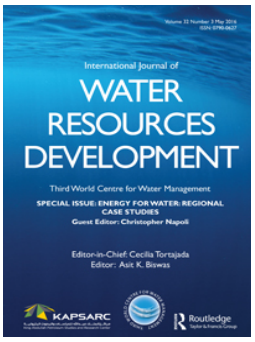

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Evaluating the economic viability of solar-powered desalination: Saudi Arabia as a case study

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ABSTRACT
This article constructs a cost calculator to estimate the economic competitiveness of solar-powered desalination in Saudi Arabia. Solar desalination is defined as a plant that obtains solar energy from a closed system. This is done to focus the investigation on desalination technologies, rather than the efficacy of replacing conventional energy sources with renewables in an integrated electricity grid. The results suggest that current options for solar-powered desalination are not cost-competitive compared to incumbent technologies in Saudi Arabia. The article offers insight into where costs must decrease before solar technologies are economically competitive in the country.

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As societies become more populous and wealthy, many increasingly place strains on their natural resources. This phenomenon is evident in Saudi Arabia, a country endowed with few natural resources that has experienced tremendous population and economic growth over the past half-century. Since 1960, the population of Saudi Arabia has risen from roughly 4 million to 29 million (World Bank, 2014a), while GDP per capita grew from USD 780 to USD 25,850 between 1968 and 2013 (World Bank, 2014b).

The growth in population and wealth has led to substantial increases in many types of consumption. For example, historically agriculture in Saudi Arabia was limited to date farming, small-scale herding and vegetable production. In the 1970s, however, the government created an intensive agriculture subsidy regime. The goals of the subsidies were to facilitate the modernization of farming techniques to meet increasing domestic demand and to improve the standard of living and employment opportunities in rural areas (Ouda, 2013). This resulted in an 18-fold increase in cereal production, an 8-fold increase in alfalfa production, and a 7-fold increase in meat production between 1973 and 2000 (Elhadj, 2004).

Similarly, and in part because of the growth in agricultural production, Saudi Arabia's water use has increased alongside population and wealth. In 1975, Saudi Arabia used roughly 1.75 km^3 of water. By 2006, that figure had risen to 23.67 km^3 (Aquastat, 2014). It is important to note that roughly 70% of the water withdrawn in Saudi Arabia comes from non-renewable

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fossil aquifers located deep within the earth. At current consumption trends, Saudi Arabia's renewable water resources per capita are depleting by 2% per year (Giansiracusa, 2010).

To combat the rising demand for water and depleting reserves, Saudi Arabia uses advanced treatment technologies to convert saline water into freshwater. In 2012, roughly 1.5 km^3 of desalinated water was distributed across municipal water networks for industrial, commercial and residential use in Saudi Arabia, making the country the largest producer of desalinated water in the world (Ministry of Water & Electricity, 2013). The development of large-scale desalination is aided by the country's expansive energy resources, which are sold domestically to utilities at low administered prices (Abderrahman, 2010).

While desalination has somewhat reduced the strain on non-renewable aquifers, it comes at a significant financial and environmental cost. Financially, Saudi Arabia used roughly 28 million barrels of oil equivalent (boe) to desalinate all water distributed to municipal and industrial water networks in 2011 (Matar, Murphy, Pierru, & Rioux, 2014b). As oil and natural gas are sold domestically at administered prices much lower than their international market values, this domestic use comes at a large opportunity cost – i.e. the difference between the domestic sale price and the price that could be obtained by selling the product on the international market at higher world prices.

This point is of particular importance given current oil consumption trends in Saudi Arabia. In the last 40 years, oil consumption in Saudi Arabia has risen by an average of 5.7% annually, resulting in a ninefold increase. This has made Saudi Arabia the sixth-largest consumer of oil globally, trailing only five (much larger) economies: the US, China, India, Japan and Russia (Gately, Al-Yousef, & Al-Sheikh, 2012). These trends have led some to suggest that, despite Saudi Arabia's currently being the world's largest crude oil exporter, it could become a net importer of oil by 2030 (Daya & El Baltaji, 2012). Given that oil represents 86% of the country's annual revenue, managing the long-term sustainability of the resource is of critical importance. Likewise, from an environmental perspective, using fossil fuels as energy sources for desalination, particularly energy-intensive thermal technologies like multistage flash (MSF), have increased the carbon footprint of the country.

Given the financial and environmental concerns, policy makers have begun examining how renewable energy sources, and in particular solar technologies, might be used to power desalination plants. A number of studies have tried to address this question. For example, Qiblawey and Banat (2008) described how direct solar desalination could be used for small-scale output in rural areas. Similarly, Gude, Nirmalakhandan, Deng, and Maganti (2012) offered a detailed analysis of the feasibility of using solar collectors augmented by thermal energy storage for low-temperature desalination. In 2012, an analysis by the World Bank (2012) explored the extent to which concentrated solar power (CSP), which can be stored and used during times of low sunlight, could be used to power large-scale desalination plants around the clock. The study concluded that CSP had tremendous potential to provide energy security and reduce greenhouse gas emissions, particularly in the Middle East and North Africa.

While there has been research on the engineering of solar-powered desalination, less attention has been paid to the economic costs and benefits. This article introduces the KAPSARC Cost Calculator for estimating the efficacy of using solar power as an energy source for desalination. The derived costs are then compared to the costs of desalination using incumbent technologies. The conclusions estimate whether current solar desalination options are cost-competitive with incumbent technologies, and which technological improvements may improve the attractiveness of solar-powered desalination.

It should be noted that the costs and operational parameters for water desalination can vary significantly, depending on plant configuration as well as the costs of labour and energy. The costs used in this article are taken from recent desalination infrastructure projects in Saudi Arabia. Given that costs may change based on project size and local conditions, the primary objective of this article is not to calculate the economic attractiveness of specific projects so much as to illustrate a framework for comparing the costs of different technologies. The calculator allows users to insert their own cost and other economic data. The benefits of this approach are twofold. First, as time changes the costs of technologies, these changes can be placed into the calculator to find new costs of each desalination method. Second, by offering a harmonized approach for calculating the cost of different desalination technologies, the framework can be used by other water-scarce regions, allowing international comparison of the costs of solar-powered and conventional desalination technologies.

Desalination in Saudi Arabia

Saudi Arabia has a long history of desalination. In 1938, the world's first large-scale desalination plant was established in Jeddah, Western Region. However, it was not until the 1970s, when windfall profits from oil exports made the process financially viable on a large scale, that the country truly adopted desalination as a method for meeting national water demand. It should be noted that desalination was strategically selected as the option for satisfying current and future domestic water supply requirements over alternatives such as large water transfer projects and heavy dependence on deep groundwater extraction (Al-Ibrahim, 2013). The choice of desalination was due to the country's expanding oil production (which negated the high energy costs), the geographical limitations of large water transfers, and a fear that over-reliance on deep groundwater withdrawals was not sustainable in the long term. The strategy to employ desalination technologies was executed with the 1974 Royal Decree No. R/49, which led to the creation of the Saline Water Conversion Corporation as an independent public body. The corporation was given the resources and mandate to increase the presence of desalination plants throughout the country. This mandate led to a 100-fold increase in the production of desalinated water by the 1990s. By 2010, there were 1595 desalination plants operating in Saudi Arabia (including both private and state-run plants), and roughly 50% of municipal water demand was being met with desalination technologies. Today, 57% of the output capacity for desalination in Saudi Arabia comes from thermal technologies, namely MSF (46.8%) and multi-effect distillation (MED, 10.3%), while roughly 40% comes from reverse osmosis (RO), a membrane process. The remaining 3% comes from advanced desalination technologies such as nanofiltration and membrane bioreactors (own calculations, data from Desal Database, 2014).

The reasons for the dominance of thermal technology in Saudi Arabia are threefold. First, because thermal technologies use the simple process of distillation to separate freshwater from salt and other impurities, it has historically been a more reliable method for large-scale desalination (Bernat, Gibert, Guiu, Tobella, & Campos, 2010), particularly in the highly saline seawater of the Gulf region (where the salt content is roughly 45,000 ppm, compared to the global average of 35,000 ppm). Second, thermal desalination can use waste heat from

Table 1. Baseline and solar desalination scenarios.

	Desalination type	Description	Pros	Cons
1	RO grid-powered (baseline)	RO powered by an electric grid	Low overall energy consumption	High operations and maintenance costs, membrane fowling, reliability issues under high salt concentrations and other impurities
2	RO solar PV with electric storage	RO powered by a solar PV plant with electric power storage	No fuel consumption	High capital cost (renewable power and electric storage), complex system integration
3	RO solar PV with water storage	RO powered by a solar PV plant with water storage	No fuel consumption	High capital cost (renewable power and spare desalination capacity), variable power supply, complex system integration
4	RO solar CSP with water storage	RO powered by a CSP plant with thermal and water storage	No fuel consumption	High capital cost (renewable power and spare desalination capacity), variable power supply, complex system integration
5	MED cogeneration (baseline)	MED plant with a combined-cycle gas turbine cogeneration power plant	Lower operations and maintenance costs, less sensitive to salt concentrations	High energy consumption and capital cost
6	MSF cogeneration (baseline)	MSF plant with a combined-cycle gas turbine cogeneration power plant	Lower operations and maintenance costs, less sensitive to salt concentrations	High energy consumption and capital cost
7	MED solar	MED plant powered by an inexpensive solar heat collector	Simple direct solar power	High heat demand and high overall systems cost

Note: RO = reverse osmosis; PV = photovoltaic; CSP = concentrated solar power; MED = multi-effect distillation; MSF = multistage flash.

cogeneration power plants, thus allowing water and energy needs to be met simultaneously from one utility.

Last, and most importantly, when energy prices are very low, thermal technologies, which are more energy-intensive but less capital- and labour-intensive, produce water more cheaply than membrane technologies like RO. Given the salinity of the Gulf region, seawater must often pass through two or three membranes before its salt content is completely removed, which increases the overall capital costs and non-fuel operating costs of membrane desalination plants (Saif, 2012).

As stated, while desalination has helped Saudi Arabia combat water scarcity, this has come at a significant financial and environmental cost, particularly given the dominance of energy-intensive thermal technologies. As a result, increased emphasis is now being placed on how renewable resources might be used to harmonize Saudi Arabia's desire to meet increasing water demand with financial and environmental objectives. For example, a solar desalination plant is being constructed in the town of Al-Khafji, in the north-east of Saudi Arabia. It is designed to provide 60,000 m^3 of desalinated water per day using RO with a solar photovoltaic (PV) plant capable of supplying the power for the desalination process (Abengoa, 2015).

Cost calculator description

A calculator has been constructed to estimate the unit cost of producing a cubic metre of potable water using conventional and solar desalination technologies. The calculator takes into account the capital costs, non-energy variable costs and energy costs of each technology. All costs are discounted over the technology's anticipated lifetime and converted to US dollars per cubic metre of water.

This article defines *solar desalination* as a desalination plant that obtains solar energy from a closed system. Thus, the article does not assess the efficacy of using solar power to supplement power obtained from an electricity grid. This strict definition was chosen in order to isolate the discussion to the costs and benefits of solar power, which requires excess investment in capacity and storage to ensure that water is provided even when the sun is not shining. Supplementing power from the grid with solar power does not isolate this discussion, as it is effectively akin to having a power station replace conventional fuels with solar options.

The costs of four different solar-powered desalination techniques are compared with three baseline scenarios: RO grid-powered, MSF cogeneration and MED cogeneration. The seven scenarios are described in Table 1.

Solar and conventional reverse osmosis scenarios

In Scenario 1, a baseline scenario, the cost of conventional RO desalination is calculated for an open system powered by an electric grid. RO has a low capital cost, but it requires relatively high materials costs to maintain the membranes used to separate salt and other impurities from the feed water. Pressure is applied across the membrane with electrical pumps, requiring a stable source of electrical energy.

Energy costs are defined by the price paid for electricity from the local grid provider. This scenario represents the standard way RO operates in Saudi Arabia. It should be noted that this scenario could also be used to represent RO powered by an off-grid conventional power supply, such as the diesel generators typically used in remote areas.

In general, solar desalination using RO technology can be achieved in two ways. Both involve investment in sufficient renewable power capacity to replace the consumption of conventional fuels. The first approach involves investment in *electricity storage*, so the desalination unit can operate at full capacity when the solar power output is below the peak (Scenario 2, RO solar PV with electric storage). A second approach is investing in spare desalination capacity and using *water storage* to capture the excess water produced during the day. The article assesses two different solar options involving water storage: Scenario 3 (RO solar PV with water storage) and Scenario 4 (RO solar CSP with water storage). Each option has costs and benefits: PV provides a lower capital cost to supply solar power, while the thermal storage provided by CSP increases the overall capacity factor of the power element.

Solar and conventional thermal desalination scenarios

The baselines for conventional thermal desalination are represented by Scenario 5 (MED cogeneration) and Scenario 6 (MSF cogeneration). These technologies heat the feed water, producing steam. The steam is then condensed back into a pure source of water, recovering some of the heat back into the feed water. These thermal distillation technologies typically use a conventional boiler, but nuclear and other renewable heat sources can also be used. Compared to MED, MSF has higher capital and operating costs. Both require significantly more energy than RO to boil the feed water, but at lower operating costs. As mentioned earlier, when primary energy prices are low enough, the cost of thermal desalination can drop well below that of modern RO.

In each scenario, a power and desalination plant are combined to provide both electricity and water. This coupling, known as cogeneration, has the added benefit of diversifying a utility's revenue stream. In a market such as Saudi Arabia, where revenues from the sale of electricity are greater than from providing freshwater, cogeneration provides a commercial advantage over stand-alone desalination plants. Although MSF is typically more expensive and energy-intensive than MED, in cogeneration an MSF plant will provide a higher power-to-water ratio, increasing overall electricity production and related revenues. The equivalent electrical energy of desalination, a measure of the useful electrical energy extracted from the steam turbine for desalination, is used to calculate the fuel cost of cogenerated water.

Last, Scenario 7 (MED solar) represents solar-powered thermal desalination. In this scenario, solar heat collectors are used to power an MED plant. A review of seawater desalination by Kalogirou (2005) references several pilot studies for solar-powered distillation using flat-plate, parabolic, and solar pond heat collectors. A unit cost calculator was not introduced for this scenario. A recent techno-economic analysis estimated that MED powered by evacuated-tube solar thermal collectors could cost as little as RMB 26/m^3, or close to USD 4/m^3 (Liu, Chen, Gu, Shen, & Cao, 2013).

Cost equations for desalination technologies

The total unit cost of conventional desalination *TC* is a function of capital costs *K*, non-fuel operating costs *V*, and fuel operating costs:

$$TC = \frac{K_D}{365 \cdot d_D} + \left(V_D \cdot \frac{L_D}{d_D}\right) + (E_e \cdot C_e + E_t \cdot C_f) \tag{1}$$

where K_D is the capital cost of the desalination plant (USD/m^3 per day), V_D is the non-fuel variable operation and maintenance costs (USD/m^3), L_D is the plant lifetime in years, E_e and E_t are electric and thermal energy consumption rates (kWh/m^3 and MBTU/m^3), respectively, and C_e and C_f are the costs of electricity and fuel (USD/kWh and USD/MBTU), respectively. A discount, d_D, is attributed to the desalination plant's capital and variable cost lifetime. It is calculated using an estimated amortization rate, *i*:

$$d_D = \frac{i(1+i)^L}{(1+i)^L - 1} \tag{2}$$

The unit costs of solar-powered desalination include the capital and non-energy operating costs above. Energy (fuel and electricity) costs are replaced by the per unit capital and operating costs of solar power $S_{K,V}$. The unit cost of electricity storage $B_{K,V}$ and water storage with spare desalination capacity $W_{K,V}$ are also added to the total unit costs in the appropriate scenarios. In the equations below, the capital costs, variable costs, plant lifetimes and discount rates are labelled with respect to the corresponding technology: solar (*S*), battery (*B*), or water storage (*W*):

$$S_{K,V} = \frac{1}{365 * 24} \cdot \frac{K_S}{d_S} \cdot \frac{E_e}{CF} + V_S \cdot \frac{L_S}{d_S} \cdot E_e \tag{3}$$

where K_S and V_S are the per unit capital (USD/MW) and variable cost (USD/MWh), respectively, of the solar technology, and CF is the capacity factor of the solar technology.

$$B_{K,V} = \left(\frac{K_B}{d_B} \cdot \frac{L_B}{N \cdot \varepsilon \cdot \tau} + V_B \cdot \frac{L_B}{d_B}\right) \cdot E_e \cdot (1 - CF) \tag{4}$$

where K_B and V_B are the capital (USD/MW) and variable costs (USD/MWh) of electric battery storage, τ is the discharge period in hours, ε is the discharge efficiency, and N is the number of discharge cycles.

$$W_{K,V} = \frac{K_W}{365 \cdot d_W} \cdot (1 - CF) + V_W \cdot \frac{L_W}{d_W} + \left(\frac{K_D}{365 \cdot d_D}\right)\left(\frac{1}{CF} - 1\right) \tag{5}$$

where K_W and V_W are the capital and variable costs of water storage (USD/m^3). The last term in Equation (5) represents the capital cost associated with constructing spare desalination capacity.

Energy costs play a significant role in desalination, particularly in thermal processes, where they can constitute more than half of total costs. These costs will vary significantly between countries, depending on the endowment of energy resources and the regulations placed on prices by governments: some countries tax energy, while others sell it at prices below international market values. As stated above, in cases like Saudi Arabia, where fuel and natural gas are sold domestically at administered prices below international market values, domestic use comes at an opportunity cost. This opportunity cost will fluctuate with changes in international energy prices: when international fuel prices are high, the opportunity cost of consuming fuel domestically at administered prices is also high. The unit cost calculator takes into account the opportunity cost associated with the value of consumed energy. Specifically, the calculator investigates what opportunity cost of fuel would be necessary to balance the cost of renewable desalination options with incumbent technologies.

Finally, environmental carbon costs *(CC)* can be added to fossil-fuel-consuming technologies:

$$CC = \left(GHG_t \cdot E_t + GHG_e \cdot E_e\right) C_{GHG} \tag{6}$$

where GHG_t and GHG_e are the greenhouse gas emissions associated with thermal and electrical energy consumption (ton CO_2/MWh), respectively, and C_{GHG} is the unit cost of the emissions (USD/ton).

Although not explicitly included in this cost calculator, the land costs associated with solar power plants can be calculated separately, since they typically require a large area. In Saudi Arabia industrial land prices are typically around USD 0.02/m^2 per year, which is considered part of the fixed operating cost for solar technologies (Royal Commission for Jubail & Yanbu, 2014). Assuming that a solar power plant requires roughly 5 acres per GWH per year, land costs would contribute roughly USD 0.002/m^3, or about 0.1% of the total water cost.

Results for Saudi Arabia

The results below offer insight into the economic costs of current desalination in Saudi Arabia, as well as the prospects for adopting solar-powered technologies (see Tables 2, 3 and 4 for all figures and assumptions). These results should be interpreted as representative

Table 2. Capital and operating costs of conventional desalination technologies.

		RO on-grid	MED cogeneration	MSF cogeneration
	Capacity (m^3/day)	100,000	1,000,000	1,000,000
	Capacity factor (%)	90	90	90
L_D	Plant lifetime	25	30	30
K_D	Plant capital cost (USD/m^3 per day)	1100	1250	1500
V_D	Plant variable O&M cost (USD/m^3)	0.26	0.16	0.19
	Conventional energy			
E_e	Electrical energy (kWh/m^3)	5	2	4.25
	Thermal energy (MJ/m^3)	-	226.7	256
E_t	Thermal energy extracted for cogeneration (kWh/m^3)*	-	12	16
	Power-to-water ratio (MW/MIGD)	-	10	16
	* Electrical equivalent energy divided by 50%, which represents the estimated efficiency of a stand-alone plant			

Sources: Capital costs of thermal desalination plants, from UNESCO Centre for Membrane Science and Technology, University of New South Wales (2008). Capital costs of RO plants, from a project statement for the Shuaiba Expansion Project (ACWA 2014). Operating costs of all plants were extracted from Thye (2010). Thermal energy from an MED cogeneration plant based on two reported top brine temperatures in Abdel-Jawad (2001).

Table 3. Additional variables used to calculate costs of conventional and solar desalination technologies.

	Additional variables	
i	Discount rate of capital and operation costs	6%
	Administered fuel prices for Saudi Arabia	
C_t	Crude oil price for water and power utilities (2011 value)	USD 4.24/barrel
	Gas price for utilities	USD 0.75/MBTU
C_e	Industrial electricity tariff set by Saudi Electricity Company (annual average over summer and winter periods)	USD 3.84/kWh
eff	Fuel efficiency of electricity supplied by the power grid	32%

Sources: Discount rate, from Matar et al. (2014). Crude oil price and gas price for utilities, from personal communication with ECRA management (2014). Industrial electricity tariff set by Saudi Electricity Company (ECRA, 2014). Efficiency of fuel consumed for RO derived from International Energy Agency (2012).

cost estimates; actual costs will differ between projects, requiring more detailed technical analysis. As stated, the costs and operational parameters for water desalination can vary significantly, depending on plant configuration, regional labour costs, and energy. Values have been selected to represent recent desalination infrastructure projects in Saudi Arabia.

Under the current low administered energy prices in Saudi Arabia, the variable energy costs of MED represent around 23% of the operational costs. Using international fuel prices would cause energy to represent roughly 70% of operational costs. As seen in Figure 1, thermal technologies such as MED and MSF have a significant competitive advantage over RO, which has a lower dependency on primary fuel cost. When considering only administered prices (black bars), MSF cogeneration (at USD 0.85/m^3) and MED cogeneration (at USD 0.78/m^3) are about 8% and 15% cheaper than RO (at USD 0.92/m^3), respectively. The higher unit costs of the solar technologies reflect the high capital cost of investing in electricity storage or excess desalination capacity and water storage. Figure 1 shows that electricity storage is more expensive than water storage with spare desalination capacity, due to the high cost of sodium sulphur flow batteries.

Table 4. Capital and operating costs of solar desalination technologies.

		RO solar PV with electric storage	RO solar PV with water storage	RO solar CSP with water storage
	Capacity	100,000	100,000	100,000
	Capacity factor (%)	22	22	40
L_D	Plant lifetime	25	25	25
K_D	Plant capital cost (USD/m^3)	1100	1100	1100
V_D	Plant variable O&M cost (USD/m^3)	0.26	0.26	0.26
$S_{K,V}$	Solar technology costs			
K_S	Capital cost (USD/kW)	2500	2500	7700
V_S	Variable O&M cost (USD/kWh)	0.0034	0.0034	0.011
L_S	Technology lifetime	25	25	25
CF	Capacity factor (%)	22	22	40
$B_{K,V}$	Electricity storage costs			
K_B	Battery capital cost (USD/kW)	6100	-	-
V_B	Battery O&M cost (USD/kWh)	0.01	-	-
L_B	Lifetime	15	-	-
ε	Battery charge discharge efficiency (%)	86	-	-
τ	Discharge period (hours)	7.2	-	-
N	Discharge cycles (over lifetime)	4500	-	-
$W_{K,V}$	Water storage costs			
K_W	Capital costs (USD/m^3)	-	200	200
V_W	Variable O&M costs (USD/m^3)	-	0.02	0.02
L_W	Lifetime	-	30	30
CC	Carbon cost			
GHG_t	Thermal energy CO_2 emissions (g/kWh)	202		
GHG_e	Electrical energy CO_2 gas emissions (g/kWh)	630		
C_{GHG}	Cost of CO_2 gas emissions (USD/ton)	40		

Sources: Capital costs of RO plants come from a project statement for the Shuaiba Expansion Project (ACWA, 2014). Operating costs of all plants were extracted from Thye (2010). Solar PV and CSP plant costs and average yearly capacity factors from World Energy Outlook 2013 (IEA, 2014) for Middle Eastern countries. Electricity storage cost is derived for sodium sulphur (NaS) flow batteries (Akhil et al., 2013). Capital costs of water storage, from an online news article (Arab News, 2014). All costs have been adjusted to 2014 real USD.

The lower costs of thermal technologies under administered prices are unsurprising. First, the non-fuel operating expenses of thermal technologies are roughly 38% lower than membrane technologies. Second, although the energy requirements of RO are low, the primary energy must be converted to electricity, which is more capital-intensive than simply using the thermal energy from fuel. This also explains why the solar RO scenarios, which have no variable fuel component and high capital costs, are more expensive under the current fuel pricing structure.

Effectively, under these conditions, thermal desalination represents a substitution effect away from more expensive non-fuel operating costs towards relatively inexpensive fuel. Given the low administered price of fuel in Saudi Arabia, this substitution effect offers a significant cost reduction for producers.

Grey bars have been added to Figure 1 to represent the opportunity cost of consuming fuel in the three baseline scenarios: RO grid-powered, MSF cogeneration and MED cogeneration. The opportunity costs were calculated assuming a fuel price of USD 70/boe. In reality, water utilities use both natural gas and crude oil to power desalination in Saudi Arabia. Gas is more prevalent in the east, while crude oil is predominant in western provinces. When considering opportunity costs, the cost of adopting MSF cogeneration rises to USD 2.30/m^3, making it

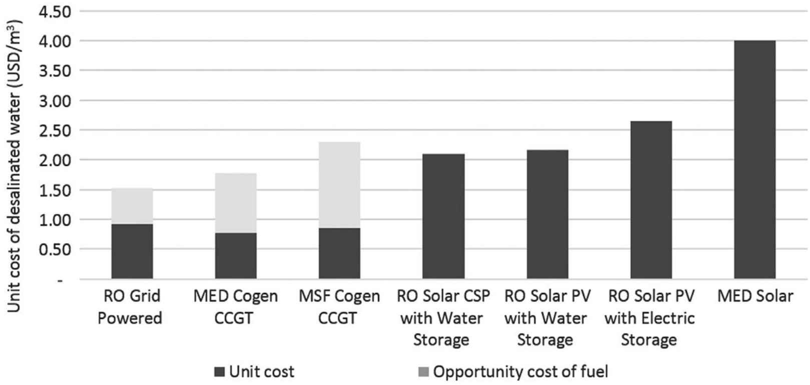

Figure 1. Estimated costs of desalination.

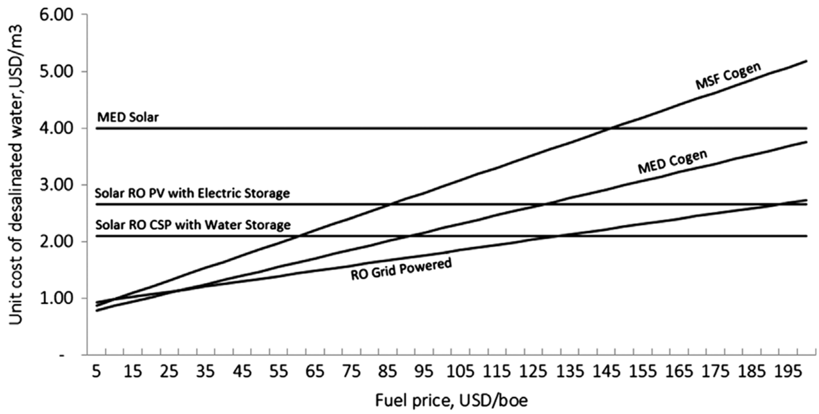

Figure 2. Relationship between energy prices and total desalination costs.

more expensive than both solar options with water storage. By contrast, MED cogeneration (USD 1.78/m^3) remains cheaper than each of the solar-powered options, but becomes more expensive than desalination using RO grid-powered (USD 1.53/m^3).

While this model offers insight into the cost of different desalination technologies in Saudi Arabia, these costs are determined using a static international fuel price of USD 70/boe. Because energy prices can change dramatically, and represent a significant portion of a desalination plant's costs, it is useful to look at how the evolution of energy prices could affect the relative costs of each scenario. Figure 2 offers this analysis, comparing the total costs of selected scenarios as the price of fuel rises.

Figure 2 highlights three points. First, as expected, the total cost of desalination powered completely by solar energy (either PV or CSP) does not vary with changes in energy prices. Second, given that thermal technologies use the most energy for desalination, the costs of MSF cogeneration and MED cogeneration are the most variable with changes in energy prices. When energy prices are below USD 30/boe, MED cogeneration offers the cheapest

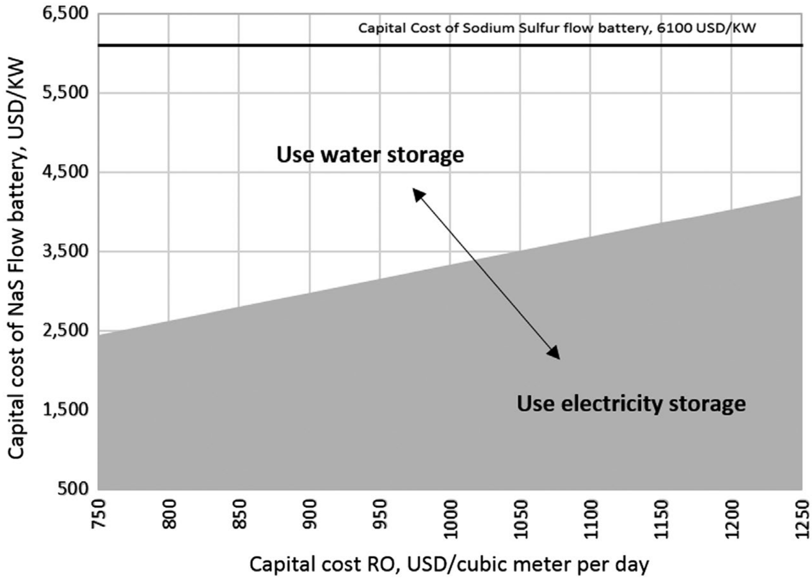

Figure 3. Breakeven cost boundary for two different solar PV desalination approaches.

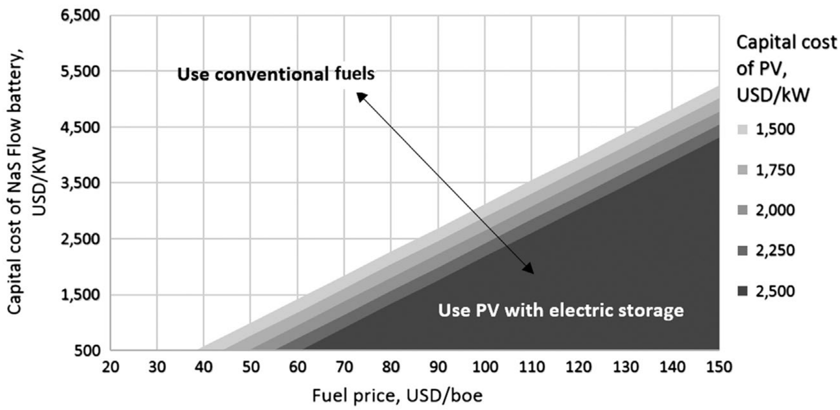

Figure 4. Breakeven cost conditions of solar PV with electricity storage versus grid-powered RO. Note: Capex = capital expenditure.

option for desalination of any technology. But MSF and MED cogeneration quickly become more expensive than solar-powered RO scenarios, exceeding the least expensive solar option once fuel prices rise above USD 60/boe and USD 90/boe, respectively.

The carbon-saving potential was also considered when assessing the breakeven price of the conventional and renewable desalination scenarios. Considering a carbon price of USD 40/ton, which is in line with the social cost of carbon estimated by the US government (Shelanski, 2013), the unit cost of RO grid-powered increases by USD 0.13/m^3, while its breakeven price with the cheapest solar option, CSP with water storage, is reduced to

USD 118/boe. Therefore, without extremely high fuel prices or a very high price on carbon, environmental costs do not sufficiently improve the competitiveness of solar desalination.

Additional breakeven analyses were performed to determine how technological innovation in energy storage, spare desalination capacity and solar power could improve the competitiveness of solar desalination compared to conventional RO. Specifically, the unit cost calculator identifies what opportunity cost of fuel would be necessary to balance the cost of renewable desalination options with incumbent technologies. This breakeven cost depends on the capital and operating costs consistent with each scenario. The article uses a simple linear cost function $f_i(X)$, see Equation(6), defined for each scenario i, depending on a vector of input cost variables ($X = x_1, x_2, \ldots$), such as the opportunity cost of fuel and technology costs, with coefficient vector A_i, and constant cost coefficient C_i:

$$f_i(X) = A_i \cdot X + C_i \quad (6)$$

Taking RO grid-powered as a baseline scenario b, $f_b(x_1, x_2)$, and equating it with a renewable scenario r, such as RO solar PV with water storage, $f_r(x_1, x_2)$, identifies the set of input variables $\{x_1^*, x_2^*\}$ where the costs of the two scenarios break even. For example, the cost boundary intersection between these two scenarios can be determined for a given breakeven desalination capital cost, K_D^*, as a function of the breakeven fuel cost C_f^* (Equation (7)). The term added at the end, f_b, accounts for the cost of fuel consumed for desalination in excess of the actual cost paid by the power utility, C_f. The coefficient eff represents the fuel consumption efficiency of the electric grid.

$$\begin{gathered} f_r(K_D) = \frac{K_D}{365 \cdot d} \cdot \frac{1}{CF} + V_D \cdot \frac{L_D}{d_D} \\ f_b(K_D, C_e) = \frac{K_D}{365 \cdot d} + V_D \cdot \frac{L_D}{d_D} + E_e \cdot C_e + \frac{E_e}{eff} \cdot (C_f^* - C_f) \\ f_r(K_D) - f_b(K_D, C_e) = 0 \rightarrow \\ K_D^*(C_f^*) = \left(\frac{E_e}{365 \cdot d} \cdot \frac{CF}{1-CF}\right) \cdot \left(C_e + \frac{1}{eff}(C_f^* - C_f)\right) - \left(W_k \cdot CF \cdot \frac{d}{d_w}\right) \end{gathered} \quad (7)$$

First, consider the trade-off between desalination powered by solar PV using either electric storage or excess desalination capacity with water storage. The breakeven conditions between these two scenarios, including the levellized cost of electricity storage (or capital cost of electric batteries) and cost of spare desalination capacity, are considered in Figure 3. Given present technologies, electricity storage using sodium sulphur flow batteries is simply too expensive compared to the cost of spare desalination capacity (USD 900–1200/m^3 per day). Under the assumptions of this article, the levellized cost of the bulk sodium sulphur batteries, accounting for a 6% discount rate, is roughly USD 0.34/kWh. The levellized cost of electric storage would have to drop well below USD 0.25/kWh before this technology could be competitive with water storage (given current capital costs).

The conditions necessary to reach the breakeven cost between RO solar with electric storage and conventional RO are illustrated in Figure 4. The variables considered are capital cost of battery storage (vertical axis), fuel cost (horizontal axis), and capital cost of solar power (shaded regions). The shaded regions identify where the unit cost of water is lower for the solar option. The figure shows that for current capital costs of sodium sulphur flow batteries (USD 6100/KW), and solar PV costs in the range of USD 2000/KW, fuel costs would have to exceed USD 150/boe for solar to break even. However, that breakeven oil price drops into the USD 70/boe range if the capital cost of battery storage falls to one-quarter (USD 1500/KW).

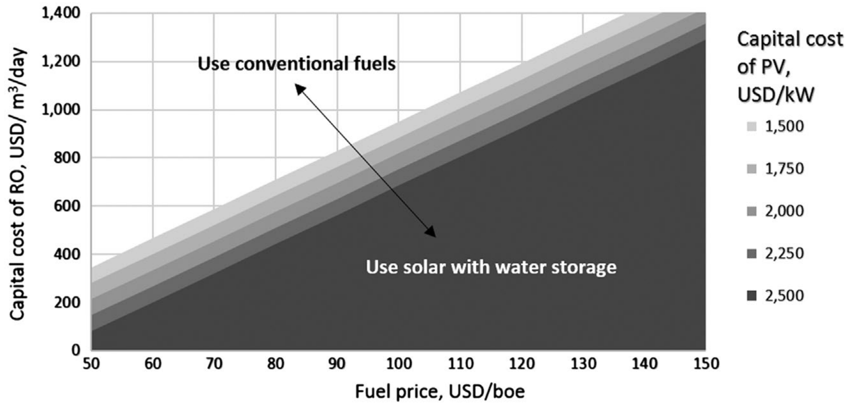

Figure 5. Breakeven cost conditions of solar PV with water storage versus grid-powered RO.

Last, the conditions in which Scenario 3 (RO solar PV with water storage) could compete with conventional RO are considered. The breakeven cost boundary between RO solar with water storage and conventional RO are illustrated in Figure 5. It should be noted that water storage costs represent less than 3% of total costs, and therefore do not play a major role in the relative economics. Assuming that innovation reduced the capital cost of PV and RO to USD 2000/MW and USD 800/m^3 per day respectively, solar desalination with water storage could become cost-competitive with energy costs of roughly USD 100/boe. This breakeven analysis was made assuming a 5 kWh/m^3 electricity consumption rate for RO. For more energy-intensive membrane treatment, which can be the case for the high-salinity Red Sea and Arabian Gulf waters, the breakeven will be reduced, thus further increasing the competitiveness of solar desalination.

The results are dependent on the discount rate assigned to these projects. A high discount rate disproportionally increases the solar desalination costs, as they are highly capital-intensive compared to conventional systems. Conversely, a low discount rate would improve the cost-competitiveness of solar technologies.

Conclusions and policy implications

As the population and economy of Saudi Arabia grow, so will demand for desalinated water. This article has offered a framework for estimating the costs of different solar desalination options compared to incumbent technologies. Here, *solar desalination* is defined as a desalination plant that obtains solar energy from a closed system. This was done to isolate the investigation to issues relevant for desalination applications, rather than studying the efficacy of replacing conventional energy sources with renewables in an integrated electricity grid.

The results demonstrate that Saudi Arabia's current strategy of using thermal desalination technologies makes economic sense only with the current administered prices of fuels. Raising fuel prices to market levels would incentivize a shift to more energy-efficient RO, reducing the total primary energy consumed for desalination. In fact, a fuel price above USD 35/boe provides the necessary condition to switch from energy-intensive thermal cogeneration to more energy-efficient RO.

The prospects for adopting solar-powered energy for desalination given the costs of current technologies, however, are less clear. As stated, integration of state-of-the-art solar power and membrane desalination technology is currently being pursued in Saudi Arabia at the Al-Khafji solar desalination plant. However, under the technical and cost assumptions presented in this article, such systems are unlikely to be cost-competitive with conventional desalination.

Given current technologies, adopting the cheapest solar desalination option, RO solar CSP with water storage, would increase the total costs of water to USD 2.10/m^3. This is the equivalent of desalinating water using RO grid-powered when fuel prices are in the range of USD 132/boe. Should a transition to solar power be adopted, the increased costs would probably be borne by producers, given that consumers in Saudi Arabia are sensitive to utility price increases. Increasing costs to producers, however, would place further strain on the finances of water utilities. Under the current cost structure, total annual revenues do not exceed 2.5% of annual expenditure (Abderrahman, 2007), with most revenues coming from the industrial sector, as residents pay less than USD 0.05/m^3 (Zetland, 2014). For this reason, any shift to more expensive solar desalination technologies is likely to be politically sensitive.

While solar desalination options are presently uncompetitive, innovation is likely to bring down costs. Presently, the cost of bulk flow batteries is very high, so without a major technological breakthrough it is unlikely that electricity storage will be competitive compared to alternative technologies. However, some advances have been made in this area. For example, compressed-air energy storage, in which air is compressed and stored in an underground cavern and released to power a turbine, provides a low-cost energy storage option. Studies suggest that compressed-air energy storage can achieve levellized electricity storage costs in the range of USD 0.12 kWh. At this cost, RO solar PV with electric storage could break even with conventional RO at a fuel cost of roughly USD 80/boe. But this technology is geographically constrained to areas with access to both well-characterized subsurface aquifers and saline water supplies, so it is not presently considered a viable option on a large scale.

A more promising development is the cost of spare desalination capacity, which has fallen significantly in recent years. Should this trend continue, solar-powered desalination with excess capacity and water storage could become competitive with incumbent technologies.

Although stand-alone solar thermal desalination is currently uneconomic, at USD 4/m^3, other low-cost methods of harvesting heat could be considered, such as complementing the waste heat from a standard cogeneration power plant with solar thermal energy. The low-cost solar thermal collector could be used to reduce the heat extracted for the desalination process, increasing the overall efficiency of the power plant.

This article has limited its analysis to solar-powered technologies. There are, however, other unconventional renewable options for desalination. One example is the use of wind energy, which can complement solar technologies by supplying additional power after sunset. Another option is using low-quality geothermal energy for low-temperature desalination of brackish water. Employing the methodology of this article, further study should be done in these areas to assess the cost-competitiveness of these technologies (both in isolation and in conjunction) as energy sources for desalination.

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