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Why is powering thermal desalination with concentrated solar power expensive? assessing economic feasibility and market commercialization barriers

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ABSTRACT

Concentrated solar power (CSP) technology has the potential to reduce the environmental impacts of thermal desalination processes and supply freshwater in remote areas, but it still has not been demonstrated in a commercial project. This problem raises concerns about the long-term reliability and economic feasibility of this technology, particularly when implemented at a large scale, which is the niche market for desalination. In this study, we obtained further insights into the economics of concentrated solar thermal desalination based on a representative calculation of the levelized cost of water (LCOW) and a cost sensitivity analysis. In addition, we compared our cost estimations with those of previous studies and evaluated the reasons for their significant variation. Moreover, we discuss market commercialization barriers from a policy perspective. We found that the LCOW for solar-driven thermal desalination ranges from \$0.94–4.31 per m^3 of freshwater, where the cost is affected mainly by the capital expenditure on the solar field and the operating expenditure of the desalination plant. Little empirical evidence from previous studies supports the economies of scale argument for concentrated solar thermal desalination. Several policies are suggested to improve the competitiveness of large-scale concentrated solar thermal desalination.

1. Introduction

Desalination technology is essential for achieving United Nations Sustainable Development Goal No. 6, which focuses on the provision of clean and safe drinking water. Goal No. 6 refers explicitly to desalination as one of several areas where capacity-building is required for countries in the developing world (United Nations Economic and Social Council, 2017). Around 300 million people throughout the world rely on desalination for potable water (International Desalination Association (IDA), 2015). Desalination does not refer only to the desalting of seawater but instead it also includes the purification of low-salinity water (known as brackish water, which has a salt concentration of less than 15,000 ppm of total dissolved salts), and thus many applications and industries benefit from or rely on desalination.

Two main issues related to large-scale commercial desalination have generated interest in solar desalination: high fuel consumption and subsequent adverse environmental impacts. Thermal desalination processes such as multi-stage flash (MSF) and multi-effect distillation (MED) consume 80–120 kWh of thermal energy and 1.5–4 kWh of electric energy for every cubic meter of desalted seawater (Alhaj et al., 2018; Darwish et al., 2013; European Union, 2008). The ever-increasing demand for freshwater has resulted in a higher rate of consumption for fossil fuel resources, thereby leading to the second major problem with desalination, i.e., energy-associated environmental impacts. Global demand for freshwater from desalination is expected to reach 54 billion m^3 per year in 2030; which is a 40% increase as compared to 2016 (Wakil et al., 2017). The climate change impact of desalination is estimated at 1.7–25 kg of CO_2 eq. per cubic meter of freshwater depending on the technology employed (Alhaj and Al-Ghamdi, 2019; Mannan et al., 2019; Wakil et al., 2017). Global CO_2 emissions from desalination are expected to reach 218 million tons per year in 2040 and hence more efforts are required to decarbonize this process (Wakil et al., 2017). In addition, desalination affects water ecosystems and marine life owing to the discharge of brine (Alhaj et al., 2017b). At present, many countries in the Middle East and North Africa (MENA) region have very limited renewable water resources and they are highly dependent on desalination. An example is the GCC region (Gulf Cooperation Council Countries) which has an installed desalination capacity of approximately 28 Mm^3 per day (or roughly 43% of the global capacity) (Wakil et al., 2017). These countries also have high

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solar resources (e.g the direct normal solar irradiance exceeds 1900 kWh/m^2/year (Singh et al., 2018)), thereby making them suitable for the deployment of solar energy technologies. These issues have motivated research on the potential of solar energy in large-scale desalination.

Solar desalination can be defined as any desalination system with energy requirements that are fulfilled (fully or partially) from a solar collector. Commercial-scale desalination can be categorized as two types of processes: thermal desalination (primarily MSF and MED) and membrane processes (mainly reverse osmosis (RO)). Research on commercial-scale solar desalination has focused on two broad categories of systems: (1) concentrated solar power (CSP) coupled to MSF, MED, or RO; and (2) photovoltaics coupled to RO systems. Owing to the scale of the available data and the significant differences between thermal and membrane desalination processes, the present study focuses primarily on CSP coupled to thermal desalination. Integrating CSP with large-scale thermal desalination provides many advantages as compared to non-concentrating collectors such as a higher solar field thermal capacity in a smaller aperture area (which potentially reduces the operational costs and the land-associated environmental impacts) and also facilitates the design of complex systems that produce both freshwater and electricity and those that integrate thermal energy storage for a higher plant availability. Investigating thermal desalination is essential because thermal desalination technologies have a larger market share than RO (although RO is increasing at a rapid pace) in the GCC region. In addition, thermal desalination has some key advantages such as high reliability and tolerance to harsh sea water quality.

Research on CSP coupled to large-scale desalination focuses on three main aspects: technical performance, environmental assessment, and economic feasibility. A sustainable solar desalination process should be technically sound, environmentally friendly, and economically feasible. These three key features are shown in Fig. 1. The technical performance can be assessed based on the 1st and 2nd laws of thermodynamics (energy and exergy) and the recovery ratio or gain output ratio. The environmental impact should be evaluated using quantitative methods such as life-cycle assessment and environmental impact assessment. The economic feasibility can be assessed using the levelized cost of water method or the net present value method. Numerous studies have investigated CSP coupled to desalination systems from a technical viewpoint by focusing on system optimization, improving the system reliability, pilot plant testing, exploring various system configurations, exploring hybridization strategies, and steady-state and dynamic modeling. In particular, a comprehensive review of the integration of CSP with the MED process was provided by (Alhaj et al., 2017a). Environmental assessments of CSP coupled to desalination (and solar desalination in general) were also conducted in several studies (Alhaj and Al-Ghamdi, 2019; Darwish et al., 2013; Mannan et al., 2019; Mezher et al., 2011; Raluy et al., 2005). Even though there has been significant progress in research and development of solar desalination; yet, there is still no commercially operational solar desalination plant, as noted by Diego-César Alarcón-Padilla, head of the Solar Desalination Unit at the Platforma Solar de Almeria (PSA) in Spain (Kraemer, 2018). This is possibly owing to the complex economics of large-scale solar desalination, which we investigated in the present study.

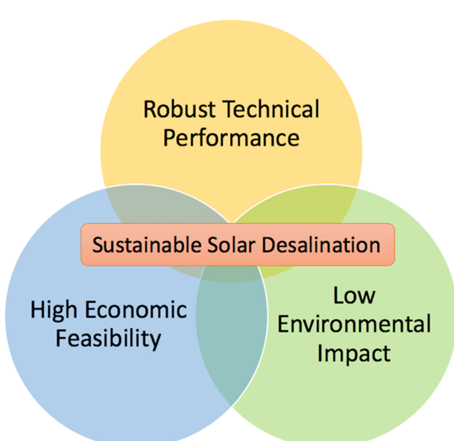

Fig. 1. Key features of sustainable solar desalination.

The economic feasibility of large-scale solar desalination is usually investigated using the levelized cost of water (LCOW) method or the net present value (NPV) method. Most studies employ the LCOW method which is preferred because it focuses on quantifying the value of the main useful output of desalination, i.e., freshwater. The LCOW can be expressed as:

$$\mathrm{LCOW} = \frac{(\mathrm{Capex}_{\mathrm{solarfield}} + \mathrm{Capex}_{\mathrm{desalination}}) + (\mathrm{O\&}M_{\mathrm{solarfield}} + \mathrm{O\&}M_{\mathrm{desalination}})}{\mathrm{D}} \quad (1)$$

where $\mathrm{Capex}_{\mathrm{solar,desalination}}$ comprise the annualized capital cost of the solar field and the desalination plant, respectively, $\mathrm{O\&M}_{\mathrm{solar,desalination}}$ comprise the annual operating cost of the solar field and the desalination plant respectively, and D is the annual plant freshwater productivity. Alsehli et al. (Alsehli et al., 2017) quantified the LCOW from a solar-driven novel MSF plant by using empirical relationships for the solar field (parabolic trough collector (PTC)) and the MSF evaporator and literature values for the O&M costs and reported a cost of $2.72/m^3. However, no parametric or sensitivity analysis were considered in this study. Askari and Ameri (Askari and Ameri, 2016) also reported a similar value ($3.32/m^3) for a MED plant with thermal vapor compression (MED–TVC) powered by a linear Fresnel collector (LFC), where they used 23 parameters to estimate the LCOW. However, the cost data for the solar field were based solely on one design point, thereby preventing an accurate investigation of the impact of the plant's scale on the LCOW. In addition, there was no discussion of the data uncertainty. Hamed et al. (Hamed et al., 2016) investigated the sensitivity of the LCOW to fuel prices for a hybrid solar-driven MED plant (using the MED–TVC process), which was partially run by solar energy with an integrated fossil fuel boiler. The average LCOW was determined as $2.84/m^3. They used previously reported values and estimates for the major system components but did not consider details of the cost breakdown for individual subsystems such as the solar field. Palenzuela et al. (Palenzuela et al., 2015) investigated the LCOW from a solar-driven cogeneration plant that operated using a PTC, thermal energy storage, auxiliary boilers, and a MED evaporator. The LCOW was reported as $0.94/m^3, which is the lowest value found in the literature. However, this study did not assess potential error margins or conduct uncertainty analysis, which is important given the scale of the data and the assumptions in the cost model.

The studies mentioned above have the following three major limitations (and this also applies to other studies on the LCOW for solar desalination):

- The economic analysis was conducted at one design point, without considering the nonlinear effects of scale, especially for the solar field.
- Several studies compared the LCOW for solar desalination with conventional fossil fuel-driven desalination. Given the low technology readiness level of solar desalination and the lack of commercial plant data, these comparisons were not meaningful at this early R&D stage. The typical costs for conventional desalination processes is: MED (0.52–1.01 $/m^3), MED-TVC (1.12–1.50 $/m^3), MSF (0.56–1.75 $/m^3), and RO (0.26–0.54 $/m^3) (Wakil et al., 2017). Instead, it is more appropriate to compare the various configurations of solar desalination systems reported in the literature.
- Most studies did not address the policy implications, i.e., investigating ways to drive the costs down and improve the competitiveness of solar desalination at regional and global scales.

The objective of this study is to calculate a more accurate value for the cost of freshwater from solar-driven thermal desalination and investigate the market commercialization barriers for this technology. We developed an economic model for evaluating the LCOW for large-scale thermal desalination driven by CSP (using the linear Fresnel collector) using representative data for commercial thermal desalination plants and solar field cost data acquired from the industry. We derived the relationships for the solar field costs as a function of the plant scale and they were used in the model. Moreover, we investigated the variations in the LCOW estimates obtained in previous studies and the impacts of economies of scale on the feasibility of large-scale solar thermal desalination systems. Market commercialization barriers and policy implications for centralized solar desalination are also discussed based on the results of the economic analysis and a critical review of previous studies. Finally, we provide an economic perspective for policy makers and researchers regarding the future prospects for large-scale solar desalination.

2. Economic model for calculating the LCOW for Large-Scale thermal desalination coupled with CSP

The proposed economic model is based on the definition of the LCOW given in Eq. (1), where a set of empirical relationships and cost assumptions from previous studies and industry-derived costs are applied in order to estimate the capital and operating costs of a solar desalination plant, disaggregate the LCOW by plant subsystem, and conduct a sensitivity analysis for the LCOW. The scope of the model is solar-driven thermal desalination and the model is used to compute the LCOW from the solar desalination plant configuration shown in Fig. 2. This plant uses low-pressure MED, which has a low pumping energy compared with the MSF process, where it can be powered by low grade heat and it has high tolerance to harsh sea water quality (i.e., levels of salinity and contaminants). The solar field is a LFC, which has greater potential for powering thermal desalination processes compared with other CSP collectors because of the following reasons (Haagen, 2012):

- It has relatively low land use requirements.
- The LFC uses flat mirrors, which are easier to manufacture and install compared with the curved mirrors in PTCs.
- The LFC has a potentially lower specific capital cost than a PTC because it does not require high-pressure joints.
- The operation and maintenance costs are lower because of easier access to the collector mirrors.

The technical performance of the plant shown in Fig. 2 was described in our previous study (Alhaj et al., 2018). In the proposed plant, thermal energy is provided by utilizing a solar LFC with pressurized water as a heat transfer fluid. The MED chamber is a low-pressure parallel feed system comprising 10 effects with brine recirculation. An air-cooled condenser is utilized instead of the conventional water-cooled condenser. Excess water produced during the day is stored in the water storage tank. This configuration is a hybrid configuration because the thermal energy is provided by the solar collector and the electric pumping energy is taken from the grid. Therefore, this plant only operates during the daytime. In the following section, we present the cost relationships for the solar field, the desalination plant, and the model inputs used for the reference case.

2.1. Cost relationships for the solar field

The cost of the solar LFC comprises the annualized capital expenditure ($Capex_{solar}$) and the operation and maintenance costs ($O\&M_{solar}$). $Capex_{solar}$ (in \$) is the sum of the direct and indirect costs, and it can be expressed as:

$$Capex_{solar} = (CC_{Dsolar} + CC_{IDsolar}) \times CRF \quad (2)$$

$$CC_{Dsolar} = ((CC_{solar} + SI) \times A) + Cont_{solar} \quad (3)$$

where CC_{Dsolar} is the solar field's direct capital cost (\$), $CC_{IDsolar}$ is the indirect capital cost (\$) (including the design and construction, land, and insurance costs; (Askari and Ameri, 2016)), CRF is the capital recovery factor, CC_{solar} is the specific capital cost per m^2 of aperture area (\$/m^2), SI are the site improvement costs, A is the aperture area (m^2), and $Cont_{solar}$ is the contingency cost. The key parameter is CC_{solar}, which must be estimated carefully using market data. Cost data for solar LFCs from Industrial Solar GmbH (a CSP project developer) at several solar field sizes were used to represent the CC_{solar} (in \$/m^2 of aperture) as a function of the plant scale (MW of thermal power) and estimated aperture area under standard testing conditions. These data are shown in Fig. 3. The nonlinear profile presented in Fig. 3 shows that the specific solar field capital can be reduced by more than 50% at large thermal capacities. The specific cost of the solar field is based on the following assumptions given by the manufacturer:

- Turn-key costs (including standard periphery).
- Costs for major substructure or civil works are not included if beyond the standard.
- Piping costs only include connections to the central interface in the collector field.

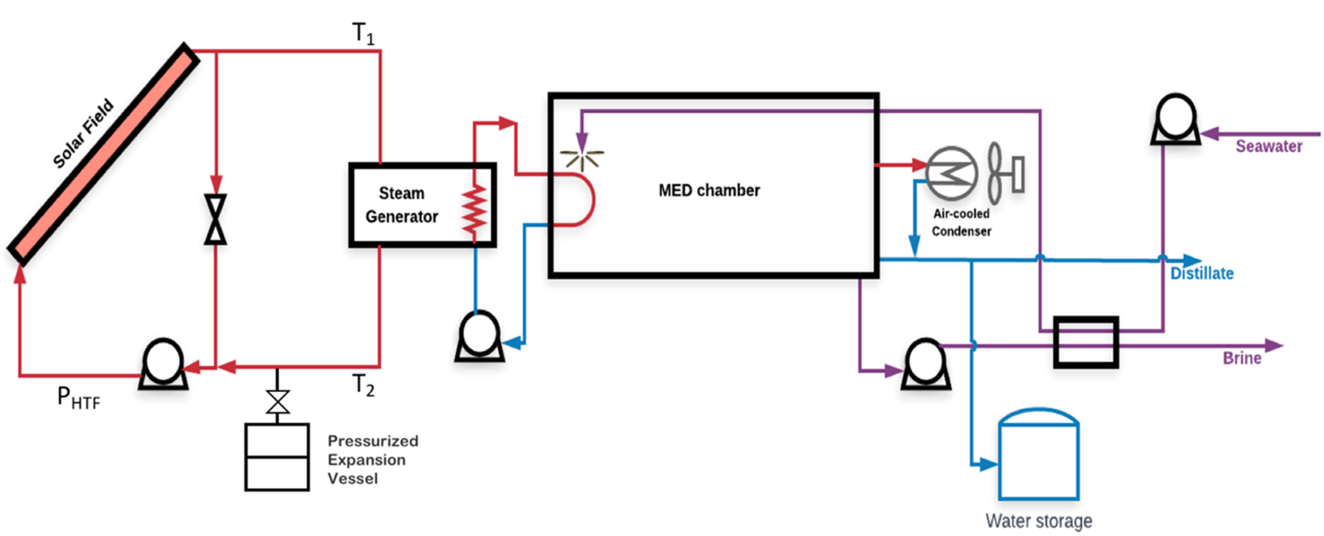

Fig. 2. Proposed solar-driven desalination plant (reproduced with permission from the publisher); (Alhaj et al., 2018).

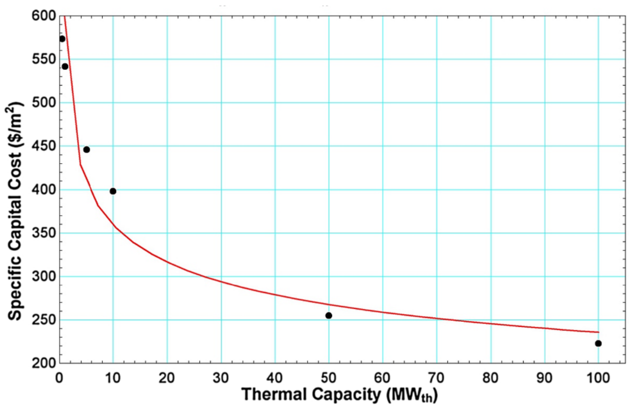

Fig. 3. Specific system capital costs for linear Fresnel collector solar fields as a function of the plant capacity.

- Customs, taxes, and transportation costs are not considered.
- Insurance costs are not included.

Using the manufacturer's data, the specific cost of the LFC solar field and the required aperture area as a function of the plant capacity (P_{solar} in MW) can be approximated by the following relationships:

$$CC_{solar} = 547.606 \times P_{solar}^{-0.183} \tag{4}$$

$$A = 1800 \times P_{solar} \tag{5}$$

The O&M costs for the solar field ($O\&M_{solar}$) were assumed to be 2.5% of the total direct costs. In general, the O&M costs for solar LFC range from 1.25% to 2.5% of the direct costs. These costs include energy, labor, materials, and fixed maintenance costs. The raw solar field cost data points and their reference conditions provided by Industrial Solar GmBH are presented in the supporting material.

2.2. Cost relationships for the desalination plant

As shown in Fig. 2, the desalination plant uses the MED technology and it incorporates an air-cooled condenser (which is not a standard in the industry). Similar to the solar field, the cost of the desalination plant is the sum of the direct and indirect costs, as shown in the following equations (Sommariva, 2012):

$$Capex_{desalination} = (CC_{Ddesalination} + CC_{IDdesalination})) \times CRF \tag{6}$$

$$CC_{Ddesalination} = (C_{MED} + PT + OSI + WTS + ERD) \times D \tag{7}$$

where $CC_{Ddesalination}$ and $CC_{IDdesalination}$ are the direct and indirect costs of the MED desalination plant, respectively ($), C_{MED} is the specific capital cost of the MED plant (in $/(m^3/day) of productivity), PT is the post treatment cost, OSI is the open seawater intake cost, WTS is the water transmission system cost, and ERD is the cost of the energy recovery device to the discharge pipeline. Accurately estimating C_{MED} has a major influence on the LCOW. In the present study, we used the relationship proposed by Kosmadakis et al. (Kosmadakis et al., 2018), which is an improved version of the regression equation derived by Rahimi et al. (Rahimi et al., 2015), in order to estimate C_{MED}. In addition, a factor (called C_{acc}) was added to the C_{MED} relationship to model the predicted increase in the capital costs owing to the use of an air-cooled condenser as mentioned in (Palenzuela et al., 2013).

$$C_{MED} = C_{acc} \times 6291 \times D^{-0.135}\left[(1 - f_{hex}) + f_{hex}\left(\frac{N}{N_{ref}}\right)^{1.277} \times \left(\frac{T_{ref}}{T}\right)^{1.048}\right] \tag{8}$$

where C_{acc} is the cost adjustment factor for integrating an air-cooled condenser, f_{hex} is the cost fraction of the evaporator (estimated as 0.4), N is the number of effects, N_{ref} is the number of effects for the reference plant (eight effects), T is the steam temperature in the first effect (°C), and T_{ref} is the reference plant steam temperature (70 °C). C_{acc} was estimated as 1.24 by comparing the power plant block capital cost increase for two PTC solar power plants (one using 100% wet cooling and the other using 100% dry cooling) given in a report by the National Renewable Energy Laboratory (NREL) (Turchi et al., 2010). It was assumed that the cost difference between the two plants was equal to the capital cost of the dry-cooling system (i.e., the air-cooled condenser). The major assumptions and limitations of Eq. (8) were given in previous studies (Kosmadakis et al., 2018; Rahimi et al., 2015). The annual operation and maintenance costs for the MED desalination plant were estimated as $1.21/m^3, which are typical for MED plants in the Arabian Gulf region (Verdier, 2011). This estimate includes the costs of chemicals, energy (thermal and electric), labor, and maintenance.

2.3. Summary of economic model inputs

A computer program was developed with the Engineering Equation Solver (EES) using 67 equations, which were solved simultaneously to evaluate the LCOW. The complete EES program is provided in the supporting material. The specifications of the concentrated solar thermal desalination plant and the assumptions for the economic analysis are given in Table 1. The aperture area of the solar field was set as the same size as the largest operational LFC plant in the world, i.e., the 30-MW Puerto Errado 2 (PE2) plant in Spain.

3. Results and discussion

Two analyses were conducted using the proposed economic model:

1. Calculating the LCOW and comparing it with values reported in previous studies.
2. Sensitivity analysis based on the LCOW.

The results of these analyses and a critical assessment of relevant studies were then used to identify the key market commercialization barriers for large-scale thermal desalination powered by CSP and the way forward from a policy perspective.

3.1. LCOW of concentrated solar thermal desalination

The LCOW from the solar desalination plant, the annualized capital and operation and maintenance costs, and the annual plant productivity are given in Table 2. The disaggregated LCOW is shown in Fig. 4. These results show that that most of the LCOW was derived from the capex of the solar field ($1.81/m^3), followed by the opex of the desalination plant ($1.21/m^3), thereby indicating the key areas for cost optimization in large-scale concentrated solar thermal desalination, which are discussed in greater depth in the market commercialization section of this study.

The LCOW value of $4.31/m^3 is slightly higher than the maximum LCOW found in previous studies for solar desalination (in studies that considered a commercial plant scale), but it is within the LCOW range of $2–32/m^3 for desalination powered by renewable energy according to earlier reports (Moser et al., 2013; Papapetrou et al., 2010). In general, we expected that the LCOW would be higher than previously reported values, mainly owing to the incorporation of the air-cooled condenser which has a higher investment cost compared with the conventional water-cooled condenser. In addition, it should be noted that the plant's availability was only 25% and there was no thermal energy storage or auxiliary fossil fuel boiler (in the reference case). When an auxiliary natural gas boiler (to allow 100% plant availability) was included in the model, the LCOW decreased to $2.89/m^3 because of the increased plant productivity with a relatively small increase in the plant's capital and operating costs.

To consider our results in an appropriate context, the LCOW values

Table 1
Specifications of the concentrated solar thermal desalination plant and inputs used for evaluating the LCOW for the reference case.

Parameter	Value	Reference
Concentrated Solar Thermal Desalination Plant Specifications		
Desalination process	Multi-effect distillation	
Solar collector	Linear Fresnel collector	
Plant productivity	13,422 m^3/day	
Solar field aperture area	302,000 m^2	(Novatec Solar, 2012)
Solar field thermal capacity	167.8 MW	
Plant capacity factor (or availability)	25%	(Verdier, 2011)
Specific thermal power	75 kWh/m^3	(Alhaj et al., 2018)
Number of effects (N)	10	
Steam temperature (T)	70 °C	
General Plant Cost Assumptions		
Plant lifetime	25 years	
Interest rate	8%	(Rahimi et al., 2015)
Solar Field Cost Assumptions		
Direct Costs (CC_{Dsolar})		
Site improvement (SI)	\$20/m^2	(Askari and Ameri, 2016)
Contingency ($CONT_{solar}$)	10% of total direct costs	(Askari and Ameri, 2016)
Indirect Costs ($CC_{IDsolar}$)		
Design and construction (D&C)	15% of total direct costs	(Askari and Ameri, 2016)
Land	\$10/m^2	(Askari and Ameri, 2016)
Insurance costs	1% of total direct costs	(Askari and Ameri, 2016)
Operation and maintenance ($O\&M_{solar}$)	2.5% of total direct costs	
Desalination Plant Cost Assumptions		
Direct Costs ($CC_{Ddesalination}$)		
Adjustment factor for air-cooled condenser(C_{acc})	1.24	Derived from the cost data in (Turchi et al., 2010)
Cost fraction for evaporator (f_{hex})	0.4	(Kosmadakis et al., 2018)
Post treatment plant costs (PTP)	\$55/(m^3/day)	(Olwig et al., 2012)
Open sea water intake costs (OSI)	\$217/(m^3/day)	(Olwig et al., 2012)
Water transmission system (WTS)	\$292/(m^3/day)	(Olwig et al., 2012)
Energy recovery device (ERD)	\$29/(m^3/day)	(Olwig et al., 2012)
Indirect Costs ($CC_{IDdesalination}$)		
Freight and insurance (F&I)	5% of total direct costs	(Ettouney et al., 2002)
Owner's cost (OC)	\$0.0025/m^3	(Loutatidou and Arafat, 2015; Verdier, 2011)
Construction overhead (CO)	12.24% of total direct costs	(Barak, 2012)
Contingency ($CONT_{desalination}$)	10% of total direct costs	(Ettouney et al., 2002)
Operation and maintenance ($O\&M_{desalination}$)(energy costs account for approximately 68% of the total O&M costs)	\$1.21/m^3	(Verdier, 2011)

Table 2
Results of the economic analysis for the reference plant. These results are representative of a desalination plant that uses low-pressure MED and solar linear Fresnel collectors, and operates at a capacity factor of 25%.

Parameter	Value
LCOW	\$4.31/m^3
CAPEX (Solar Field)	\$8.83 million
CAPEX (Desalination Plant)	\$4.42 million
O&M (Solar Field)	\$1.97 million
O&M (Desalination Plant)	\$5.93 million
Specific Solar Field Capex	\$214.3/m^2 of aperture
Annual Productivity	4.89 million m^3

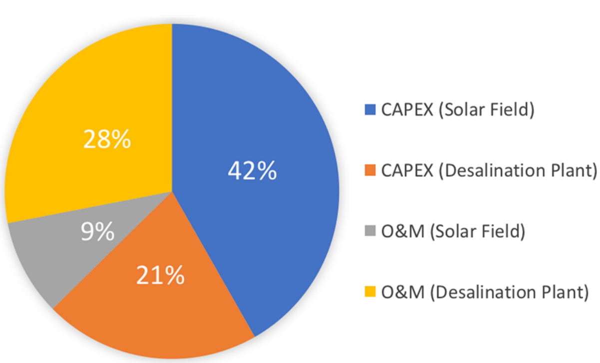

Fig. 4. Disaggregated LCOW for the concentrated solar thermal desalination plant.

obtained from several previous studies of solar desalination systems were mapped as a function of the plant productivity, where this map (Fig. 5) compared studies that modeled commercial-scale solar-driven thermal desalination plants (MED or MSF), but excluded small-scale solar-desalination units. Fig. 5 is merely plotted to show where our results stand within the literature and must not be used to draw conclusion on the impact of plant scale on the LCOW. According to Fig. 5, the LCOW varied from \$0.94/m^3 to \$4.31/m^3 and these different results may be explained by the following reasons:

- Cost data assumptions: These assumptions are probably the most significant causes of variation in the estimates. In general, the capital cost estimates for desalination plants appear to be inconsistent. For example, Askari and Ameri (Askari and Ameri, 2016) reported a value of \$1700/(m^3/day), Hamed et al. (Hamed et al., 2016) reported \$2200/(m^3/day), Palenzuela et al. (Palenzuela et al., 2015) reported \$1230/(m^3/day), and using the relationship given by Kosmadakis et al. (Kosmadakis et al., 2018), we obtained a value of \$2166/(m^3/day) for MED. These estimates differ by up to 78% and hence the large variance in LCOW estimates. The same trend is found in the solar field. By considering the solar LFC as an example, we found that Askari and Ameri (Askari and Ameri, 2016) assumed a system cost of \$235/m^2, Hamed et al. (Hamed et al., 2016) assumed \$279/m^2, and our economic model estimated a system cost of \$214/m^2. Estimating a more realistic value for the cost of solar desalination requires the use of regression equations derived from real desalination plants and CSP plants. Previous studies (Kosmadakis et al., 2018; Rahimi et al., 2015) of this issue should be considered, but further validation is still required for some of the

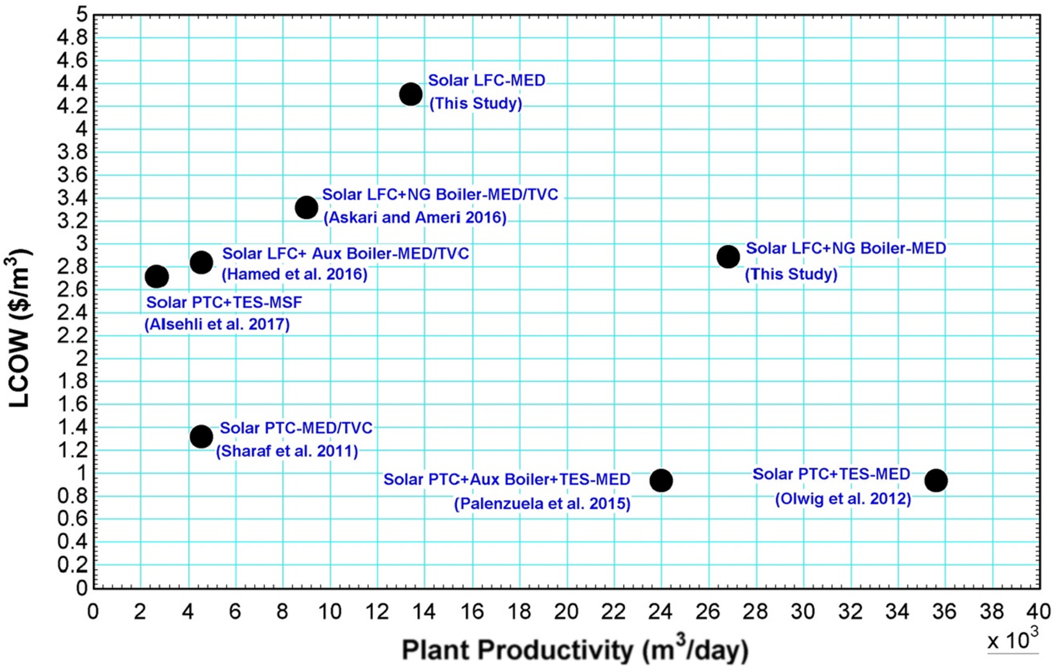

Fig. 5. Mapping the LCOW estimations for large-scale CSP-driven thermal desalination in previous studies. The studies mapped are: (Alsehli et al., 2017; Askari and Ameri, 2016; Hamed et al., 2016; Olwig et al., 2012; Palenzuela et al., 2015; Sharaf et al., 2011)).

cost correlations. The system boundaries defined in previous studies are another issue related to the cost assumptions. Several studies did not state the data included and excluded in their cost estimates, and qualitative or quantitative uncertainty analyses were not conducted. Given that research on solar desalination ultimately aims to inform policy makers, it is vital that some form of uncertainty analysis is conducted.

- System configuration: Several studies considered the desalination plant as part of a cogeneration system (e.g., see (Palenzuela et al., 2015)), which adds significant complexity to the design of the solar field, thereby affecting the final cost of freshwater. The cogeneration of power and desalted water from a solar-powered plant is still a controversial issue according to previous studies (Alhaj et al., 2017a; Pouyfaucon and García-Rodríguez, 2018). The inclusion (or exclusion) of other system components, such as auxiliary boilers, thermal energy storage, and heat pumps, will also affect the LCOW estimate.

3.2. Sensitivity of the LCOW and economies of scale

The LCOW for the concentrated solar thermal desalination plant was further investigated by considering its sensitivity to the plant productivity, plant lifetime, interest rate, $O\&M_{desalination}$, and $O\&M_{solar}$. These parameters affect the entire cost breakdown of the LCOW, as shown in Fig. 4, and as implied explicitly by Eq. (4) and Eq. (8). The upper and lower bounds for each variable are given in Table 3. The sensitivity analysis results are presented in the tornado chart in Fig. 6, which shows that the LCOW was most sensitive to the plant productivity (i.e., scale), thereby highlighting the need to consider the concepts of economies of scale and learning curves in the context of concentrated solar thermal desalination.

The economies of scale concept refers to a reduction in the unit cost of a product owing to mass manufacturing. Since the 1930 s, economists have observed that a doubling in the cumulative production volume results in an almost fixed percentage reduction in the unit cost, as first discussed by Wright in the context of the aviation industry (Wright, 1936). Economies of scale are studied based on technology log-linear learning curves, which describe the relationship between the cumulative production capacity and unit cost. Plotting a learning curve requires a large amount of historical data, which was beyond the scope of this study, so we conducted an assessment based on previous studies. The learning curve concept assumes that we accumulate more knowledge as the production volume increases, thereby identifying methods for optimizing the unit cost (Ferioli et al., 2009).

The potential impact of economies of scale on the economic feasibility of large-scale CSP-driven thermal desalination can be examined by studying the learning curves for both thermal desalination technologies and CSP technologies individually, and then deriving a conclusion regarding the future outlook. To the best of our knowledge, no previous studies have plotted learning curves for thermal desalination technologies such as MSF and MED. Clearly, Eq. (8) suggests that as the plant scale increases, the specific capital cost reduces, but it is not possible to derive a learning curve and evaluate the progress of technological innovation without a plot of the historical cumulative capacity and annual average LCOW. This is can be explained by the high commercial maturity of thermal desalination, which has been in operation in the GCC region since the 1960 s, and thus there has been little motivation to study the learning curves for this technology. The existing literature indicates that research progress in thermal desalination (MSF and MED) is relatively modest as compared to RO; however, there are several studies that aim to improve thermal desalination by examining ways to increase the top brine temperature, improving the MSF flashing efficiency, using forward osmosis in feedwater pretreatment, and re-utilizing the brine within the plant (Choi, 2016; Lv et al., 2019; Mezher et al., 2011; Thabit et al., 2019). Furthermore, R&D efforts into thermal desalination methods have been minor compared with RO because of the higher interest in energy-efficient RO systems. Historically, although it is highly energy intensive, thermal desalination was only suitable for the GCC region because of the abundant oil and gas reserves, and the process's reliability in treating highly saline seawater. However, owing to the current reduction in oil prices and advances in RO membranes that can treat highly saline and contaminated seawater (Ghaffour et al., 2013), we anticipate that the thermal desalination market will shrink (even in the GCC region), unless supported by technological breakthroughs in advanced brine treatment technologies such as zero liquid discharge and brine valorization. This conclusion

Table 3
Values used for sensitivity analysis and rationale for selecting the lower and upper bounds.

Variable	Lower bound	Base value	Upper bound	Comment
Plant productivity	120 m^3/day	13,422 m^3/day	68,190 m^3/day	The lower bound is the capacity of the largest pilot solar-MED plant, i.e., the Abu Dhabi Solar Desalination Plant (Chaibi and El-Nashar, 2009), and the upper bound is the capacity of the largest commercial MED plant, i.e., the Yanbu Phase 2 MED plant in Saudi Arabia (Water-technology.net, 2012).
Plant lifetime	15 years	25 years	50 years	Based on the range given by (Papapetrou et al., 2017).
Interest rate	6.5%	8%	10%	Based on the range given by (Papapetrou et al., 2017).
$O\&M_{solar}$	1.9%	2.5%	3.1%	Base value varied by ± 25%.
$O\&M_{desalination}$	\$0.9/m^3	\$1.21/m^3	\$1.5/m^3	Base value varied by ± 25%.

was also emphasized in previous studies (Caldera and Breyer, 2017; Ghaffour et al., 2013). The current capacities for desalination worldwide and in the GCC region by technology share are shown in Fig. 7, which indicates that RO has almost the same share as MSF in the GCC market (42% vs 46%). The aforementioned conclusion is also supported by the decision of Saudi Arabia to cease building MSF plants after the Ras Al-Khair independent water and power production plant, which is the largest seawater desalination plant in the world with a capacity of 1 million m^3/day (Caldera and Breyer, 2017). By contrast, the impact of economies of scale on RO desalination plants is rather optimistic. A plot of the capital expenditures learning curve for 4,237 RO plants worldwide indicated that the learning rate is 15% (Caldera and Breyer, 2017), so for every doubling of the global cumulative RO plants' capacity, the plant's capital expenditure will be reduced by 15%. The previous study by Caldera and Breyer (2017) did not examine the LCOW (which depends on both the operating and capital expenditure), but its results support the anticipated impact of economies of scale when applied to RO desalination plants, which is logical given the justifications outlined above.

In terms of the learning curves for CSP plants, a study by (Platzer and Dinter, 2016) estimated a learning rate of 18% for PTC solar power plants without thermal storage based on capital expenditure data from 20 PTC plants in Spain. Thus, for every doubling of the cumulative thermal capacity (in MW), the solar field's specific cost (in \$/m^2 of aperture) will be reduced by 18%. An assessment of the potential of CSP power plants in Africa and Europe (Viebahn et al., 2011) estimated a learning rate of 12% for the solar collector field in solar thermal power plants. These previous studies had some limitations but they support the argument that the CSP industry is indeed learning by experience and there is still the potential to reduce capital expenditure by increasing the plant scale. However, these studies considered the

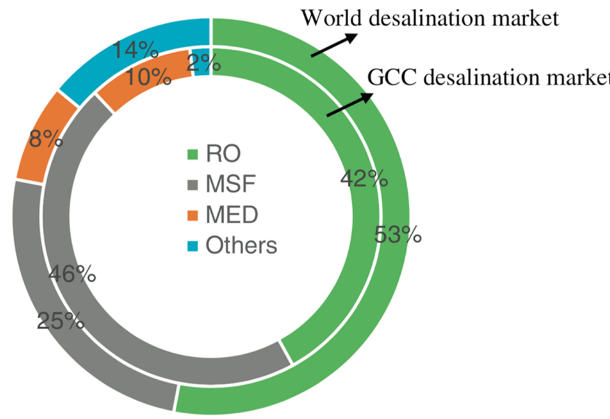

Fig. 7. Technology breakdown for the global and GCC desalination markets (Shahzad et al., 2017); (reproduced with permission from the publisher).

application of CSP for power generation and not process heat applications. Hence, it can be concluded that there are major potential cost reductions for large-scale solar desalination systems that integrate a CSP power plant with a RO desalination plant.

These previous studies have two major implications, as follows:

- Insufficient data are available to support the economies of scale argument for large-scale thermal desalination coupled with CSP. In particular, when considering LFCs, few cost data are available for analysis (Morin et al., 2012). If we map previous studies of the economic feasibility of solar-driven thermal desalination and compare them with conventional desalination, there is a considerable

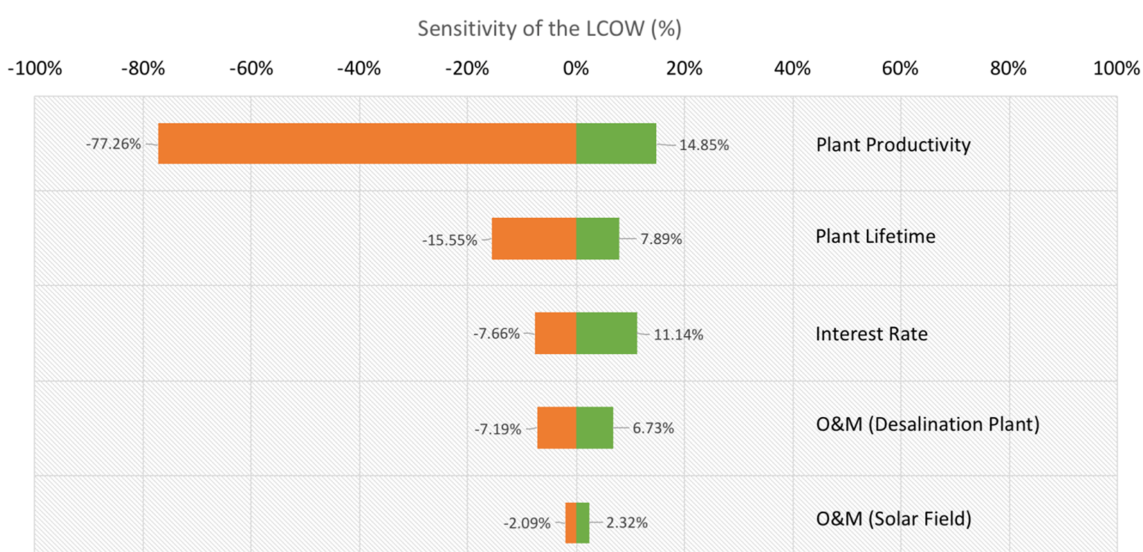

Fig. 6. Sensitivity of the LCOW to major cost parameters. The base value is \$4.31/m^3.

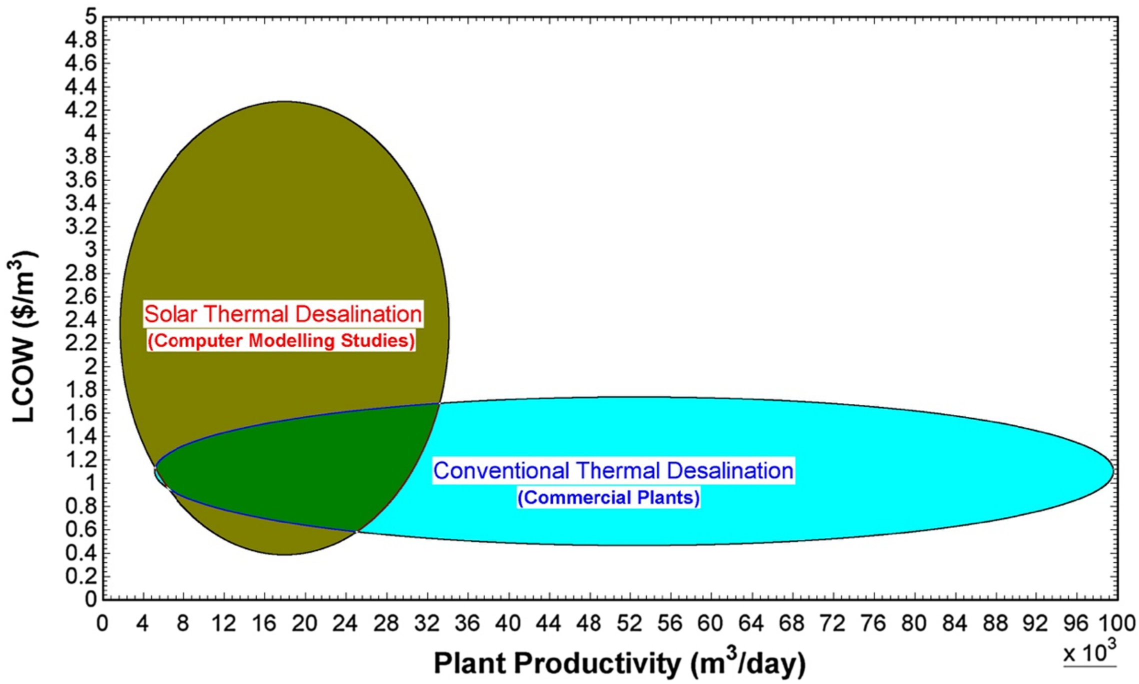

Fig. 8. Mapping the cost of large-scale solar-driven thermal desalination and conventional desalination systems. The computer modeling studies are the same as those cited in Fig. 5. The LCOW range and plant capacity for conventional thermal desalination (MSF and MED) were based on the values reported by (Wakil et al., 2017). The plant productivity is representative of a single unit (commercial plants comprise several units).

gap, as shown by the plot in Fig. 8. The maximum scale of computer modeling studies is less than 40,000 m^3/day, whereas commercial scale thermal desalination capacities can reach 100,000 m^3/day for one unit. There is a general trend toward a lower LCOW as the plant scale increases, as indicated in Fig. 5. However, given the limited number of studies, it is difficult to make conclusions about the impact of economies of scale on solar-driven thermal desalination. The market share for thermal desalination (even in the GCC) is expected to reduce owing to the construction of more RO plants and thus the market opportunity for commercial-scale solar-driven thermal desalination is very poor. In fact, a previous study (Pouyfaucon and García-Rodríguez, 2018) clearly rejected solar thermal desalination as a candidate technology for the solar desalination market. By contrast, the market potential for RO powered by photovoltaics is significant. Nevertheless, we still believe that there is a market potential for concentrated solar thermal desalination under certain boundary conditions.

- The only markets where commercial scale solar-driven thermal desalination might possibly succeed are those where both the CSP capacity is growing rapidly and where there are relatively limited renewable water resources (thereby creating a considerable demand for desalination). These markets are primarily in the MENA region and to a lesser extent in Spain and the USA (the two largest CSP markets in terms of operational capacity according to the SolarPaces database; (SolarPaces, 2018). In these markets, future thermal desalination plants can be designed for integration with existing CSP plants. There is also a significant potential for using CSP technology in brine treatment for zero-liquid discharge processes (by evaporation methods) so as to extract added value products and simultaneously reduce the environmental impacts of brine. Developing this application can expand the global market for solar-driven thermal desalination.

3.3. Market commercialization barriers

The results of our economic analysis and the critical literature review indicate that several market commercialization barriers exist, which can be overcome by research, as well as other barriers that simply impose limitations on the application of CSP technology in thermal desalination. In the following section, we discuss the market commercialization barriers for thermal desalination powered by CSP collectors (and specifically LFCs).

The capital expenditure for the solar field forms the main cost contribution to the LCOW, as shown in Fig. 4, and thus the solar field costs should be optimized. In general, 40–60% of the solar field's total system costs (for LFCs) are owing to the collector itself, which mainly includes the frame and reflective mirrors. Thus, reducing the material processing and manufacturing costs could have significant impacts. An assessment of the cost of the commercial SkyTrough PTC by NREL showed that the collector's cost is sensitive to the cost of raw aluminum alloy and the cost of steel according to its source country (Kurup and Turchi, 2015). We expect that the LFCs would have similar cost sensitivities. The construction material costs for the largest operational LFC plant (the PE2 plant in Spain) compiled by (Aurélie et al., 2013) showed that steel (reinforcing steel and chromium steel) accounted for approximately 71% of the total mass of the solar field assembly (this percentage was calculated by summing the mass of steel in the collector, the receiver, and the air-cooled condenser, and dividing this sum by the total mass of all the components, excluding the materials in the power block and concrete). Thus, using tools such as Design for Manufacture and Assembly (DFMA) as well as tracking commodity prices could greatly facilitate cost optimization for the solar field. The issue of cost uncertainty must also be considered. Indeed, given the limited amount of data available for LFCs and the high level of uncertainty regarding each manufacturer, it is not practical to make direct cost comparisons between PTCs and LFCs when coupled to thermal desalination.

The system integration strategy for concentrated solar thermal desalination is another barrier to commercialization. As discussed earlier, there is a potential market for this technology if any future thermal desalination capacity is constructed alongside existing CSP plants. Several studies have suggested this cogeneration strategy as the potential future for concentrated solar thermal desalination (Darwish et al., 2012; Iaquaniello et al., 2014; Palenzuela et al., 2015). Among the advantages of co-generation of power and desalted water is reducing some overall shared costs such as operating expenditures. However, the main drawback is the misalignment of the optimal CSP location for power generation and thermal desalination plants. The most suitable sites for thermal desalination plants are near the feedwater source (i.e., near the coast), but the performance of CSP plants is negatively affected near the coast owing to salt air corrosion and the relatively lower solar radiation (Kraemer, 2018). Another problem is the competition for water resources between the CSP plant (which requires cooling water for the condenser and for collector mirror washing) and the desalination plant, which also requires excessive amounts of water for the end condenser (assuming the use of wet cooling). Advances in dry cooling technologies (especially evaporative dry cooling) can overcome this problem, thereby facilitating the integration of thermal desalination with CSP plants (Palenzuela et al., 2013). Another way to overcome this barrier is the hybridization of desalination technologies (such as MED + RO and MED with energy adsorption (AD)), which can potentially reduce the operating expenditure component of the overall desalination block. Recent studies on hybrid desalination processes indicates high potential for increasing plant productivity and improving overall process energy efficiency (Ng et al., 2015, 2014; Shahzad et al., 2017, 2014). In addition, the integration of the system can be improved by adding both a backup fossil fuel boiler and thermal energy storage. In general, the economic feasibility of incorporating energy storage with renewable energy powered desalination depends on many factors, such as the location, desalination technology, and plant scale (Gude, 2015), thereby highlighting the need for optimization to achieve the lowest LCOW. Advances in the materials used for thermal energy storage and the available storage temperature range can also improve the reliability of concentrated solar thermal desalination.

In addition to technological barriers, the regulatory enabling environment is the greatest market commercialization barrier for large-scale solar desalination. In particular, desalination is a highly conservative and risk adverse industry in the GCC region where 80% of the potable water is obtained from desalination (Alhaj et al., 2018), and thus there is very little possibility of experimenting with new technologies. For example, in Qatar, all of the power generation and desalination capacity is owned by the government (Qatar Electricity and Water Corporation) and fuel is supplied to the independent water and power production plants at the production cost or only slightly higher (Darwish et al., 2015). The realistic cost of desalted water (from commercial plants) in Qatar is \$1.1/m^3 from MSF and \$0.63/m^3 from RO, which is at least four times lower than the base LCOW calculated for concentrated solar thermal desalination (see Fig. 5). This market ecosystem is partly justified given the critical nature of desalination, but it leaves little room for competition from renewable energy technologies, and thus there is little incentive for GCC countries to adopt cleaner energy technologies (for desalination and power generation applications). Therefore, a shift in the market driven by government policies is required to allow commercial scale solar desalination to expand and compete with conventional desalination. Policy makers are recommended to encourage more private sector investment in CSP power generation through long-term power purchase agreements. In addition, the subsidies for desalted water when sold to the end consumer should be revised to reflect the true production cost. Implementing a tariff on desalted water from clean energy sources could also be a useful strategy (Kraemer, 2018). Over the medium and long terms, these strategies may facilitate a higher penetration of solar desalination into the global desalination market. Regulators are also encouraged to invest more in pilot plant testing for solar-powered hybrid desalination technologies. Moreover, the policies related to large-scale solar desalination must be aligned with existing regional energy and water security policies. Indeed, researchers can assist policy makers by highlighting the economic and environmental benefits of solar desalination. For the oil-rich GCC countries, the economic benefit of solar desalination is related to the fuel opportunity cost (which can be exported instead of being used locally). The environmental benefits, in terms of reducing greenhouse gas emissions owing to the use of solar energy, should be aligned with the climate change response commitments of GCC countries.

4. Conclusions

In this study, we investigated the economic feasibility and market commercialization barriers for large-scale thermal desalination coupled with CSP. We developed an economic model for calculating the LCOW with EES software, which incorporates updated empirical relationships for the capital expenditure for the solar field (acquired from CSP manufacturers) and the MED desalination system. The model was used to compute the LCOW for low-pressure MED powered by a solar LFC. We assessed the impact of economies of scale on concentrated solar thermal desalination by critically analyzing previous studies. We also examined the major market commercialization barriers and methods for overcoming them from policy and R&D perspectives.

Given the boundary conditions in the analysis, we found that the LCOW for large-scale concentrated solar thermal desalination (without any fossil fuel boiler) is \$4.31/m^3. The LCOW would be reduced to \$2.89/m^3 when a natural gas boiler is used to extend the plant's operating period. Our survey of previous studies showed that the reported LCOW values for concentrated solar thermal desalination varied from \$0.94/m^3 to \$4.31/m^3. The LCOW is affected mainly by the capital expenditure for the solar field and the operating expenditure for the desalination plant. Our investigation of economies of scale showed that the learning rate for CSP plants (based on the PTC) is 18%, but no data were available for thermal desalination. These results suggest that the market potential for stand-alone concentrated solar thermal desalination is poor under current conditions. Data limitations regarding solar LFC plants and the potential cost reductions for thermal desalination plants make it difficult to forecast the market potential for concentrated solar thermal desalination. Three major market commercialization barriers were identified and discussed: solar field capital costs, system integration strategies, and the conservative nature of the desalination market. Government policies are needed to accelerate pilot plant testing for hybrid concentrated solar thermal desalination systems and to provide more financial incentives for clean energy-powered desalination systems.

Several areas of research in large-scale concentrated solar thermal desalination could be investigated to enhance our understanding of the extent and limitations of this technology such as:

- Forecasting the market share of thermal desalination in the GCC region is particularly important. Given the rapid development of RO systems (specifically membrane materials and feedwater pretreatment processes), an important question arises: are we approaching a phase of 100% RO in this region? Saudi Arabia and Oman already have a higher share of RO in their desalination capacity than thermal desalination processes (Darwish, 2015). Hence, it is important to investigate the projected market share and learning curves for thermal and membrane desalination processes.
- Calculations of the LCOW for concentrated solar thermal desalination require constant updating and the inclusion of industry data regarding solar field costs. However, this is a tedious task owing to the large amount of uncertainty and data confidentiality concerns. As an example from the present study, the total system costs for turn-key solutions for solar LFC have an uncertainty of up to 25%. It is recommended that an integrated database for market costs (current and projected) of CSP technologies and desalination processes is developed in cooperation between industry firms and research centers. In addition, it is important that the current business model for desalination plants is clearly understood when conducting economic assessments. For example, the cost of financing is a major component of the total project costs. Indeed, some markets in the GCC region (such as Dubai) have realized very low CSP project costs

mainly owing to the low cost of financing. These factors must be considered when assessing the economic feasibility of solar desalination using the NPV method.
- There is a need to study in depth the technical potential, economic feasibility, and optimal system configurations of small-scale solar-driven desalination systems which tap into a larger pool of potential users around the globe.

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Appendix A. Supplementary material

The supporting material includes the raw specific capital cost data for the solar LFCs from Industrial Solar GmBH and the entire EES program used for the LCOW calculations. This material is available free of charge via the internet. Supplementary data to this article can be found online at https://doi.org/10.1016/j.solener.2019.07.046.

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