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LETTER

Integrating concentrated solar power with seawater desalination technologies: a multi-regional environmental assessment

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Abstract

Using renewable energy to power seawater desalination technologies can reduce the environmental impacts of a process which is essential for global water security. However, the uneven geospatial distribution of renewable energy resources and regions of water scarcity results in unequal environmental benefits which creates uncertainty for global policy making. Hence, this study explores the relation between renewable energy resources, freshwater demand, and associated environmental impacts of desalination plants driven by renewable energy at a global scale using a comparative life-cycle assessment approach. We focus on an optimized solar-driven thermal desalination plant that we developed which can be used in seawater and brackish water treatment. By examining the life-cycle impact of the proposed plant in seven water-stressed cities, we found that the mean value for CO_2 emissions is 4.32 kg CO_2 eq./m^3 of desalted water which is 47% lower than conventional thermal desalination. There is a variation by as much as 80% and 95% in the climate change and water depletion, categories respectively across the selected cities. The multi-city analysis provides energy and water utilities, CSP project developers, and environmental authorities a global assessment of the environmental impact of solar desalination and sheds light on the correlation between solar intensity and seawater conditions on the overall environmental impact of this technology.

Introduction

At a global scale, around two billion people reside in regions with some form of water scarcity (United Nations Economic and Social Council 2017). This problem can be partially addressed, in coastal areas, using seawater desalination and treatment technologies (Semiat 2008). Seawater desalination technologies currently supply 92.5 Mm^3 of freshwater daily to millions of people around the globe (International Desalination Association (IDA) 2017). Several plants are currently operational in many regions globally such as the Middle East and North Africa, the Southern Western Coast of the United States, Spain, and Australia (Stokes and Horvath 2009). The applications of this technology also extend to brackish water treatment and hence desalination can also be used for treating agricultural drainage water in remote farms (Stuber *et al* 2015). Small coastal communities, with limited access to freshwater, can utilize desalination to reduce the stress on renewable water resources. This technology can potentially elevate water poverty in regions with scarce freshwater resources and help developing countries achieve their food security goals.

However, desalination technology, although essential for water and food security, is an energy intensive process, traditionally using fossil fuel combustion as energy source, consequently contributing to the increase in global greenhouse gas emissions and fossil fuels depletion. The environmental impacts of desalination also include brine disposal to the sea which damages the marine life and ecosystem (Alhaj *et al* 2017b). The most efficient way to mitigate the energy-associated impacts of desalination technologies is supplying the process's energy needs (either fully or partially) from clean renewable energy sources such as solar power (Alhaj *et al* 2017a). Thus, this aspect presents an attractive research opportunity, not

Table 1. Comparison between MSF, MED, and RO in terms of energy requirements and integration with solar collectors. The values for MED are typical of MED plants with thermal vapor compression (MED-TVC) and using the horizontal tube falling film evaporator. The equivalent mechanical energy is representative of the case of cogeneration of electricity and fresh water.

	Thermal energy consumption (kWh m^{-3})	Electric energy consumption (kWh m^{-3})	Equivalent mechanical energy consumption (kWh m^{-3})	Integration with solar collectors	References
MSF	120	4	20	Can be supplied heat from parabolic trough collectors, linear Fresnel collectors, or flat plate collectors. Can be operated in direct steam generation mode or cogeneration mode.	(Darwish *et al* 2013)
MED	80	1.5–2.5	19		(European Union 2008, Alhaj *et al* 2018)
RO	—	5	5	Can be powered using PV panels or concentrated PVs.	(Darwish *et al* 2013)

just from the environmental view point, but also from the operational efficiency view point since renewable energy could be utilized to simultaneously generate electric power and freshwater. Current thermal desalination plants (that operate using the multi-stage flash (MSF) or multi-effect distillation (MED) processes) are usually co-located with fossil fuel-driven power plants. At a global scale, there is a close correlation between demand for electricity and demand for freshwater and hence the role of renewable energy-driven desalination has to be investigated carefully. This aspect was the main motivation driver for this study. Given that global solar energy resources (global horizontal irradiation in kWh m^{-2}) are geographically aligned with regions facing some form of freshwater scarcity (SolarGIS© 2013 GeoModel Solar 2013, Luo *et al* 2015), the technical potential for solar-driven desalination technologies becomes exceptionally high.

The global desalination market is dominated by two technology categories: thermal desalination and membrane desalination. Thermal desalination processes like MSF and MED are the most widely used technologies in the Arabian Gulf region, whereas membrane technologies like reverse osmosis (RO) are dominant in the rest of the world.

Table 1 shows a comparison between these three technologies (MSF, MED, and RO) in terms of thermal energy consumption, electric energy consumption, equivalent mechanical energy consumption, and integration with solar collectors. Given their lower energy requirements, the MED and RO are possibly the most suitable for integration with solar power. In this paper, we focus only on solar-driven MED (referred to as: solar-MED). Thermal desalination processes (such MED) are generally more tolerant to harsh sea water quality (i.e. high salt concentration and contaminants such as algal blooms) and are also more resistant to red tides which can cause an RO plant to be shut down and would also increase membrane replacement costs (Darwish *et al* 2013, Mabrouk *et al* 2015). Such harsh sea water quality is predominant in many parts of the Middle East and North Africa region. Moreover, the MED process requires lower pumping energy as compared to MSF and realizes a lower levelised cost of water (Alhaj *et al* 2017a).

Although this study focuses only on solar-driven MED, it does not neglect the fact that other solar desalination technologies, especially PV-RO systems, are equally, and sometimes more feasible than solar-driven MED, for desalting water at an economical cost and with lower environmental impacts. The modular nature and easy operation of PV-RO systems also results in their suitability for decentralized applications. Given the above, we believe that realizing the maximum potential of solar desalination most likely requires a hybrid systems approach (combining multiple desalination technologies with multiple solar collectors). In this regard, a good first step is to study individual solar desalination systems before examining complex configurations, and this is the domain area of this study.

Extensive works in the literature investigated solar-driven MED or solar-driven thermal desalination in general which indicate significant interest in these technology category (Mittelman *et al* 2007, Nafey *et al* 2010, Norwood and Kammen 2012, Askari and Ameri 2016, Bataineh 2016, Cipollone *et al* 2016, Alhaj *et al* 2017a). Most of these papers investigated plant design, solar collector choice, process optimization, or development of better computer models. Few studies in the literature addressed the environmental impacts in a systematic way (Raluy *et al* 2004, 2005, 2006) and many merely followed a qualitative approach without quantifying the impacts (Morton *et al* 1997, Lattemann and Höpner 2008, Mezher *et al* 2011, Darwish *et al* 2013). There was hardly any study that compared several categories of solar-driven desalination technologies from an environmental view point. When integrating solar power with a desalination plant, the evaluation of the environmental

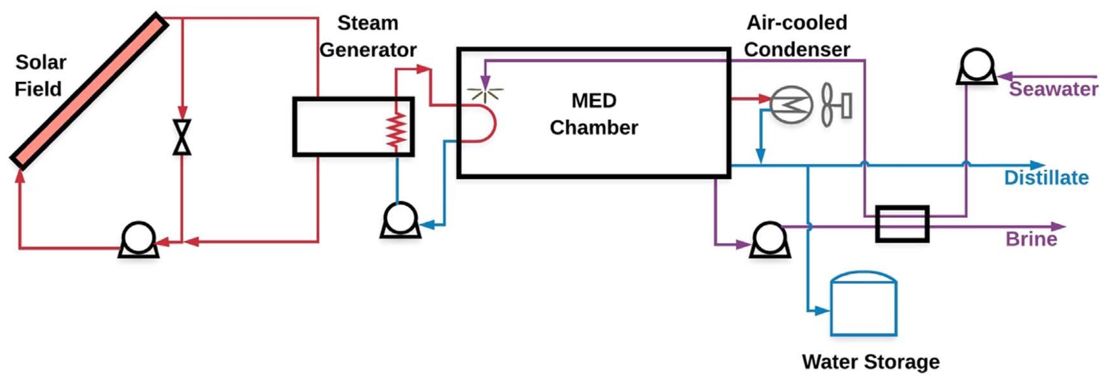

Figure 1. A solar-MED system using a solar linear Fresnel collector (LFC), low pressure MED based on the horizontal tube evaporator, an air-cooled condenser, and a water storage tank (reproduced with permission from the publisher) (Alhaj *et al* 2018). In this configuration, the desalination plants' thermal energy is provided by the solar field whereas the electric pumping energy is provided by the grid.

benefits must be given a priority, considering that this is the main reason why a renewable energy source was selected initially. We are choosing a clean energy source for desalination because 'we care' about the environment and we want government policies to reflect this (Small 2012). Without properly understanding the consequences of alternative systems, environmental policy will be misinformed (Lave 1995). A well-informed policy for the integration of renewable energy with desalination, particularly in developing world countries, can result in great economic benefits (Al-Ghamdi and Bilec 2016) as well as support climate change mitigation strategies. Such policies require sound understanding of the environmental impacts of integrated renewable energy systems (Pacca and Horvath 2002).

Life cycle assessment (LCA) is an established methodology for quantifying the environmental impacts of systems from cradle to grave across multiple impact categories (The International Standards Organisation 2006). Although solar-driven desalination has lower energy-associated impacts than conventional fossil fuel driven desalination, yet, quantifying these impacts remains uncertain. We also understand less about their sustainability under a variable LCA system boundary. Examining this issue requires investigating the relation between solar intensity, solar collector choice, sea water salinity, and regional electricity grid mix.

Materials and methods

The main scope of this study is to evaluate the environmental impacts of fresh water produced by solar-driven thermal desalination (using the low-pressure MED process) in multiple water-stressed global regions. The solar-MED process investigated in this study is based on a previous study by the authors in which a low-pressure MED process powered by solar heat from a linear Fresnel collector (LFC) was optimized to reduce its equivalent mechanical energy consumption to only 8 kWh m^{-3} (which is comparable to the energy efficient RO process Alhaj *et al* 2018). Figure 1 shows a schematic of the solar-MED process used in this study. In the proposed plant, the thermal energy is provided by the solar LFC whereas the electric pumping energy (to circulate the heat transfer fluid in the solar field and the feedwater and the brine in the MED plant) is provided by the local grid.

The environmental impact of solar-MED is assessed in seven locations distributed in six continents whereby in each location several variable geospatial parameters were considered in the LCA boundary (like: sea water temperature, salinity, solar intensity, ambient air conditions etc). Our goal is shed more light on the relation between renewable energy resources and seawater desalination from a multi-regional and multi-criteria environmental view point. Expanding the LCA boundary to multiple regions allows us to examine the sensitivity of the impact categories to variation in key reference flows and hence provides a better understanding of the life-cycle impact of solar-driven desalination systems. Further, it facilitates making recommendations for global climate change and water policy. The investigative approach in this study is motived by the UN sustainable developments goals (SDGs) No.6 (provision of clean water and sanitation) and No.7 (affordable and clean energy) and their corresponding targets and indicators. Targets: 6.1, 6.4, 6.A, 7.1, 7.2, 7.A, and 7.B outlined by the UN all relate directly to solar-driven desalination technologies which can reduce global water stress and increase share of renewables in the total energy supply mix. More about the relation of this LCA study to the SDGs can be found in the supporting information which is available online at stacks.iop.org/ERL/14/074014/mmedia.

Building on the above, the goal of this comparative LCA study is to quantify the environmental impacts of producing 1 m^3 of freshwater from a solar-driven

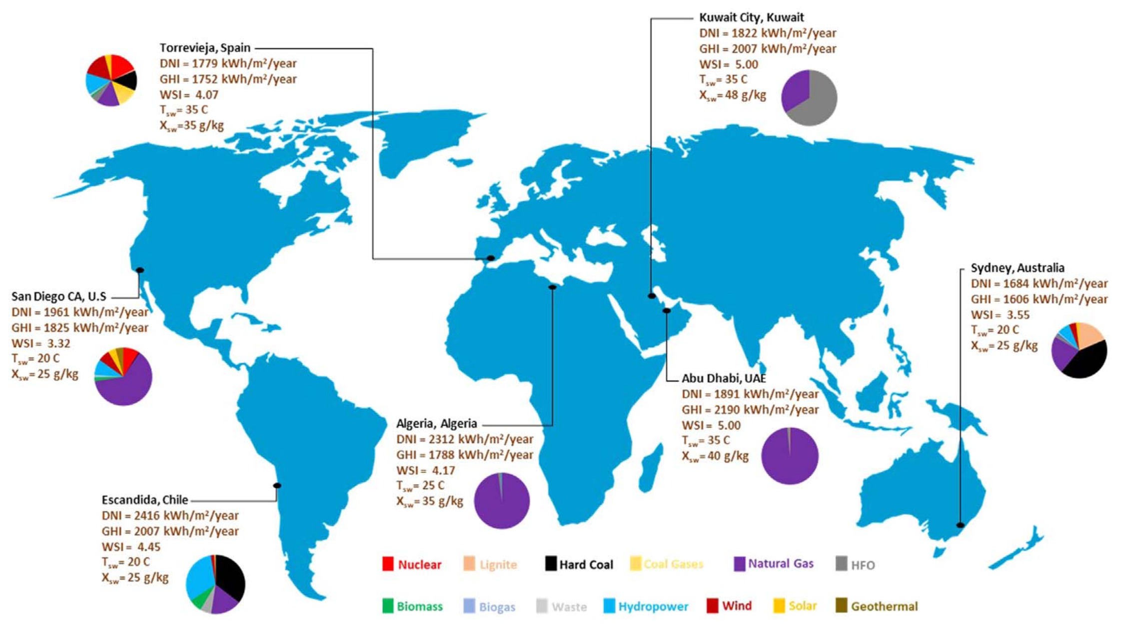

Figure 2. Locations selected for the comparative LCA study. Each location is characterized by: DNI, water stress index (WSI) in 2040 under the 'business-as-usual' scenario as forecasted by the World Resources Institute (Luo *et al* 2015), seawater temperature (T_{sw}), seawater salinity (X_{sw}), and regional electricity grid mix. The WSI is used to characterize water stress in each location.

Table 2. Data used to construct the life-cycle inventory.

Life-cycle inventory component	References
Construction materials for the LFC; based on the 30 MW Puerto Errado 2 (PE2) solar power plant in Spain	(Aurélie *et al* 2013)
Construction materials for a MED evaporator; based on data from commercial plants	(Alhaj *et al* 2018)
Annual average DNI; based on the estimations of the World Bank in the Global Solar Atlas	(The World Bank 2018)
Specific plant electric power consumption for each location; derived from our EES model	(Alhaj *et al* 2018)
Annual average seawater temperature and salinity for each location; based on data provided by NASA through the Scientific Visualization Studio webpage	(NASA 2009)
Chemicals dosages; based on several literature values for thermal desalination plants	(Darwish *et al* 2013)

MED plant in seven different locations. The selected locations (shown in figure 2) all experience some form of freshwater scarcity and all rely on seawater desalination to meet some of their freshwater demand (albeit by varying contributions). In this comparison, the independent variable is the plant's productivity; $1\ m^3\ h^{-1}$, while the dependent variables are the required solar field aperture area and the specific thermal and electric energy consumption rates which change due to variations in solar direct normal solar irradiance (DNI), seawater temperature and salinity, and ambient air conditions (in the month selected for the simulation) in the selected cities. The LCA system boundary (which is given in the supporting information) includes the solar desalination plant's construction and operation phases only. The end of life phase was neglected because previous studies on the end of life phase's impact of concentrated solar power (CSP) plants and thermal desalination plants indicated the minimal impact of this phase (Raluy *et al* 2005, Heath *et al* 2011). Further, the brine disposal phase, although has a significant impact on marine life (Mannan *et al* 2019), was excluded from the system boundary so as to focus only on the energy associated impact mitigated by using a clean energy source. The data used to construct the life-cycle inventory is composed of: construction materials for a solar LFC, construction materials for a MED evaporator, annual average solar DNI for each location, specific plant electric power consumption for each location, annual average seawater temperature and salinity for each location, dry bulb temperature and relative humidity for each location, and pre and post treatment chemicals consumption for each location based on the distillate recovery ratio. Table 2 summarizes this data and the sources used, which are also explained in more details in the supporting information.

A computer model was developed and validated in the engineering equation solver (EES) software to simulate the solar-MED plant's performance. The EES model was used to evaluate some of the reference flows to the LCA boundary such as the solar field aperture area and specific thermal and electric energy consumed. The remaining reference flows (construction materials and chemicals) were based on values from the literature. The LCA flowchart, calculation steps,

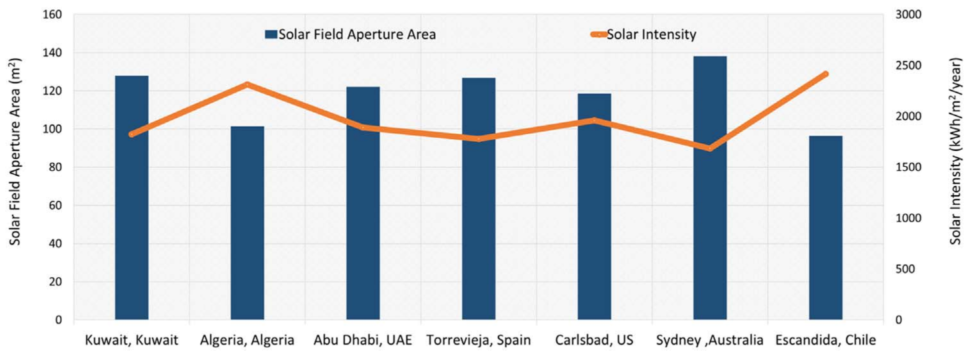

Figure 3. Solar field aperture area required to produce 1 m^3 of freshwater for each location. The solar intensity is the annual average direct normal irradiation.

Table 3. Pumping energy, distillate recovery ratio, ambient air temperature (in July), and seawater salinity for all locations.

Location	Pumping energy (kWh m^{-3})	Recovery ratio	Dry bulb temp. (C)	Seawater salinity (g kg^{-1})
Kuwait, Kuwait	7.9	0.32	41	45
Algeria, Algeria	7.8	0.45	37	35
Abu Dhabi, UAE	6.8	0.33	35	45
Torrevieja, Spain	4	0.46	29	35
Carlsbad San Diego, CA	2.8	0.58	22	25
Sydney, Australia	2.7	0.58	19	25
Escandida, Chile	1.5	0.58	16	25

inputs to the LCA model for all cities, and the EES model are all given in the supporting information.

GaBi software (by ThinkStep) was used to conduct the LCA study using the ReCiPe 2016 impact assessment method (Thinkstep 2018). The impact categories selected are: climate change, fossil depletion, and water depletion. These categories represent impacts due to energy consumption and resource depletion and hence are the most suitable given the focus of our study (i.e. reducing the energy associated impacts only of desalination). The functional unit is 1 m^3 of desalted water at the plant.

It should be noted here that the multi-city LCA study in this paper is conceptual to a great extend because several of the selected cities do not currently use a thermal desalination plant, mainly due to the high operational costs as compared to RO and the low feedwater salinity (an example is the location in California in the US). However, the implementation of thermal desalination plants in these locations is still technically feasible and worthy of examination due to the high DNI resources which means that a MED plant can be co-operated with a CSP plant by utilizing the exhaust steam from a low-pressure turbine.

Results and discussion

We first present the system technical results for the solar-MED plant in each location which are: calculated solar field size, distillate recovery ratio, and specific electric energy consumption. This is followed by a discussion on the environmental impacts for our selected categories. The paper is concluded by outlining data limitations and our recommendations on future work. The most important calculations procedures and assumptions in the EES model are in the supporting information.

Technical results from the EES model

Figure 3 shows the calculated solar field aperture area for each location alongside the solar intensity. The solar intensity is characterized by the DNI which is the component that has the highest impact on the performance of concentrating collectors. As evident from the figure, the higher the solar intensity, the smaller the solar field area. The difference in aperture area between the location with highest DNI (Chile) and lowest DNI (Australia) is 43%. The significant variation in DNI between one location and another highlights the need for accurate solar resource assessment before plant commissioning. As the solar field area increases, we expect higher land-associated environmental impacts. There was also a considerable difference between each location and the other in terms of electric energy consumption. This is attributed to the variation in seawater salinity, seawater temperature, and ambient air conditions which all directly affect the process's energy performance. Table 3 shows the pumping energy and recovery ratio for all locations. The recovery ratio is defined as the ratio of distillate to feed water which is affected by the sea water salinity. Thermal desalination plants can operate at a high recovery ratio if the feedwater's

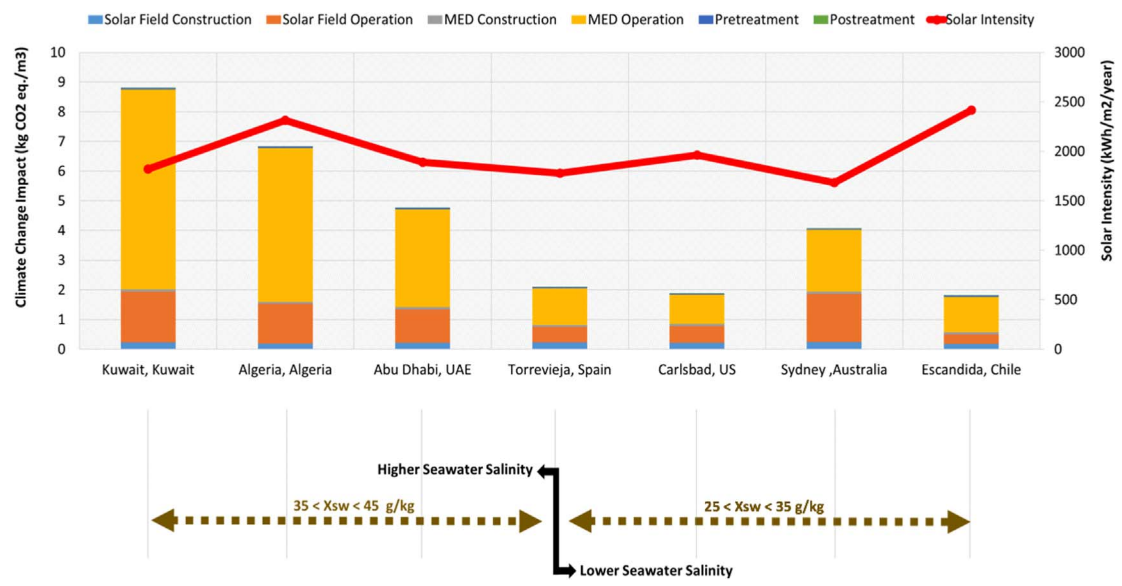

Figure 4. Disaggregated climate change impact in all locations. These results are representative of the construction and operation phases only.

salinity is low, which can be observed in table 3. The drastic variation in pumping energy in is caused by dry bulb temperature variation, which greatly affects the energy consumed by the air-cooled condenser (Alhaj *et al* 2018) (i.e. at higher ambient temperatures, the air-cooled condenser consumes more energy).

Life-cycle environmental impacts

The disaggregated climate change impact for all locations is shown in figure 4. The most interesting finding from this figure is that the environmental impacts of a solar-driven desalination plant are not necessarily inversely related to the solar intensity. As this figure shows, Kuwait, Algeria, and Abu Dhabi all have relatively high DNI levels and yet the solar MED plant located in these three locations had the highest impacts. Such trend is caused by high sea water salinity and high ambient temperature which cause higher electricity consumption, as evident from the pumping energy values in table 3. We can observe from figure 4 a trend of lower emissions for locations where the sea water salinity is between 25 and 35 g kg^{-1}. The mean value of emissions is 4.32 kg CO_2 eq./m^3 which is significantly lower than literature values for conventional MED desalination plants; 18.05 kg CO_2/m^3 reported by Raluy *et al* (Raluy *et al* 2005) and 8.18 kg CO_2/m^3 reported by Darwish *et al* (Darwish *et al* 2013). In all locations, the plant operation phase (MED operation and solar field operation) both contribute the highest to total emissions. The impact in the fossil depletion category had a similar profile as the climate change category. The above categories are both directly affected by the regional grid mix in each location. We observed that locations with a diversified grid (i.e. more than four sources such as Spain, US, Chile, and Australia) had lower impacts. The three Middle Eastern locations (Algeria, Kuwait, and UAE) all relied on natural gas or heavy fuel oil which have more emissions as compared to hydropower, nuclear power, and wind power. This great variation is a major reason why the difference, in CO_2 emissions, between the best and worst locations is 7 kg CO_2 eq./m^3. This highlights the fact that the potential of reducing associated impacts of desalination by utilizing the solar energy is highly variable and is affected by multiple geospatial factors, many of which are beyond the scope of desalination engineering. We must note here that locations where the seawater salinity was low (e.g. Carlsbad San Diego and Escandida) would normally employ a RO system because it is more efficient from an energy and cost viewpoints. However, a thermal desalination system may still be used under some circumstances such as operation with brine recirculation or operation as a cogeneration plant producing electricity and water. The experimental work by Stuber *et al* (2015) (was a pilot project implemented at California's Central Valley) indicate a significant potential of using solar thermal collectors and MED for treating brackish water.

Water depletion refers to the reduction in freshwater availability which has a direct impact on human health (Huijbregts *et al* 2016). For all locations, water is depleted in the plant's life cycle by two main processes: the power generation cycle (from raw materials extraction to electricity generation) and water used for cleaning the solar field's mirrors. We found that in all cases, at least 56% of the water depletion impact occurs due to the energy consumption phase as shown in figure 5. In general, CSP plants (such as the one addressed in this study, that uses the LFC) require immense amounts of water to clean the mirrors in order to maintain optimal mirror reflectivity. For all

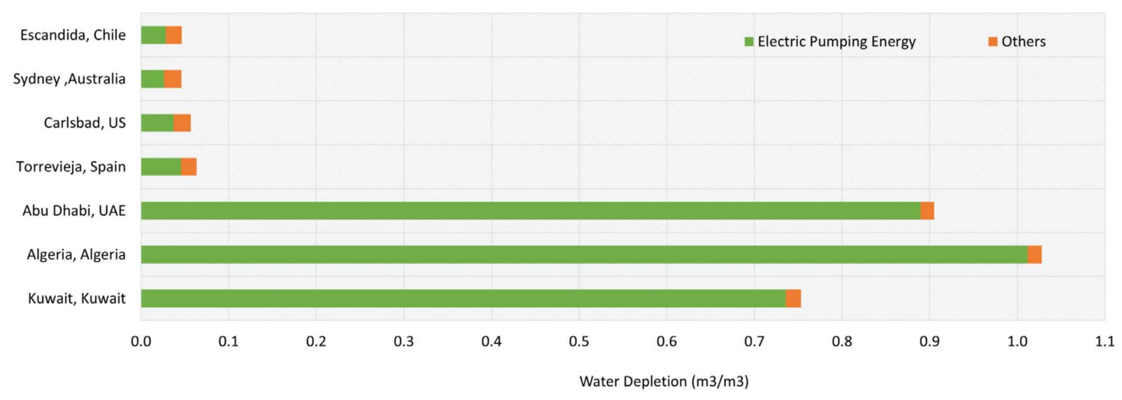

Figure 5. Life-cycle water depletion impact across all locations.

Table 4. Data quality index and estimated basic uncertainty.

Parameter	Data quality index	Estimated basic uncertainty	Comment
Annual average direct normal irradiation	(2,1,3,1,1)	±8% to ±15%	The basic uncertainty (expected yearly deviation for the DNI) was provided by (The World Bank 2018)
Seawater conditions	(2,1,5,1,1)	—	
Air conditions	(1,1,1,1,1)	—	
Treatment chemicals	(4,5,5,3,1)	—	
Construction materials	(1,2,1,1,1)	—	
Energy flows from EES model	(2,2,1,1)	8%	The basic uncertainty was estimated to be the maximum absolute deviation of the EES model from real plant data as described in (Alhaj *et al* 2018)

locations studied, it was assumed that 27 l of water per m^2 of mirror aperture per year is required for such purpose (Palenzuela *et al* 2015). However, our previous result highlights that the electric pumping energy has a significantly higher impact in terms of life-cycle water consumption. The locations with the highest water depletion impact (Abu Dhabi, Algeria, and Kuwait) all have a grid that relies heavily on fossil fuels, such as heavy fuel oil and natural gas, and hence, they had a high score for water depletion. Locations in which the grid is more diversified (for example: by relying on more renewable energy) had a far lower impact—producing electricity from renewable energy technologies, such as solar PV and wind, requires less water as compared to nuclear power and coal technologies (Meldrum *et al* 2013). Such result highlights the need for a comprehensive environmental assessment of solar-desalination plants. However, given that solar-desalination plants operate within a complex water and energy ecosystems, their life-cycle impacts will vary significantly as the system boundary changes. We must also emphasize here the issue of water value. Desalted potable water has a notably higher value in water stressed regions like the Arabian Gulf, where renewable water resources are limited. Hence, we must not assume that 1 m^3 of desalted water in Abu Dhabi has the same value as 1 m^3 of desalted water in California. For detailed information about the disaggregated grid mix for each location, the readers are referred to the supporting information.

Study limitations and results uncertainty

There are several limitations of this study due to data constraints and the conceptual nature of the multi-city comparison. From the data perspective, the LCA was conducted using some data at one design point (for example: the ambient air conditions) and this can affect the representativeness of the results. The solar radiation estimates were based on satellite-derived data and are also averaged for the entire year. Using solar radiation from ground measurements and at a smaller resolution (e.g. monthly data) would refine our results. Furthermore, the estimation of the bill of materials was based on a linear scale, which is not necessarily accurate. Due to data unavailability, we also assumed that the pre and post treatment stages are the same for all locations (i.e. same chemicals and same dosages). In reality, each desalination plant will have different chemicals due to the variation in sea water quality.

The uncertainty of our results was investigated by an assessment of the data quality index (in the categories: reliability, completeness, temporal correlation, geographical correlation, and further technological correlation) using the pedigree matrix method proposed by Weidema and Wesnæs (1996) (explained in more details in the supporting information) and by an estimate of the basic uncertainty of each parameter where available. The data quality indices and the estimated basic uncertainties are shown in table 4. These results show that more effort is needed in refining the data quality for the seawater conditions and the treatment chemicals.

One of the major limitations of this study which affects the extent to which the results can be interpreted is the conceptual nature of the multi-city analysis. However, and as highlighted earlier, implementing a solar-MED in several of these cities is technically feasible in a cogeneration system. As such, the readers should interpret these results as being partly representative of a bigger solar thermal plant that produces both power and desalted water.

Our LCA study did not draw comparisons with other solar desalination technologies like PV-RO due to missing or inconsistent data. Among the published works on the impacts of PV-RO systems, Stokes and Horvath (2009) reported a value of 0.72 kg CO_2/m^3 using a hybrid LCA decision support tool. This is more than 80% lower than the mean emissions value for solar-MED from our results, albeit the system boundaries and the LCA methodology are different. The multi-city analysis conducted in this study can be replicated on PV-RO systems and hybrid CSP-MED-RO systems and would be very beneficial especially because the global capacity of RO is higher than thermal desalination processes. Such an analysis would greatly assist utilities and environmental scientists in determining the optimal location for clean energy-driven desalination systems, whose performance and environmental impact is affected by numerous interrelated flows and processes.

Solar-desalination and the energy-water nexus

Tackling the challenge of global water scarcity requires exploring thoroughly the role of renewable energies and seawater desalination technologies in light of the energy-water nexus. Renewable energies like solar power can drastically reduce the energy-associated impacts of desalination. However, the uneven spatial distribution of renewable energy resources will lead to uneven avoided impacts as depicted from our results in figure 4. There is no solution that 'fits all'. Cities in which the grid mix is more diversified, seawater has low salinity, and where solar intensity had the lowest impacts as per our analysis. A higher solar intensity does not necessarily mean lower CO_2 emissions for solar-desalination plants, since the environmental impact is also affected by other parameters like seawater temperature and salinity. Further, the LCA results given in figures 4 and 5 highlight the importance of accurate solar energy and water resources assessment when evaluating the environmental footprint of solar-desalination plants.

The multi-city analysis provides energy and water utilities, CSP project developers, and environmental authorities a global assessment of the environmental impact of solar desalination and sheds light on the correlation between solar intensity and seawater conditions on the overall environmental impact of the plant. Utilities, CSP project developers, and environmental authorities are the main stakeholders who are involved in the construction and operation of solar desalination plants. The results of this study encourage these stakeholders to do the following:

(a) Accurately assess the solar and water resources in a given site to identify the most suitable solar desalination technologies.

(b) Investigate the potential for thermal desalination technologies alongside RO systems in hybrid configurations.

(c) Assess the environmental impact of solar desalination on a life-cycle basis and not by merely considering the CO_2 emissions.

(d) Develop decision support tools for the optimal location of solar desalination systems based on several geospatial parameters.

An important conclusion from this study to LCA researchers is recognizing the unequal value of desalted water. We need to propose ways to incorporate this externality in our definition of the functional unit. Another externality we must consider is land. Our results in figure 3 highlighted that a difference of up to 43% in solar field aperture area can occur due to the variation in solar intensity. This has direct land use impacts such as destruction of vegetation and damage to wildlife. However, in many of the desert-like arid environments in the Middle East region, these land use impacts are negligible.

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Associated content

The supporting information contains detailed information about the data used in the LCA study, the calculation steps, the LCA flow diagram and the system boundary, the EES model, and the results' tables for the environmental impacts in each location disaggregated by life-cycle phase. This material is available free of charge via the Internet.

Notes

Any opinions, findings, conclusions, or recommendations expressed in this article are those of the author(s) and do not necessarily reflect the views of Hamad Bin Khalifa University (HBKU) or Qatar Foundation (QF).

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