be recompressed in a thermal vapor compressor and fed back inside the tubes of the first effect to supply additional heating (MED-TVC or MEDT) [13].

MSF is characterized by high capacities, high reliability, and simple operation [14]. However, it is also known to have significantly higher energy consumption than many alternatives, and so many MSF plants are being replaced by newer and more efficient technologies.

3.2 Emerging Technologies

The two emerging technologies considered in this analysis are forward osmosis (FO) [15] and membrane distillation (MD) [16]. Both of these technologies have been demonstrated at lab scale and pilot scale, but have yet to be demonstrated at large scale, and the performance data for these technologies comes from projections, rather than field data. Therefore, results dealing with these technologies should not be taken with the same confidence as those calculated with proven technologies, but should instead be treated as more speculative.

MD is a thermal desalination process that uses microporous membranes and heated seawater to separate pure water vapor from saline brine. Many configurations that have been proposed and demonstrated at small scale [17–18], including air gap, direct contact, permeate gap, sweeping gas, and vacuum MD. Each seeks to increase the GOR by reducing heat loss from the heated seawater, and reusing the heat of vaporization from the collected vapor. MD has the added benefit of small vapor spaces, reducing the overall system size compared to other evaporative technologies. We consider a multi-effect vacuum MD system which has been commercialized by Memsys [19]. The configuration's flow paths are similar to a forward-feed MED system. The performance is similar in many ways to the MED system as well, with a GOR of approximately 9, although this remains to be proven at scale [20]. Other MD systems with a GOR of over 7 have been demonstrated at small scale [21].

FO is another emerging technology that employs membranes to separate water out of a saline solution. In FO, pure water flows from seawater, through a semipermeable membrane, and into a concentrated draw solution by osmosis. The draw solution is then regenerated, and the water separated from the draw solution by one of a number of processes, while the concentrated brine is disposed of. Forward osmosis operates at lower pressures and is said to have reduced fouling propensity when compared to reverse osmosis [22–23]. These factors may help to make FO cost-competitive with RO, in spite of an intrinsically higher thermodynamic minimum energy than RO [24].

The FO system we consider in this analysis [25] uses TOYOBO hollow fiber membranes to separate the feed solution from the draw, which is an ethylene oxide-propylene oxide copolymer solution developed by Trevi Systems, Inc. Heat is supplied to regenerate the solution, which becomes immiscible with water at high temperatures. The water is then physically separated from the draw solution in a coalescer. The hot draw solution and product water can be cooled in heat exchangers, transferring heat back into the system to reduce the thermal energy input to the system. The concentrated FO draw solution is then recycled and used again. In published data from a pilot system, the FO system operated at a recovery ratio of 30%, had a product water concentration of approximately 180 ppm, and had a remarkably high GOR of approximately 20, although this performance remains to be proven at large scale.

3.3 Power plants

We analyze desalination plants powered by one of four different types of power plant: combined cycle gas turbine (CCGT), oil fired, and solar thermal power plants of both parabolic trough and power tower type. The performance characteristics for these power plants is derived from field data and quoted performance characteristics. Additional data can be found in the literature [11].

3.4 System variants

In addition to the baseline systems described in Sections 3.1 and 3.2, we also consider hybridized systems comprising two of the technologies from the above sections, along with systems with nanofiltration (NF) pretreatment. There are many potential benefits of hybridizing technologies. For example, combining RO with MED or MSF allows for the blending of RO and MED or MSF product waters, which may allow for one-pass RO to be used instead of two-pass RO. Additionally, waste heat from thermal desalination plants can preheat membrane process feed streams, increasing membrane permeability[26], and flexible operation of hybrid systems can allow for constant balancing and optimization for variable power costs, seawater temperatures, or other environmental parameters. FO can also improve the recovery ratio of thermal processes like MSF by reducing the makeup water salinity, allowing for higher recovery ratios and operating temperatures [27–28].

Nanofiltration membranes have a looser pore structure than RO membranes, allowing them to operate at high fluxes and low pressures, while still removing many of the ions that cause hard scale in seawater, especially Mg^{2+}, Ca^{2+}, HCO_3^-, and SO_4^{2-}. The removal of these ions allows for higher recovery ratios in many desalination systems due to the reduced risk of forming performance-degrading scale. Increasing the top brine temperature in evaporative desalination systems allows for higher values of GOR, and increased recovery ratios in RO systems allow for smaller systems and potentially lower capital costs, although increasing the recovery ratio often reduces the energy efficiency of the plant. Diagrams for many of the systems described in this paper are shown by Altmann et al.[11].

3.5 Operating Parameters

The environmental conditions and baseline operating conditions are chosen to reflect annual average conditions in the GCC region. These parameters are shown in Table 1.

Table 1. Operating conditions constant across all plant types.

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

The data for all of the 48 combinations investigated in this analysis comes from a combination of data from real plants already in use and quoted performance numbers from real projects.

Table 2. Operating condition ranges for combined cogeneration power plants.

	CCGT	Oil Fired	CSP – Trough	CSP – Tower
Fuel combustion or solar absorber temperature, T_H	1250°C	1300°C	450°C	610°C
Carnot efficiency	79.9%	80.5%	57.7%	65.3%
First law efficiency range	56–59%	42–46%	37–41%	38–43%
Second law efficiency range	74–75%	55–57%	71–73%	64–66%
Gross power produced	823-868 MW[2]	660 MW	400 MW	400 MW

This data is used along with Thermoflow software to determine the energy requirements for each desalination and power plant combination. Table 2 shows the operating ranges for the different power plant types. Tables 3 and 4 show the recovery ratios of the desalination systems in question. Additional information on every combination discussed here is provided by Altmann et al.[11].

The goal of this analysis is to to compare desalination plant performance and efficiency under representative operating conditions. The operating temperatures, recovery ratios, pressures, and other operating conditions are chosen to reflect typical conditions using field data. For desalination plants that have not been built or demonstrated at large scale, operating information comes from quoted performance figures from plant bids.

Table 3. Recovery ratios of desalination systems with only one system producing product water.

Desalination Technologies		RO	MED	MEDT	MSF	FO*	MD*	NF-MED	NF-MEDT	FO*+MSF
Technology share	%	100	100	100	100	100	100	100	100	100
Recovery Ratio	%	40	30	30	36	35	60	35	35	40

Table 4. Recovery ratios of desalination systems with multiple systems producing product water.

Hybrid technologies	%	RO+MED		RO+MEDT		RO+MSF		NF-RO+MED		NF-RO+MEDT		FO*+MED		RO+FO*	
Component technologies		RO	MED	RO	MEDT	RO	MSF	RO	MED	RO	MEDT	FO*	MED	RO	FO*
Technology share	%	25	75	25	75	25	75	25	75	25	75	25	75	75	25
Recovery Ratio	%	45	30	45	30	45	36	50	35	50	35	35	30	40	35
Total Recovery Ratio	%	33.75		33.75		38.25		38.75		38.75		31.25		38.75	

It is also important to consider that, in order to maintain a fair basis of comparison, the power to water ratio (PWR) is kept constant when comparing different desalination plants, while in real operation this would be allowed to vary in order to arrive at optimal operating parameters for the combined system. This ratio may even vary throughout the day in order to optimize around variable power and water prices.

[2] We note here that the CCGT plant is simulated as a system with constant fuel input, resulting in a variable gross power output, while the other power plants are operated with fixed gross power production. Because comparisons should not be done between systems with different fuel sources, and all systems of the same type are analyzed on the same basis, this does not affect the results.

IV. RESULTS

Results showing the specific primary energy (where primary energy is the post-combustion or post-absorption energy depicted as $\dot{Q}_H$ in Figure 1) are shown in Figures 3 and 4. Figure 3 shows the specific primary energy of all desalination technology and power plant combinations, analyzed using the first method described in Section 2. Figure 4 shows the differences in calculated specific primary energy consumption between methods I and II.

We would expect that thermal desalination technologies would have a performance improvement relative to electrically driven technologies when the comparison is on the basis of primary energy. This relative performance gain is due to the fact that electrical technologies pay a heavy thermodynamic penalty to convert post-combustion or post-absorption thermal energy into electricity, which has a higher specific exergy than heat. Thermal technologies are not required to pay the same penalty. Instead, high-exergy thermal energy is converted into low exergy steam, with electricity being generated along the way as useful byproduct. When these thermodynamic penalties occurring in the power plants, or lack thereof, are figured into the analysis, thermal technologies receive a performance boost relative to electrical technologies.

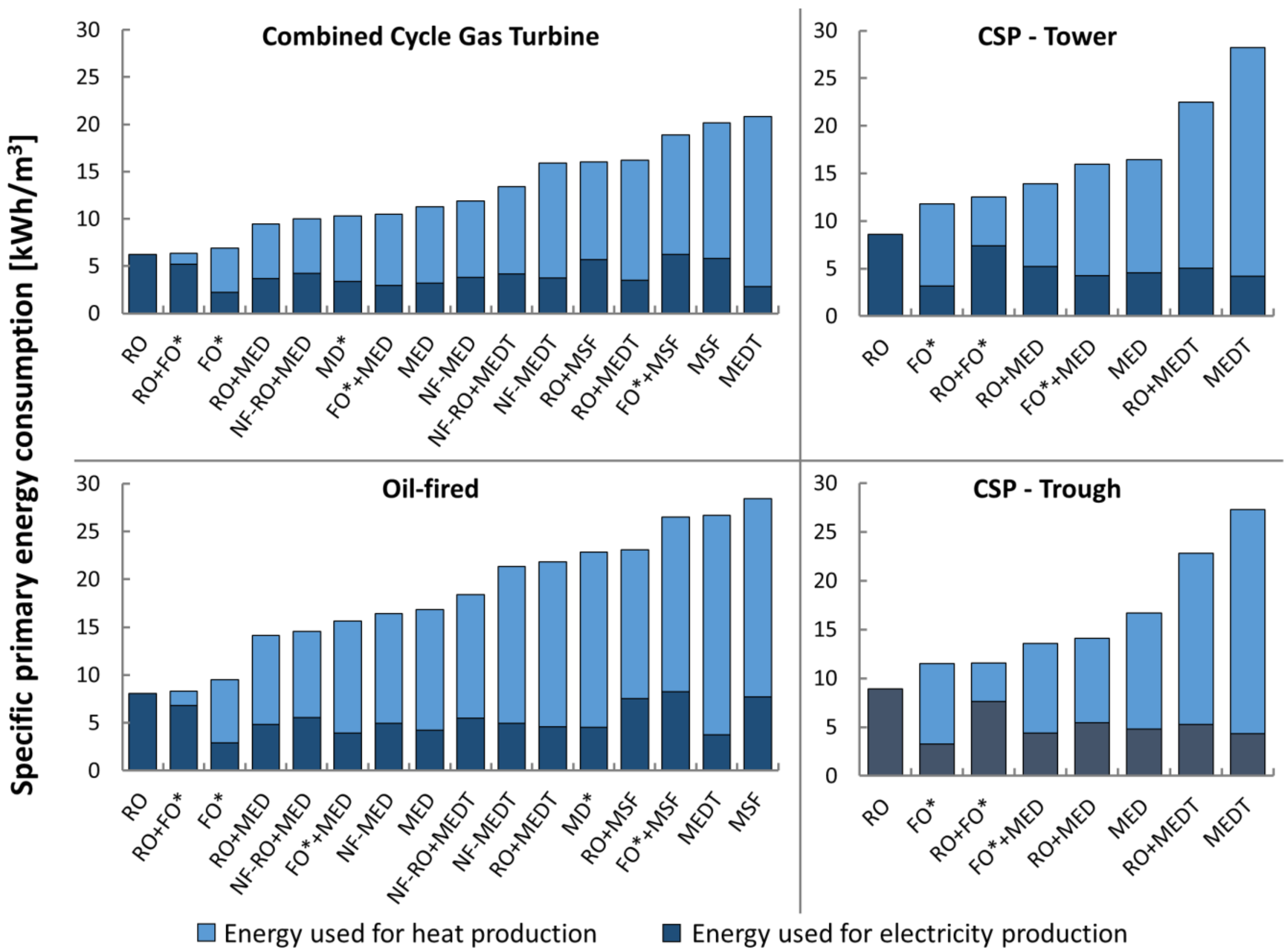

Figure 3. Specific primary energy consumption of all systems analyzed in this paper. Systems that have not had their performance validated at large scale are marked with an asterisk.

In previous analyses that compared desalination technologies on a standalone basis [1,29–30], RO was determined to be approximately 6 times more efficient on the basis of second law efficiency than MED. When we compare the second law efficiency of RO and MED on the basis of primary energy consumption using Equation 6, however, RO is approximately twice as efficient as MED. Additionally, FO looks to be a viable competitor to RO in terms of energy consumption under these conditions. Although the reported GOR for the FO system of over 20 [11,29] is very high, if it can be reproduced at large scale, then FO may be able to approach RO in terms of energy consumption. This improvement is due both to improvements in FO technology itself, especially improvements in novel draw solutions, as well as the thermodynamic benefits of using low temperature steam.

The results also show that MED outperforms MEDT in all cases, even though MEDT has a higher GOR than MED. This disparity is due to the fact that MED uses steam of a lower temperature and lower exergy than MEDT. Thus, although MEDT uses less thermal energy, the high exergy content of that thermal energy leads to a greater power loss than MED, and is therefore less efficient in terms of primary energy efficiency. While there is plenty of research that uses GOR as a figure of merit to compare desalination plants [31–32], this example shows the dangers of comparing desalination plants by using metrics that do not consider the relative exergetic value of energy inputs. While MED is more energy efficient than MEDT, there may be other reasons to choose to implement MEDT anyway. For example, the low temperature and low-pressure steam required by MED has a low density, which may require very large and very expensive ducting, while the higher temperature and pressure MEDT steam is easier to transport, reducing plant capital costs.

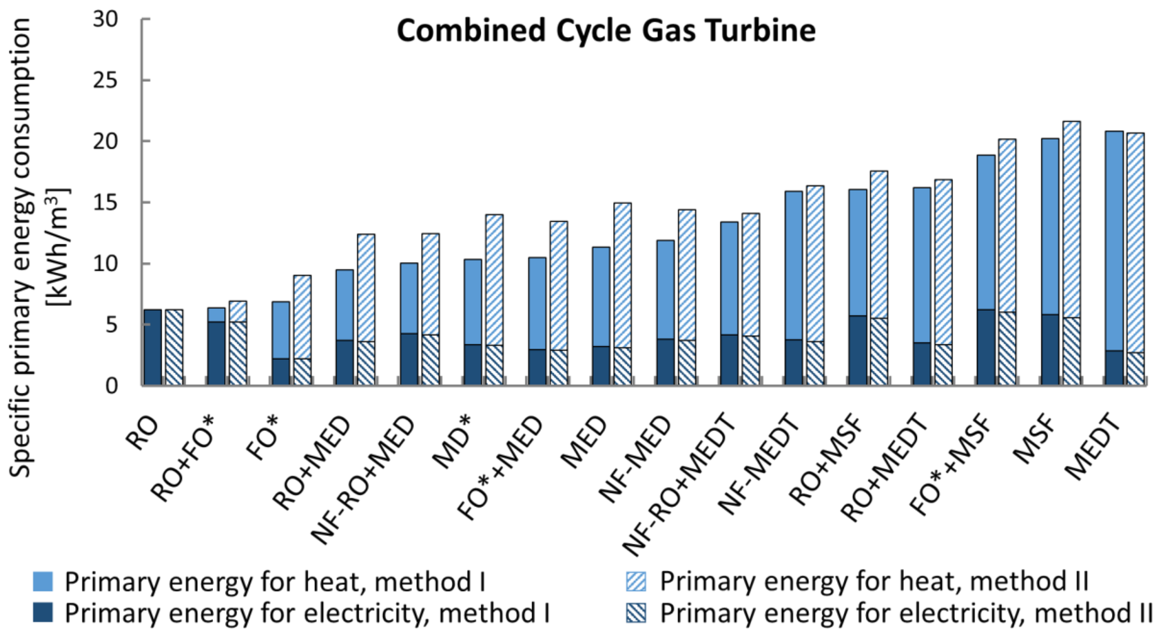

Figure 4. Figure comparing the calculated specific primary energy consumption when computed by the two different methods discussed in Section 2. Technologies that have not had their performance validated at large scale are marked with an asterisk.

Figure 4 shows that extracting steam from a power plant can have enough of an effect on the power plant operation that the second law efficiency should not be thought of as constant in most cases. As a result, method II sometimes overestimates and sometimes underestimates the primary energy consumption. Comparison of desalination plants that use different steam extraction temperatures should be avoided, since they will have varying effects on the power plant performance. If the second law efficiency of each section of the turbine is known, the primary energy can be calculated directly; however, it will likely be easier to simply use method I.

These results can also provide insights into operating hybrid desalination plants or including NF as a pretreatment technology. Hybridizing two different desalination technologies can sometimes provide synergistic benefits, such as preheating RO feed or blending product waters of multiple technologies to obtain a desirable permeate quality. The benefits may not always appear in terms of saved primary energy consumption, however. For example, adding NF may allow for operation at increased recovery ratios, which will likely increase the primary energy consumption and increase the cost of fuel for the system. However, the increased recovery ratio made possible by NF may allow for other savings, such as smaller intakes and outfalls, smaller plant footprints, or improved permeate quality. In order to truly gauge the benefit of hybridizing desalination systems or adding NF pretreatment, a complete technoeconomic analysis must be performed.

V. CONCLUSIONS

We draw a number of key conclusions from the results of this analysis:

- The energy efficiency of desalination plants should not be compared simply by the amount of energy that goes into the desalination plant itself if varying grades of energy are used. The exergetic value of the input energy must be considered. One fair basis on which to compare the energy consumption of desalination is primary energy.
- When an energy efficiency analysis is done on the basis of primary energy, the relative order of performance of desalinations systems changes relative to a standalone plant analysis. The gap between reverse osmosis and thermal desalination technologies shrinks markedly. While RO remains the most efficient in all cases, forward osmosis could be competitive if it can be scaled up and still achieve claimed performance metrics.
- MED, which is powered by low pressure and temperature steam, is more efficient in terms of primary energy consumption than MED with thermal vapor compression, even though MEDT has a higher GOR. This example illustrates that not all energy inputs are equivalent.
- Hybridizing or pretreating with NF can improve performance, but some of these improvements may not be reflected in terms of energy efficiency. Energy efficiency is only one part of evaluating the overall performance of a plant design, and a full technoeconomic analysis is needed to truly determine the benefits and drawbacks of different technology combinations.
- Assuming that the second law efficiency of the power plant remains constant when steam is extracted in cogeneration systems may seem like a good idea when considering the relatively small change in performance relative to the power plant, but this small change in performance may have large impacts on desalination system performance.

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