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Systems-level thermodynamic and economic analysis of a seawater reverse osmosis desalination plant integrated with a combined cycle power plant

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Abstract: This study includes thermodynamic and economic analyses of a seawater reverse osmosis (RO) plant integrated with a small-scale combined cycle natural gas (CCGT) plant ranging from 36–71 megawatts (MW). These analyses model electricity produced by the CCGT plant as power for the RO plant or for sale to the power grid. These analyses consider the coolant flow rate, carbon intensity, and capital and operating costs of the CCGT plant. For a case where the RO plant is sized according to the rated capacity of the CCGT plant, the maximum flow rate of coolant for the CCGT plant is only 8–10% of the total rate of seawater intake for the RO plant. Thus, no additional intake capacity is needed for the CCGT plant. The carbon intensity of the CCGT plant varies from 802-885 pounds per megawatt-hour (lb/MWh) compared to an average carbon intensity of 1285 lb/MWh for the Texas power grid. The economics of the integrated facility are evaluated using a levelized cost of water (LCOW) framework, which accounts for the capital cost associated with the CCGT plant and electricity sales to the grid. Results indicate that integrating an RO plant with a CCGT plant reduces LCOW by 8–10% compared to an RO plant powered by electricity from the Texas power grid.

Keywords: integrated power generation, desalination

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Terms used in paper

Short name or acronym	Descriptive name
C_{cap}	levelized capital cost for integrated power generation and desalination plants [$/kgal]
CCGT	combined cycle natural gas turbine power plant
CF	capacity factor for the desalination plant
CI	carbon intensity [lb/MWh]
C_{power}	cost of powering the desalination plant [$/kgal]
CRF	capital recovery factor
C_{RO}	unit cost of reverse osmosis desalination [$/kgal]
DAM	day-ahead market for electricity sales
DEEP	Desalination Economic Evaluation Program
DT	down time for the desalination plant [hr]
EIA	Energy Information Administration
ERCOT	Electric Reliability Council of Texas
E_{RO}	specific energy consumption for reverse osmosis [kWh/kgal
$F_{O\&M}$	fixed operation and maintenance cost for the power plant [$/kW-yr]
HHV	higher heating value, measurement of energy content in fuel
IWPP	independent water and power project
kgal	one thousand gallons
LCOW	levelized cost of water [$/kgal]
MED	multiple effect distillation
MSF	multiple stage flash
MW	megawatts
MWh	megawatt-hour
OCC	overnight capital cost [$/kgal per day for desalination or $/kW for power]
P_{elec}	cost of purchasing of electricity from the grid [$/MWh]
$P_{elec, sell}$	price at which electricity can be sold to the grid [$/MWh]
P_{ng}	price of natural gas [$/MWth]
R_{elec}	revenue from electricity sales [$]
RO	reverse osmosis
RR	recovery ratio of clean water out versus seawater into the RO plant
SGT	Siemens Gas Turbine
T	number of hours in a year
t	independent variable for an hour in a year
$T_{GT,out}$	gas turbine exhaust temperature [°C]
$\dot{V}_{in}$	maximum seawater intake flow rate [kgal/hr]
$V_{O\&M}$	variable operation and maintenance cost of the power plant [$/MWh]
V_{RO}	desalination plant output [kgal]
$\dot{V}_{RO, max}$	maximum desalination plant capacity [kgal/hr]
W_{gen}	electrical energy generated by the CCGT plant [MWh]
$\dot{W}_{max}$	maximum power plant output [MW]
W_{RO}	energy consumption by the desalination plant [MWh]
W_{sell}	electricity sold to the grid [MWh]
x_{RO}	on/off variable for the desalination plant
η_{HHV}	power plant efficiency [MWe/MWth]

INTRODUCTION

This study includes thermodynamic and economic analyses of a seawater reverse osmosis (RO) desalination plant integrated with a small-scale combined cycle natural gas turbine (CCGT) power plant. Approximately 27% of the global population lives within 100 kilometers of the coast and less than 100 meters above sea level, making seawater desalination a viable alternative to conventional freshwater sources for much of the population (Kummu et al. 2016). At the same time, demand for both water and electricity is increasing, and an integrated power generation and desalination facility can help address both needs simultaneously (OECD 2012, EIA 2016a). There are several motivations for integrating a desalination plant with a power plant. Depending on the specific arrangement of the desalination and power plants, an integrated facility might benefit from a variety of different features, including shared site permits and intake infrastructure and greater utilization of waste energy streams, which can reduce the cost and environmental impact caused by two separate facilities. Desalination is more energy intensive and has a greater "carbon footprint" than conventional water treatment, but an RO plant integrated with a CCGT plant can be less carbon intensive than an RO plant that uses electricity from a grid reliant on generation from coal or oil-fired power plants (Shrestha et al. 2011; Liu et al. 2015). Additionally, the facility's operation and participation in both electricity and water markets can be optimized to maximize profitability while meeting demand for electricity and water.

There are numerous desalination plants worlmaxidwide that are integrated or co-located with power plants. For example, the Tuaspring Reverse Osmosis desalination plant in Singapore has a capacity of 70 million gallons per day (MGD) that is integrated with a 411 megawatts (MW) combined cycle natural gas plant (Water Technology [no date]). In the United States, the Tampa Bay Seawater Desalination plant has a capacity of 25 MGD and shares intake infrastructure with Tampa Electric's Big Bend Power Station, a 1700 MW coal plant (Tampa Bay Water [no date]; TECO [no date]). By sharing intake infrastructure, the feedwater for the RO plant can be preheated by using it as the coolant for the condenser of the power plant, and preheating the feedwater decreases the specific energy consumption of desalination (Davis and Cappelle 2013).

This study seeks to answer several questions about the technical and economic tradeoffs of integrating a seawater RO plant with a small-scale CCGT plant. First, this analysis includes an estimation of the flow rate of seawater required for the cooling system of a small-scale CCGT plant compared to the feedwater flow rate of seawater going into a seawater RO plant. If the flow rate of coolant is less than the flow rate of feedwater for the RO plant, the CCGT plant can share a seawater intake with the RO plant. Otherwise, the CCGT plant would require additional seawater intake capacity or have to use a recirculating cooling system with a cooling tower. Regulations on intakes for power plant cooling systems such as section 316(b) of the Clean Water Act in the United States tend to restrict the use of open cycle cooling systems (EPA 2015). A downside of recirculating cooling systems with a cooling tower is that they consume more water than open-loop systems (Stillwell 2010). Cooling towers can use saltwater instead of freshwater, but using saltwater increases the maintenance cost and decreases the performance of the cooling tower (Sharqawy et al. 2010). Second, this study includes an estimation of the carbon intensity of a small-scale CCGT plant compared to the average carbon intensity of electricity purchased from the Texas power grid. Even though a natural gas fueled power plant will generate carbon emissions, the carbon intensity might be less than electricity purchased from a power grid that is still heavily reliant on coal-burning power plants.

Lastly, an optimization analysis and levelized cost of water (LCOW) framework is used to estimate the cost of an RO plant integrated with a small-scale CCGT plant compared to a stand-alone RO plant. This framework takes into account the capital and operating costs associated with a seawater RO plant, the cost of powering an RO plant with electricity generated by a small-scale CCGT plant or purchasing electricity from the grid, the capital and fixed costs associated with a small-scale CCGT plant, and the revenues that can be earned by selling electricity to the grid. This kind of cost analysis is called a credit method because the revenues that can be earned by selling electricity to the grid are credited against the costs of desalinating water (Mussati et al. 2003). This analysis considers the hourly wholesale price of electricity, and an optimization model is used to schedule the operation of an integrated CCGT-RO so as to maximize revenues from electricity sales while also achieving a prescribed capacity factor for the RO plant. This analysis differs from other cost analyses that only consider the average price at which electricity can be sold to the grid, such as the International Atomic Energy Agency's Desalination Economic Evaluation Program (DEEP) (IAEA 2014).

This study builds on the body of research on integrated power generation and desalination plants and relies on existing reports for the cost and specific energy consumption of desalination. A wide range of real-world costs and cost estimates for desalination has been reported in the literature (Blank et al. 2007; Reddy and Ghaffour 2007; Akgul et al. 2008; Karagiannis and Soldatos 2008; Ghaffour et al. 2013). The cost of desalination has tended to decrease over time, particularly with improvements to RO technology in recent decades. The cost of desalination depends on a number of factors, including the type of desalination technology, the capacity and availability of the desalination plant, and the cost of energy. The cost of desalination varies based on site-specific factors such as feedwater quality and the cost of intake and outfall systems (Ghaffour et al. 2013). The cost of energy depends on the specific energy consumption of the desalination plant and the cost of electricity used to power the desalination plant. The specific energy consumption of a desalination plant depends on a number of factors including the type of desalination technology, the quality and temperature of feedwater, the length of intake, the recovery ratio, and the use of energy recovery devices such as pressure exchangers (Stover 2007; Semiat 2008; Stillwell and Webber 2016). In general, the specific energy consumption of RO is lower than for thermal desalination technologies such as multiple stage flash (MSF) or multiple effect distillation (MED).

Much of the literature on integrating desalination plants with power plants focuses on fossil fuel-burning cogeneration or "dual-purpose" power and desalination plants wherein low-pressure steam is removed from the power cycle and used as the heat source for a thermal desalination plant (Mussati et al. 2003; Kamal 2005; Nisan and Benzarti 2008; Mabrouk et al. 2010; Wu et al. 2013, 2014). This kind of arrangement is common in the Persian Gulf countries because of its reliability and the availability of cheap energy (Reddy and Ghaffour 2007). There are also numerous studies that consider or focus on fossil fuel power plants integrated with a RO plant (Bouhelal et al. 2004; Kamal 2005; Nisan and Benzarti 2008; Wu et al. 2013, 2014). These studies include in-depth analysis of the thermodynamic efficiency and economics of cogeneration power and desalination plants. Some of these studies also include an optimization analysis to determine the optimal design of a cogeneration plant with constraints on water and electricity production (Mussati et al. 2003; Wu et al. 2013, 2014). Several of these studies use the International Atomic Energy Agency's DEEP cost-estimating tool, which can estimate the cost of desalination for different technologies based on a variety of parameters including feedwater quality, fuel cost, and power plant availability (Bouhelal et al. 2004; Nisan and Benzarti 2008; IAEA 2014). The DEEP cost-estimating tool also estimates revenues earned from electricity sales based on an average price of electricity.

There are also many articles focused on integrating desalination plants with nuclear power plants (Nisan and Dardour 2007; Nisan and Benzarti 2008; Khamis 2010; Khamis et al 2011; Alonso et al. 2012; Khamis and El-Emam 2016). These studies consider the prospects for integrating desalination systems, both thermal and RO, with existing nuclear power plants as well as the potential for integrating desalination plants with next generation nuclear technologies. There are both economic and environmental motivations for these studies to focus on integrating desalination systems with nuclear power plants instead of fossil fuel-burning power plants. Nuclear power plants do not emit carbon dioxide, and nuclear power plants are cheaper to operate than fossil fuel-burning power plants in terms of fuel and variable operation and maintenance cost per unit of electricity generated (Lazard 2017). Some of these analyses also take advantage of the DEEP cost-estimating tool and estimate that the cost of desalination with nuclear power is lower than the cost of desalination with fossil-fueled power plants, particularly when the cost of environmental externalities are also taken into consideration (Nisan and Dardour 2007; Nisan and Benzarti, 2008). However, these studies do not account for the capital cost associated with building new nuclear plants.

Much of the research on integrating desalination plants with fossil fuel and nuclear power plants focuses on large, commercial-scale power plants. The focus on commercial-scale plants can be explained by the fact that many large power plants have already been built and are operating worldwide, so integrating desalination plants into these existing systems does not require investment in new power generation capacity. Commercial-scale power plants also tend to be more efficient than smaller power plants, resulting in lower energy costs for desalination. What these analyses fail to address, however, is whether it is cost effective to build new power generation capacity specifically for powering a desalination plant. A major technical difference between large- and small-scale power plants is the flow rate of water needed for a once-through cooling system. While a large power plant may need a much higher flow rate of cooling water than can be processed by a desalination plant, a small-scale power plant needs a much lower flow rate of cooling water and may be able to share an intake with a desalination plant.

In addition to fossil fuel and nuclear power plants, there have also been many studies focused on integrating desalination plants with renewable energy sources such as wind, solar, and geothermal energy (Al-Karaghouli et al. 2009; Charcosset 2009; Eltawil et al. 2009; Al-Karaghouli and Kazmerski 2013; Gold and Webber 2015). As with nuclear plants, one of the motivations for integrating desalination systems with renewable energy sources is that they do not emit carbon dioxide. Another benefit of renewable energy systems is that they may be better suited than large power plants for providing energy in remote locales that aren't connected to a power grid. However, the intermittency of renewable energy sources like wind and solar results in a lower capacity factor for the RO plant, which results in a higher LCOW. For example, the capital cost for a 1000 MGD RO plant with a capacity factor of 50% is twice as much as a 500 MGD RO plant with a capacity factor of 100%, even though both plants produce the same amount of water on average.

With the exception of Gold and Webber (2015), the existing literature lacks much consideration on the time-dependency of electricity demand and the price of electricity). Such time-dependent factors have a significant effect on how an integrated power generation and desalination plant would optimally operate with the objective of minimizing operating costs and maximizing revenues from electricity sales. In general, an integrated power generation and desalination facility would tend to schedule the operation of the desalination plant around peak electricity demand and sell electricity to the grid instead.

While the analytical framework presented in this manuscript is generalized in nature, it is illustrated for a site in Texas for several reasons. Texas' annual water demand is projected to grow by more than 17% from 2020–2070, while Texas' electricity demand is projected to grow by almost 14% by as early as 2025 (ERCOT 2017; TWDB 2017). Thus, there is a need for additional water and electric power capacity. Since 2003, the Texas Water Development Board has had a mandate to research the feasibility of investing in desalination as a means of increasing the state water supply (Texas House of Representatives 2003). Even though the high cost and specific energy consumption for desalination has historically made it an unattractive water supply option compared to conservation or treating water from other sources, the availability of relatively affordable natural gas and ability to participate in a competitive power market might improve the economic viability of a desalination plant integrated with a CCGT power plant in a state expecting severe water stress (Sturdivant et al. 2007; TWDB 2017). This analysis focuses on the power market managed by the Electric Reliability Council of Texas (ERCOT), which accounts for about 90% of the state's electric load (ERCOT [no date]). ERCOT is responsible for managing the grid and settling the buying and selling of electricity on a wholesale market. Retail electric providers who purchase electricity on one of the ERCOT wholesale markets can then sell the electricity to end-users at a contracted rate.

Table 1. Cost and performance specifications for the CCGT plants considered in this analysis.

SGT Model	W_{max}[MW$_e$]	η_{HHV}	OCC [$/kW]
600	35.9	0.45	1359
700	45.2	0.47	1277
800	71.4	0.5	1091

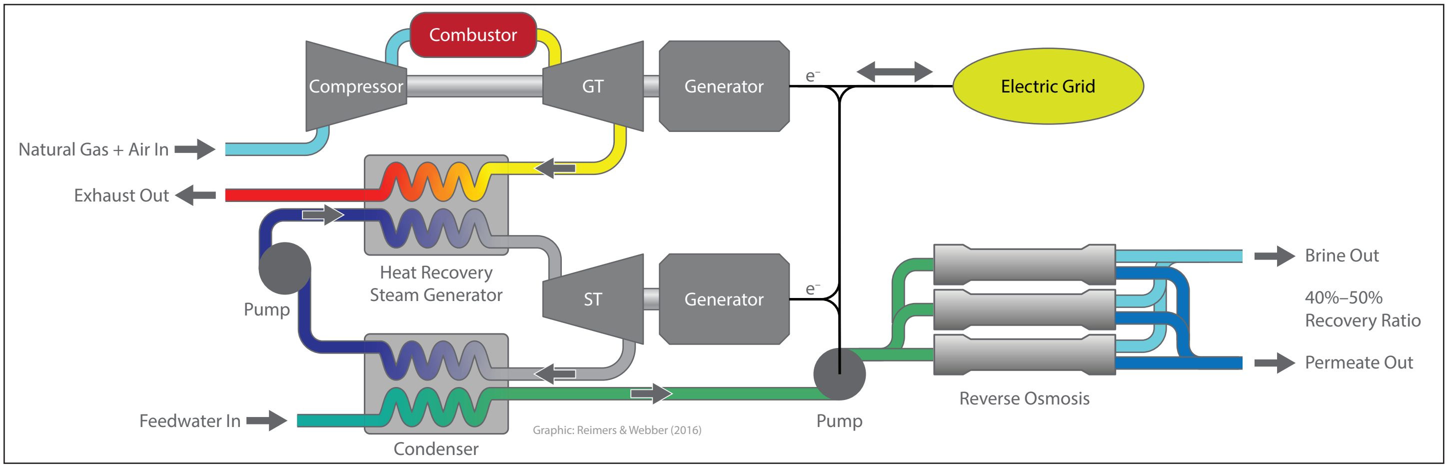
METHODS

Integrated CCGT-RO plant specifications

A schematic of an RO plant integrated with a CCGT plant is shown in Figure 1. The CCGT plants considered for this analysis are based on the Siemens Gas Turbine (SGT) line—SGT 600, 700, and 800, specifically—because of the suitability of these gas turbines for combined cycle applications, the availability of performance and cost-related data, and a range of sizes capable of running a large-scale seawater RO plant (Siemens [no date]). The maximum power output ($\dot{W}_{max}$), higher heating value (HHV) efficiency (η_{HHV}), and overnight capital cost (OCC) of the CCGT plants were taken from the Gas Turbine World Handbook (GTW 2015). Higher heating value is a measure of the energy content of the fuel, and power plant efficiency is a measure of the electricity generated per unit of fuel energy consumed by the plant. These specifications are shown in Table 1.

The maximum power output of the CCGT was used to determine the maximum RO capacity, $\dot{V}_{RO,max}$, that could be powered by the CCGT, as shown in Equation 1:

$$\dot{V}_{RO,max} = \frac{\dot{W}_{max}}{E_{RO}} \tag{1}$$



Graphic: Reimers & Webber (2016)

Figure 1. For an RO plant integrated with a CCGT plant, electricity generated on site can be used to power the RO plant or sold to the grid. (GT = gas turbine; ST = steam turbine)

where E_{RO} is the specific energy consumption of the RO plant. Note that the units for flow rates in the model are in thousand gallons per hour. This analysis assumes a specific energy consumption of 13.75 kWh per thousand gallons (kgal) for both the stand-alone RO plant and CCGT-RO plant (Semiat 2008). Note that the specific energy consumption of the integrated CCGT-RO plant could be slightly lower because of the feedwater being preheated with waste heat from the CCGT condenser (Davis and Cappelle 2013). This effect is assumed to be negligible because of the significantly lower cooling water flow rates compared to the overall flow rate of feedwater for the RO plant.

This analysis assumes that the RO plant would have a recovery ratio, RR, between 40-50%, i.e., 40-50% of seawater intake is output as freshwater permeate, as indicated in Figure 1 (ADC [no date]; Al-Zahrani et al. 2012). The recovery ratio is used to calculate the intake size needed to accommodate the maximum RO capacity as shown in Equation 2:

$$\dot{V}_{in} = \frac{\dot{V}_{RO,max}}{RR} \tag{2}$$

where $\dot{V}_{in}$ is the maximum seawater intake flow rate.

Coolant flow rate and carbon emissions

The coolant flow rate for the CCGT plant was estimated using a thermodynamic model built in Thermoflex, a commercial software package for modeling thermal systems (Thermoflow [no date]). Thermoflex includes numerous sample models of thermal systems, including a model of a basic CCGT plant. Thermoflex also has a gas turbine library that includes performance specifications for many of the gas turbines on the market. The basic CCGT model was modified to include the Siemens gas turbines described in Table 1 and to include an open cycle cooling system rather than a cooling tower. Site conditions based on typical weather data for the Texas Gulf Coast region were also used as inputs to the Thermoflex model. These inputs include ambient temperature, 21°C, seawater temperature, 20°C, and relative humidity, 75% (NOAA [no date]; NREL [no date]). A detailed image and description of the Thermoflex model is included in the appendix. After selecting a gas turbine and setting the site conditions, the model was run to determine the flow rate of coolant into the CCGT plant. The coolant flow rate for the CCGT plant was compared to the total flow rate of seawater into the RO plant to determine if additional intake capacity would be needed for an integrated CCGT-RO.

Table 2. Operating cost components for RO desalination in $/kgal.

Component	Unit Cost $ / kgal
Chemicals	0.27
Labor	0.25
Parts	0.11
Membranes	0.11
Total	**0.75**

The carbon intensity of the CCGT plant, CI_{CCGT}, that is, the mass of CO2 released per unit of electricity generated in lb/MWh, was estimated using Energy Information Administration (EIA)'s reported values for the carbon intensity of natural gas, CI_{ng}, approximately 117 lb/MMBtu, and the efficiency of the CCGT plant as shown in Equation 3 (EIA 2016b).

$$CI_{CCGT} = \frac{3.412\ MWh}{MMBtu} \frac{CI_{ng}}{\eta_{HHV}} \tag{3}$$

For a stand-alone RO plant, the carbon emission intensity of electricity purchased from ERCOT was estimated to be approximately 1285 lb/MWh based on EIA's estimated emissions associated with power generation in the state of Texas averaged from 2011–2015 (EIA 2018a). Note that marginal emissions associated with a new RO plant in Texas would depend on the dispatch of power plants to meet the RO plant load and not just the fleet average emissions for ERCOT.

Economic analysis

An optimization analysis was used to determine how an integrated CCGT-RO plant would operate on an hourly basis with the objective of minimizing the net cost of desalination. The results of this optimization analysis were used to estimate the LCOW for an integrated CCGT-RO plant compared to a stand-alone RO plant. Data from Global Water Intelligence's DesalData.com were used to estimate the operating cost of a seawater RO plant, C_{RO}, which includes the cost of chemicals, labor, replacement parts, and membranes as shown in Table 2 (GWI 2016).

As for the cost associated with powering an RO plant, this analysis assumes that a small-scale CCGT plant could be used to power an RO plant or sell electricity into the wholesale electricity market. Conversely, a stand-alone RO plant would have to purchase electricity from a retail electric provider. Texas-specific energy prices were used for this study, but this analysis could be repeated using any electricity price data derived from an auction-based wholesale market and associated retail rates for fuel and electricity. The cost of powering a stand-alone (sa) RO plant, $C_{power,sa}$ is defined by Equation 4:

$$C_{power,sa}(t) = P_{elec,buy}(t) \times W_{RO,sa}(t) \tag{4}$$

where $W_{RO,sa}$ is the hourly electrical energy consumed by a stand-alone RO plant, and the retail price for electricity, $P_{elec,buy}$ is taken from EIA's monthly average prices for industrial customers in Texas for 2011–2015 (EIA 2016c). The hourly electricity consumed by a stand-alone RO plant is the product of the volume of water desalinated, V_{RO}, and the specific energy consumption of desalination as shown in Equation 5.

$$W_{RO,sa}(t) = V_{RO}(t) \times E_{RO} \tag{5}$$

The cost of powering an integrated (int) CCGT-RO, $C_{power,int}$, is defined by Equation 6, and the revenues from electricity sales, R_{elec}, are defined by Equation 7:

$$C_{power,int}(t) = \left(\frac{P_{ng}(t)}{\eta_{HHV}} + V_{O\&M}\right) \times W_{gen}(t) \tag{6}$$

$$R_{elec}(t) = P_{elec,sell} \times W_{sell}(t) \tag{7}$$

where W_{gen} is the hourly electrical energy generated by the CCGT, and W_{sell} is the hourly electrical energy sold to the grid. The retail price for natural gas, P_{ng}, is taken from EIA's monthly average prices for industrial customers in Texas, and the wholesale electricity prices, $P_{elec,sell}$, are based on ERCOT's day-ahead-market (DAM) settlement prices from 2011–2015 (EIA 2018b; ERCOT 2018). The variable operation and maintenance cost of the CCGT plant, $V_{O\&M}$, is 3.6 \$/MWh according to EIA (EIA 2013). All of the costs associated with operating an integrated CCGT-RO plant or stand-alone RO plant are included in the objective function defined by Equation 8:

$$\min \sum_{t \in T} \left[C_{power,j}(t) + C_{RO} \times V_{RO}(t) - R_{elec}(t)\right] \tag{8}$$

where the subscript *j* refers to either an integrated CCGT-RO (int) or stand-alone RO plant (sa). This optimization model includes several constraints on the RO and CCGT plants. The constraint on the maximum hourly output of the RO plant is defined by Equation 9, and the minimum desalination output is defined as 40% of the maximum output as shown in Equation 10 (Egozy and Faigon 2013):

$$V_{RO}(t) \le x_{RO}(t) \times \dot{V}_{RO,max} \tag{9}$$

$$V_{RO}(t) \ge 0.4 \times x_{RO}(t) \times \dot{V}_{RO,max} \tag{10}$$

where x_{RO} is a binary variable that describes whether the RO plant is on or off. The minimum down time (DT) of the RO plant, set as five hours for this analysis, is defined by Equations 11 and 12. The minimum annual capacity factor (CF) of the RO plant, set as 95% for this analysis, is defined by Equation 13.

$$\sum_{n=k}^{k+DT-1} \left[1 - x_{RO}(n)\right] \ge DT\left[x_{RO}(k-1) - x_{RO}(k)\right] \quad \forall k - 1 \cdots T - DT + 1 \tag{11}$$

$$\sum_{n=k}^{T} \left\{1 - x_{RO}(n) - \left[x_{RO}(k-1) - x_{RO}(k)\right]\right\} \ge 0 \quad \forall k = T - DT + 2 \cdots T \tag{12}$$

$$\sum_{t \in T} V_{RO}(t) = \dot{V}_{RO,max} \times T \times CF \tag{13}$$

where T is the number of hours in a year. The RO plant integrated with a CCGT plant can only run when the CCGT plant is also running as shown in Equation 14:

$$x_{RO} \le x_{gen} \tag{14}$$

where x_{gen} is a binary variable that describes whether the CCGT plant is on or off. The maximum hourly electricity generation from the CCGT plant, W_{gen}, is defined by Equation 15, and hourly electrical energy consumed by the RO plant, $W_{RO,int}$, is defined by Equation 16.

$$W_{gen}(t) \le x_{gen}(t) \times \dot{W}_{max} \tag{15}$$

$$W_{RO,int}(t) = V_{RO}(t) \times E_{RO} \tag{16}$$

Lastly, the hourly electricity generated has to be used to run the RO plant or sold to the grid as defined by Equation 17.

$$W_{gen}(t) = W_{sell}(t) + W_{RO,int}(t) \tag{17}$$

This optimization analysis used fuel and electricity price data from 2011–2015 to determine whether the lower operating costs associated with generating electricity on site and the revenues associated with electricity sales are sufficient to justify the additional capital cost for integrating the CCGT plant with the RO plant. For a stand-alone RO plant, the amortized capital cost, $C_{cap,s.a.}$, is a function of the OCC of the RO plant, the annual capacity factor of the RO plant, and the capital recovery factor, CRF, as shown in Equation 18.

$$C_{cap,s.a.} = \frac{OCC_{RO} \times CRF}{365 \times CF} \tag{18}$$

The OCC of the RO plant is defined as 4280 \$/kgal per day per the cost-estimating tool on Global Water Intelligence's DesalData.com. The CRF was calculated using Equation 19 and assuming an interest rate, i, of 8% and a project lifetime, n, of 20 years. Note that these values were chosen for illustrative purposes and that this analysis can be done using any values for the interest rate and project lifetime. A higher interest rate or lower project lifetime would increase the capital cost.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{19}$$

For the integrated CCGT-RO, the OCC and fixed operation and maintenance cost, $F_{O\&M}$, of the CCGT plant were normalized by the specific energy consumption of desalination to be in \$/kgal as shown in Equations 20 and 21. The OCC of the CCGT plant is shown in Table 1, and the fixed operation and maintenance cost for the CCGT plant is 13.2 \$/kW-yr according to EIA (EIA 2013). The sum of amortized capital and fixed costs for the integrated CCGT-RO plant, $C_{cap,int}$, is shown in Equation 22.

$$OCC_{CCGT,norm} = \frac{OCC_{CCGT} \times E_{RO}}{24\frac{hr}{d}} \tag{20}$$

$$F_{O\&M,norm} = \frac{F_{O\&M} \times E_{RO}}{24\frac{hr}{d}} \tag{21}$$

$$C_{cap,int} = \frac{(OCC_{RO} + OCC_{CCGT,norm}) \times CRF + F_{O\&M,norm}}{365 \times CF_{desal}} \tag{22}$$

The average cost of powering an integrated CCGT-RO or stand-alone RO plant, $\overline{C_{power,j}}$, is defined as the sum of hourly power costs divided by the sum of hourly desalination volume as shown in Equation 23. Similarly, the average revenues earned from electricity sales for the integrated CCGT-RO plant, $\overline{R_{elec}}$, are defined as the sum of hourly electricity revenues divided by the sum of hourly desalination volume as shown in Equation 24.

$$\overline{C_{power,j}} = \sum_{t \in T} C_{power,j}(t) \Big/ \sum_{t \in T} V_{RO}(t) \tag{23}$$

$$\overline{R_{elec}} = \sum_{t \in T} R_{elec}(t) \Big/ \sum_{t \in T} V_{RO}(t) \tag{24}$$

The LCOW is defined as the sum of the operating cost of the RO plant, the amortized capital cost, and the average cost of power minus the average revenues earned from electricity sales as shown in Equation 25.

$$LCOW_j = C_{RO} + C_{cap,j} + \overline{C_{power,j}} - \overline{R_{elec}} \tag{25}$$

In summary, a simple Thermoflex model of a CCGT plant based on the power plant specifications (Table 1) and site conditions considered for this analysis was used to estimate the flow rate of water needed for the cooling system of a small-scale CCGT plant. This flow rate was compared with the total flow rate of seawater coming into the RO plant to determine if additional intake capacity would be needed for an integrated CCGT-RO plant. The carbon emission intensity of the CCGT plant was estimated based on the reported carbon emission intensity of natural gas and the efficiency of the CCGT plant as shown in Equation 3. The carbon intensity of the CCGT plant was compared to the fleet average carbon intensity of the ERCOT power grid.

An optimization analysis was used to estimate the LCOW of an integrated CCGT-RO compared to a stand-alone RO plant. The decision variables used in this analysis include binary variables, x_{RO} and x_{gen}, that describe whether the RO plant and CCGT are on or off. The decision variables also include continuous variables for the hourly volume of water desalinated, V_{RO}, hourly electricity generation, W_{gen}, and the hourly electricity sold to the power grid, W_{sell}. Dependent variables include the hourly electricity consumed by the RO plant, W_{RO}, the hourly cost of powering the integrated CCGT-RO or stand-alone RO plant, C_{power}, and the hourly revenue earned from electricity sales, R_{elec}. These values, along with the operating costs associated with an RO plant and the amortized capital cost of an integrated CCGT-RO or stand-alone RO plant, were used to calculate the LCOW with Equation 24.

RESULTS

For small-scale CCGT plants ranging from approximately 36–71 MW, the cooling water flow rate ranges from 13 to 24 MGD, and the maximum desalination capacity ($\dot{V}_{RO,max}$) ranges from approximately 63 to 125 MGD (3-6 million gallons per hour) as shown in Figure 2. For context, Sorek, the largest seawater RO plant in the world, has a capacity of 165 MGD (IDE [no date). Assuming a recovery ratio of 40–50%, the necessary flow rate of seawater intake would range from 125–312 MGD. Thus, only 8–10% of the seawater intake for the RO plant would be needed to cool the power plant. The carbon intensity of the CCGT plant varies from 802-885 lb/MWh, 33–39% less than the average carbon intensity of 1285 lb/MWh for electricity purchased from ERCOT as shown in Figure 3. Electricity purchased from ERCOT has a higher carbon intensity because coal accounted for 27-36% of ERCOT's generation mix from 2011–2015 (EIA 2018a).

Compared to a stand-alone RO plant with the same desalination capacity, an integrated CCGT-RO has higher amortization costs but lower power costs. Subtracting the amortized capital cost of a stand-alone RO plant, Equation 18, from the amortized capital cost of an integrated CCGT-RO plant, Equation 22, the additional capital cost associated with the power plant is approximately 0.17-0.21 \$/kgal as shown in Figure 4.

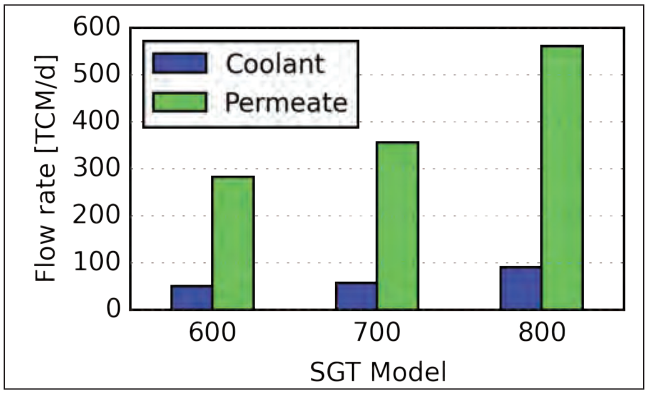


Figure 2. The flow rates [TCM/d] of power plant coolant are only 8–10% of the total flow rate of seawater intake for the RO plant assuming a 40 – 50% recovery ratio.

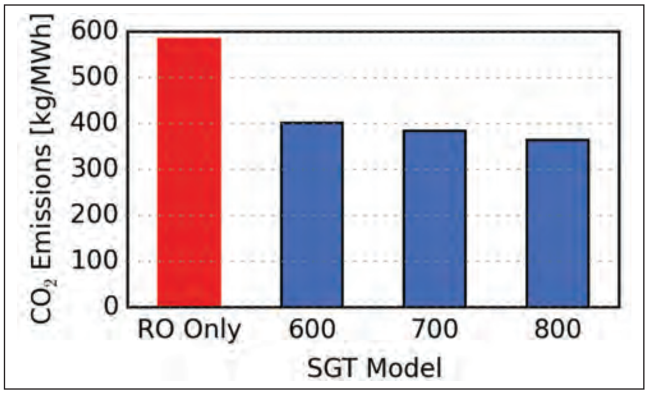


Figure 3. The average carbon intensity associated with electricity purchased from ERCOT is approximately 1285 lb/MWh compared to 802-885 lb/MWh for a range of small-scale CCGT plants that could supply power to an RO plant.

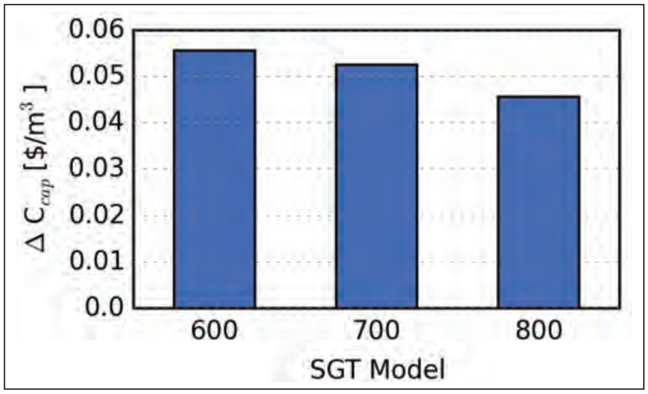


Figure 4. The additional capital cost associated with the power plant for the integrated CCGT-RO is approximately 0.17-0.21 $/kgal.

From Equation 23, the average cost of powering a stand-alone RO plant is approximately 0.68 $/kgal compared to 0.31-0.34 $/kgal for an integrated CCGT-RO plant as shown in Figure 5. An integrated CCGT-RO plant also earns approximately

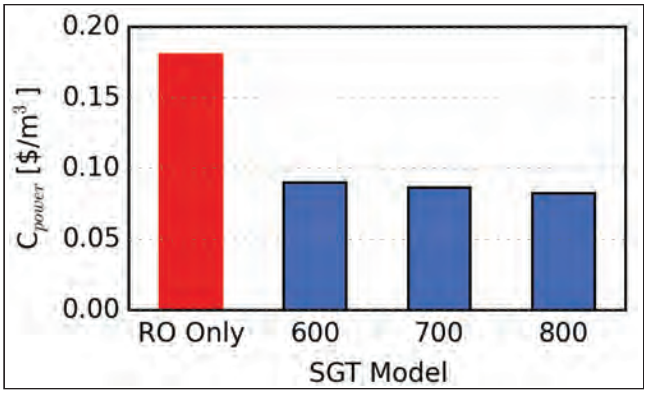


Figure 5. The power cost for a stand-alone RO plant is approximately 0.68 $/kgal compared to 0.31-0.34 $/kgal for an integrated CCGT-RO plant. An integrated CCGT-RO plant also earns approximately 0.08 $/kgal in revenues from electricity sales.

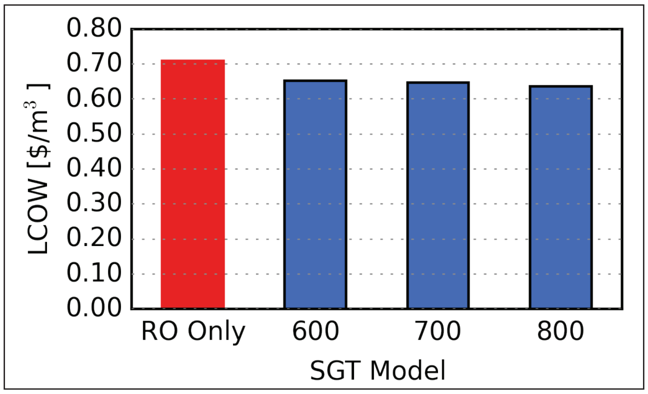


Figure 6. The LCOW for a stand-alone RO plant is approximately 2.69 $/kgal compared to 2.40-2.47 $/kgal for an integrated RO plant, a decrease of 8–10%.

0.08 $/kgal in revenues from electricity sales. From Equation 25, the LCOW for a stand-alone RO plant is approximately 2.69 $/kgal compared to 2.40-2.47 $/kgal for an integrated RO plant, a decrease of 8–10%, as shown in Figure 6. As would be expected from the decreasing amortization and power costs in Figures 4 and 5, the LCOW tends to decrease when the RO plant is integrated with a bigger, more efficient CCGT plant.

DISCUSSION

This study focused on the implications of integrating a seawater RO plant with a CCGT plant much smaller than what is typically built to be competitive in the electric power market. There were several motivations for considering such a small-scale CCGT plant. For example, even though it may make sense to integrate an RO plant with an existing large-scale power plant, it may not make as much sense to construct a new large-scale power plant just to power an RO plant. One dimension in which a small-scale CCGT plant might be preferable to a larger plant is that the cooling system of a small plant needs only a fraction of the total flow rate of seawater coming into the RO plant, and so no additional intake capacity is needed. A once-through cooling system for a 500 MW CCGT plant, on the other hand, would need an intake of more than 130 MGD, i.e., approximately 30% more than the intake for the Carlsbad RO plant outside San Diego, California, the largest seawater desalination plant in the Western hemisphere (Poseidon Water 2017).

Even though a small-scale CCGT plant is less efficient and has a higher overnight capital cost than a large-scale CCGT plant, an RO plant integrated with a small-scale CCGT plant still outperforms a stand-alone RO plant thermodynamically and economically. The carbon intensity of electricity produced by a small-scale CCGT plant is more than a third lower than the average carbon intensity of electricity on the ERCOT grid. However, ERCOT's carbon intensity is trending downward as wind, solar, and natural gas are replacing coal generation. Even so, the levelized cost analysis used in this study indicates that an RO plant integrated with a small-scale CCGT benefits enough from reduced energy costs and revenues from electricity sales to justify the capital and fixed costs associated with the CCGT plant.

This analysis assumed that the specific energy consumption of desalination was 13.75 kWh/kgal. This number is based on the most recently built large-scale desalination plants. As the specific energy consumption for seawater reverse osmosis decreases, the energy savings from integrating an RO plant with a small-scale CCGT plant decreases. For example, the Affordable Desalination Coalition has reported specific energy consumption as low as 6.6 kWh/kgal for a demonstration project (ADC [no date]). With such a low specific energy consumption, the energy savings from integrating an RO plant with a small-scale CCGT plant would be only 0.19–0.23 $/kgal instead of the 0.22-0.29 $/kgal energy savings reported in the results. Similarly, the energy savings would be higher than 0.22-0.29 $/kgal if the specific energy consumption was greater than 13.75 kWh/kgal.

The optimization analysis used to estimate the optimal hourly operation for an integrated CCGT-RO plant included an annual capacity factor constraint for the RO plant. A consequence of such a constraint is that the capacity factor of the RO can vary on a monthly basis, with the RO plant running less often in months with high wholesale electricity prices to maximize the revenues that can be earned from electricity sales. Averaging the optimal operating schedule of a CCGT-RO for the years 2011–2015 that were considered in this analysis, the capacity for the RO plant varies from as low as 86% in August to over 98% in months like November, December, and January as shown in Figure 7. These variations correspond to the monthly average wholesale electricity prices also shown in Figure 7. Note that the August prices are skewed by the extremely high prices from 2011 when the hourly average price was over 150 $/MWh. These results indicate that the owner of an integrated CCGT-RO plant would benefit from flexible purchase agreements that allow for some variation in monthly operation. Conversely, hot, dry months with high electricity prices may be coincident with high water demand or water scarcity. Thus, customers for desalinated water might choose to have water purchase agreements that require the RO plant to produce a minimum amount of desalinated water on a monthly basis. Future research should consider how stricter constraints on the monthly or daily capacity factor for the RO plant would impact estimates for the revenues that can be earned from electricity sales.

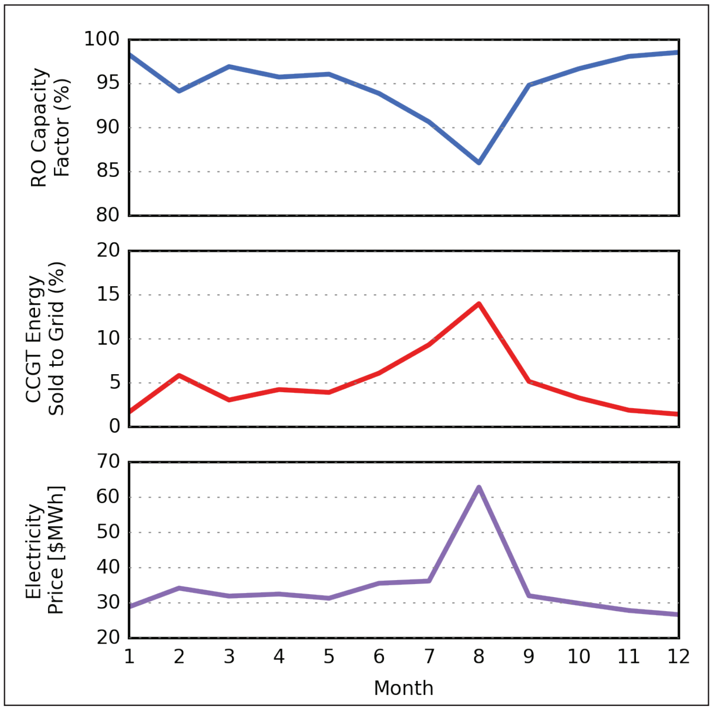


Figure 7. With an annual capacity factor constraint for the RO plant, operation of a CCGT- RO plant varies over the course of the year to maximize revenues earned from electricity sales.

When comparing the cost of an integrated CCGT-RO with that of a stand-alone RO plant, it is assumed that a stand-alone RO plant would have to purchase electricity from the grid at a monthly retail rate. If a stand-alone RO plant were instead allowed to purchase electricity at rates based on the time of use, it is conceivable that the average price of electricity could be cheaper if the RO plant is able to schedule its operation around peak electricity prices. It is also conceivable that time-of-use rates could be designed in such a way that there could be times of day or short-term market conditions when it would be cheaper to power an integrated CCGT-RO plant with electricity purchased from the grid rather than generating electricity on site. Future research should investigate how incorporating different time-of-use rates into this analysis would affect the results.

CONCLUSIONS

There are several benefits from integrating and powering an RO plant with a small-scale CCGT plant rather than purchasing electricity from the grid. With a small-scale CCGT plant, no additional intake capacity is needed for the power plant cooling system. In Texas, the carbon emission intensity for a small-scale CCGT plant is more than 33% lower than the average carbon intensity of electricity on the ERCOT power grid. From an economic standpoint, the cost of powering an integrated CCGT-RO is, on average, less than half the cost of powering a stand-alone RO plant with retail electricity. This reduction plus revenues earned from electricity sales are sufficient to justify the additional capital and fixed costs associated with the CCGT plant.

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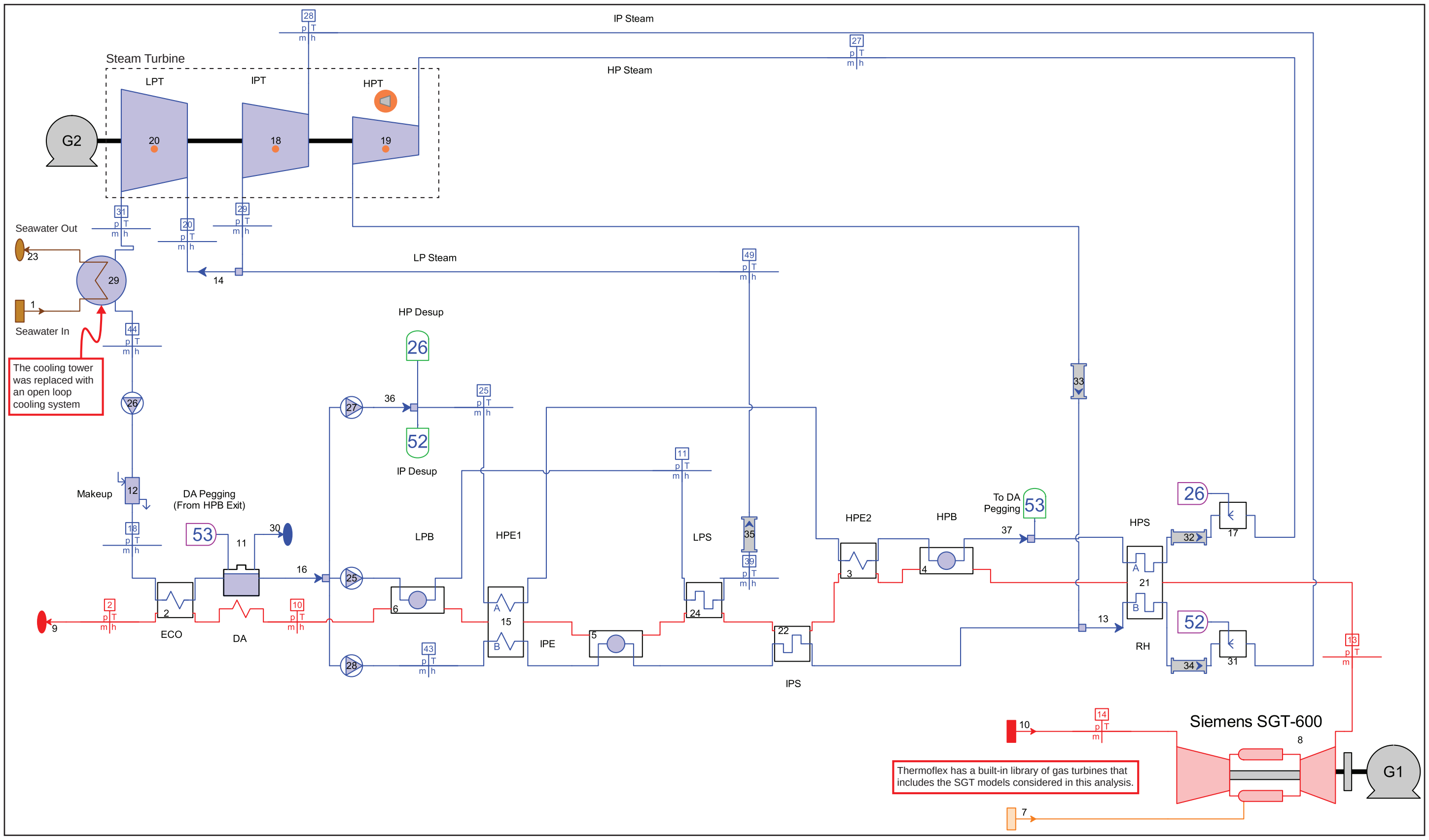
APPENDIX



The cooling tower was replaced with an open loop cooling system

Thermoflex has a built-in library of gas turbines that includes the SGT models considered in this analysis.

Figure 8. A sample CCGT model included with Thermoflex was used to estimate the coolant flow rate for a CCGT plant. This model was modified to have an open loop cooling system and the SGT models (600, 700, 800) described in the paper.