



## A Framework for Comparing the Viability of Different Desalination Approaches

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## Key Points

Most renewable powered desalination schemes are hybrids that displace fossil fuel power when renewable power is available. Their economic viability depends only on whether the renewable power source can generate electricity more cheaply than the fuels that it displaces.

The framework used here by KAPSARC compares standalone plants that are powered only by renewable energy and therefore incorporate storage, either of input energy to allow the plant to run full time or of produced water to level out the production of an oversized plant. The commerciality of such approaches is a function of the relative costs of three elements:

- energy storage (electricity or heat);
- the cost of standby desalination capacity (including treated water storage); or
- the relative costs of renewable and conventional energy.

Our research shows that, with the present state of technology, membrane plants are more cost-effective than thermal plants. It is also more cost-effective to oversize the desalination plant and store water on the back end than to store electric power on the front end. The best current configurations are only competitive if the opportunity cost of the avoided fuel consumption is more than \$60/barrel of oil equivalent (BOE).

## Summary

Water scarcity has become a recurrent challenge that leads, in some cases, to dependency on desalination technologies to convert waste, brackish and salt water into potable water. Such solutions have become regarded as essential for isolated, remote environments as well as entire countries where access to renewable water is limited.

In recent years, environmental concerns and a desire to preserve fossil fuel resources have led to proposals to use renewable energy sources and, in particular, solar technologies, to power desalination plants. However, what most people think of as solar desalination is, in reality, a hybrid plant—one that is powered conventionally, but displaces fossil fuel with solar energy (either electrical or heat) when it is available. The economic attractiveness of these hybrid arrangements does not depend on whether the electric power or heat is being used for desalination or any other purpose. Instead, their viability depends only on whether solar power is cheaper than the marginal cost of the alternative source of energy.

Using KAPSARC’s framework, we define solar desalination more narrowly. Our framework discusses systems bounded by two points along the broad spectrum of work on reducing the fossil fuel inputs to potable water production and what constitutes solar desalination:

- Systems that incorporate solar collectors and either electricity or heat storage on the front end to allow the desalination equipment to run continuously at its rated capacity; and
- Systems that run only when solar power is available and are therefore oversized to the extent of the reciprocal of the solar load factor, accompanied by sufficient water storage to allow constant water provision to its end use.

Our framework can be applied to any energy technology for powering desalination, but in this paper we have chosen solar power to illustrate this. It demonstrates that the attractiveness of such standalone systems is a function of the relative costs of three elements:

- energy storage (electricity or heat);
- the cost of standby desalination capacity (including treated water storage); or
- the relative costs of renewable and conventional energy.



We find that direct solar desalination can make sense for small-scale output in remote rural areas using solar collectors augmented by thermal energy storage. By contrast, large-scale solar powered desalination in locations that can be connected easily to electricity and water distribution grids has not yet reached the point of becoming commercially attractive.

Of the two configurations that we define as solar desalination (above), it is presently more cost-effective to oversize the desalination plant and store water on the back end than to store electric power on the front end. The most cost-effective current configurations (based on membrane technologies) are only competitive if the opportunity cost of the avoided fuel consumption is more than \$60/BOE.

The envelope of viability defined by the relative costs of the three key elements provides a framework for evaluating where R&D investment might make most progress towards overall system competitiveness. Because the opportunity costs of conventional fuels are low in major energy exporting countries, they are more likely to enter the envelope of viability for renewable-powered desalination through progress in the costs of energy storage and standby desalination capacity than through reducing the costs of renewable energy.

### Introduction

In this paper, we introduce KAPSARC's framework for evaluating the viability of a standalone renewable powered desalination facility that incorporates the major technical and economic cost parameters for a range of system configurations. It includes several scenarios to represent new desalination technologies that are used on a large scale both in the Middle East and around the world. Significant regional variations in the capital and operating costs, as well as environmental and economic conditions, can occur and we provide a calculator that users can adapt for these factors.

In demonstrating the general framework we illustrate the relative costs of the different options, using costs, fuel prices and performance metrics based on Saudi Arabian installations. However, these figures are snapshots from recent years and real investment decisions are normally taken using more detailed evaluations of the input variables. Our illustration should not, therefore, be construed as a specific recommendation on investment in any specific technology. Appendix 1 provides an outline of the water challenges and strategies for overcoming them in Saudi Arabia.

The calculator provides a tool for evaluating the opportunity cost of fuel at which both conventional and other renewable desalination technologies become viable for different options, which are outlined below. It also provides a means of identifying how far current technologies need to improve to fall within our envelope of viability and which innovations can provide the most progress towards economically attractive solar powered desalination.

### Desalination Technologies

Desalination by reverse osmosis (RO) uses electric power to pump feed water across a membrane, extracting salt and other impurities. RO accounts for the largest increment of *global* desalination capacity over the past decade. Alternative thermal desalination technologies, such as Multi Stage Flash (MSF) and Multi Effect Distillation (MED) use heat to distill water. Thermal desalination has become a standard for large-scale operation. It is frequently combined with a power plant, such as a Combined Cycle Gas Turbine (CCGT) plant—known as cogeneration—with waste heat from a steam turbine used to reduce the total energy demand for desalination.



Even with improvements from cogeneration, RO still consumes significantly less energy than advanced thermal technologies, though at a higher capital and non-energy operational costs. With access to cheap fuel sources or waste heat, thermal technologies are favored and make up the bulk of desalination capacity in many Middle Eastern countries. Rises in world energy prices have motivated many countries to invest in more energy efficient RO, which has become increasingly competitive with thermal desalination.

Renewable desalination was carried out on a small scale long before the invention of RO, MED or MSF. This typically involved a solar still, a form of *direct* solar desalination that collects heat and produces water in a simple closed system. However, due to low yields in proportion to the size of a solar still, they are not viable for large scale applications (Kalogirou 2005). In this paper three *indirect* solar powered desalination options are considered. These combine two separate systems: a solar energy collector and a modern desalination plant.

There are several different approaches to implementing *indirect* solar desalination. Photovoltaic (PV) power, consisting of panels of solar cells that convert solar energy into direct current electricity, can be used to power RO. Alternatively, Concentrated Solar Power (CSP) uses the sun's thermal energy to produce steam to drive an electric turbine that powers an RO plant. An advantage of CSP is integrated thermal energy storage—storing excess solar energy during the day—which increases the overall capacity factor. However, this comes at a significant capital cost.

Indirect solar desalination can also be applied to thermal technologies, using heat collectors to concentrate sunlight. Solar thermal applications are typically coupled with thermal storage to balance the intermittent nature of sunlight and supply additional power after the sun sets.

### KAPSARC's Cost Calculator

A unit cost calculator has been constructed to estimate the unit cost of producing a cubic meter (cm) of potable water using conventional and renewable desalination technologies. The calculator takes into account 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 2014 real U.S. dollars (\$) per cm of water.

When calculating the energy costs in a standard desalination process, the source of an identical unit of energy, electricity or heat is not relevant for the desalination process. For example, in a typical RO plant powered by an electric grid, only the cost of electric power is of concern to the water utility, not how it was generated.

We define a solar desalination technology as a closed system involving an integrated solar powered energy source, appropriate storage capacity (heat, electricity, or water, depending on the configuration) and a desalination plant (RO or MED). In this case, the operating conditions and system configurations, and the associated costs of the renewable power, play a clear role in the cost of desalination.

Different applications of solar desalination techniques are compared with baseline scenarios, using RO, MSF and MED. Seven scenarios are described in Table 1 below. In the case where solar powered desalination is more expensive, analyses of the opportunity and technology costs identify the shifts in the relative economics required to motivate adoption of solar desalination.

### Solar and Conventional Reverse Osmosis Scenarios

As RO is the most energy efficient approach to desalination, the calculator is applied to several scenarios that make use of it. In Scenario 1, a



baseline scenario, the cost of conventional RO desalination is calculated for a facility powered by the electric grid, with energy costs defined by the price paid for electricity from the local grid provider.

In general, solar desalination schemes can be achieved in two ways. Both involve investment in sufficient renewable power capacity to replace the consumption of conventional fuel:

- Investment in electricity storage, either with batteries or mechanical systems such as Compressed Air Energy (CAE), to run the desalination unit at full capacity when the solar power output is below the peak. This is shown in Scenario 2 (RO Solar PV with Electric Storage).
- Investment in spare desalination capacity running only off the available solar power, with water storage used to capture the excess water produced during the day. Two different scenarios describe this case, Scenario 3 (RO Solar PV) and Scenario 4 (RO Solar CSP). Thermal storage provided by the CSP plant increases the overall capacity factor of the power element, though PV provides a lower capital cost solar power supply.

The aim of the calculator is to identify which approach is the more economic: electricity storage or the combination of excess desalination capacity with water storage. It also points to which innovations in storage or desalination technology will most likely make solar desalination cost-competitive with a conventionally powered facility (either grid-connected or with a remote diesel power generator).

### Solar and Conventional Thermal Desalination Scenarios

The baselines for conventional thermal desalination are represented in Scenario 5 (MED Cogeneration) and Scenario 6 (MSF Cogeneration). In each power and water cogeneration plant scenario, a power plant and a desalination plant are combined to provide

both electricity and water. Cogeneration provides the additional 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 fresh water, cogeneration provides a commercial advantage over standalone desalination plants. 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.

Scenario 7 (MED Solar) represents solar powered thermal desalination, in which solar heat collectors are used to power an MED plant. A review of seawater desalination (Kalogirou 2005) references several pilot studies for solar powered distillation using flat plate, parabolic and solar pond heat collectors. We do not provide a unit cost calculator for this scenario as the technology has not yet matured. Instead, detailed technical cost estimates are included to provide a benchmark for this.

The scenarios above assume that the combination of state-of-the-art desalination, renewable and energy storage technologies neither benefits from integration efficiencies nor recognizes the likelihood that early pilot schemes will cost more than initially expected while integration issues are overcome. There is no doubt that solar desalination systems will be complex, high technology installations.

In the short term, it may be more beneficial to think about the totality of desalination systems, including the source of the water and its end-use. This might lead to consideration of other unconventional technologies to achieve cost-effective renewable desalination systems. One example is to use low quality geothermal energy—though it is unsuitable for thermal power generation—in low temperature MED desalination. Alternatively, low quality produced or partially desalinated water (not suitable for potable use) could be used to irrigate crops with high salinity tolerance.



	Desalination Type	Description
1	RO Grid Powered (Baseline)	RO powered by an electric grid
2	RO Solar PV with Electric Storage	RO powered by solar PV plant with electric power storage
3	RO Solar PV	RO powered by solar PV plant with water storage
4	RO Solar CSP	RO powered by CSP plant with thermal and water storage
5	MED Cogeneration (Baseline)	MED plant with combined cycle gas turbine cogeneration power plant
6	MSF Cogeneration (Baseline)	MSF plant with combined cycle gas turbine cogeneration power plant
7	MED Solar	MED plant fueled by an inexpensive solar heat collector

**Table 1** – Baseline and Solar Desalination Scenarios

These, and other alternative approaches to desalination, may have only limited application but could provide useful local knowledge and experience in designing and operating integrated renewable desalination systems. Breaking down the problem of cost-effective renewable powered desalination into smaller steps may help with the eventual challenge represented by the integration of state of the art, technologically complex systems.

### 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, expressed through the equation:

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

Where  $K_D$  is the capital cost of the desalination plant (\$/cm per day),  $V_D$  is the non-fuel variable O&M cost (\$/cm),  $L_D$  is the plant lifetime in years,  $E_e$  and  $E_t$  are electric and thermal energy consumption rates (kWh/cm and MMBtu/cm), respectively, and  $C_e$  and

$C_f$  are the costs of electricity and fuel (\$/kWh and \$/MMBtu), respectively. We use a typical unit capital cost for a large plant (i.e. larger than 100,000 cm/d). The thermal energy required for desalination in power and water cogeneration is calculated using an electrical equivalent thermal energy for desalination and the fuel efficiency of a standalone power plant. See Appendix 2.

A discount,  $d_D$ , is attributed to the desalination plant's capital and variable cost lifetime. It is calculated using an estimated amortization rate,  $i$ , with the equation:

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

The unit costs of solar powered desalination include the capital and non-energy operating costs above. Energy (fuel and electricity) costs are replaced with 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 labeled with respect to the corresponding technology: solar (S), battery (B), or water storage (W), as expressed below.

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

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

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

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

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

where  $K_W$  and  $V_W$  are the capital and variable costs

of water storage (\$/cm). 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 energy can constitute more than half of total costs. These costs will vary significantly between countries depending on their access to energy resources and the regulations placed on prices by governments: some countries tax energy, while other sell it at prices below international market values. In cases where oil products and natural gas are sold domestically at administered prices below international market values, domestic use may come at an opportunity cost. This 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.

### Costs vs Fuel Prices—Finding the Shortest Technology Pathway to Viability

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. We use a simple linear cost function (1) defined for each scenario ( $i$ ) depending on a vector of input cost variables ( $X = x_1, x_2, \dots$ ), such as the opportunity cost of fuel and technology costs, with coefficient vector  $A_i$ , and a 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.

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



## Case Study Results

### Current State of Technologies Available to Saudi Arabia

The prospects for adopting solar powered desalination technologies in Saudi Arabia can be judged by examining the current and future expected economic costs of desalination technologies. These results can only be interpreted as broadly representative cost estimates for the purpose of comparing different desalination possibilities in Saudi Arabia. Actual capital and operation costs will differ between projects, requiring more detailed technical analysis.

Under the current administered energy prices in Saudi Arabia, the variable energy costs of thermal desalination processes provide MED and MSF with a significant competitive advantage over RO. This is because the greater energy efficiency of RO is not sufficient to offset its higher capital costs at current Saudi prices for energy. Considering only administered prices (yellow bars) in Figure 1, MSF cogeneration (\$0.85/cm) and MED cogeneration (at \$0.78/cm), are about 8 percent and 15 percent cheaper, respectively, than RO (\$0.92/cm).

The cost savings under administered prices are unsurprising. First, the non-fuel operating expenses of thermal technologies are about 26 percent cheaper 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 of the 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.

Figure 2 directly compares the unit cost of water in each scenario over a range of fuel prices. In some countries these are actual prices and, in others, they represent the opportunity cost of fuel consumed. Conventionally powered desalination is lower cost until the opportunity cost of fuel is high enough to outweigh the high capital cost of investing either in spare desalination capacity with water storage (RO Solar CSP with Water Storage) or in electric batteries (RO Solar PV with Electric Storage). In contrast to Figure 1, electricity costs for the grid-connected options are based on the range of fuel prices analyzed rather than local administered prices.

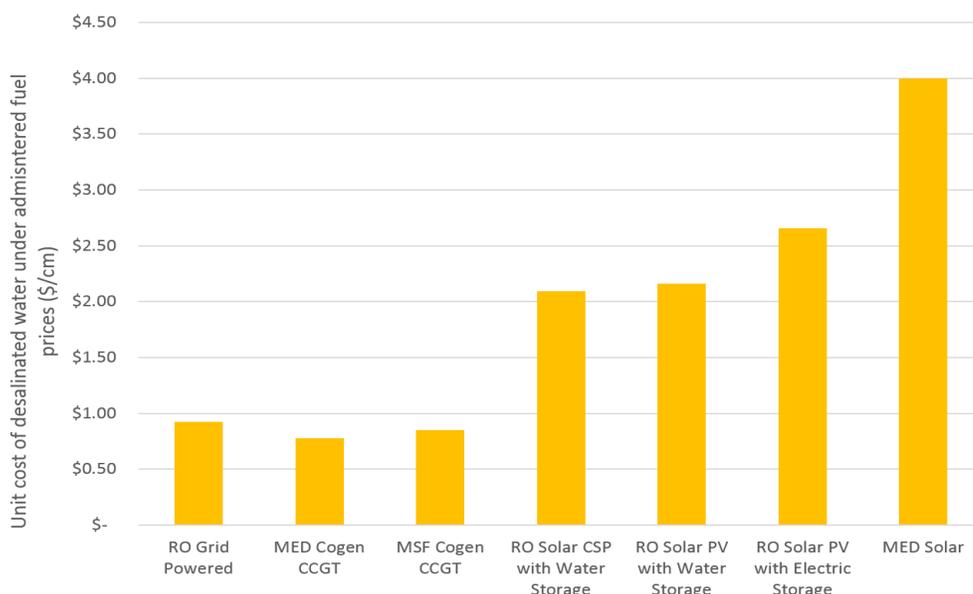
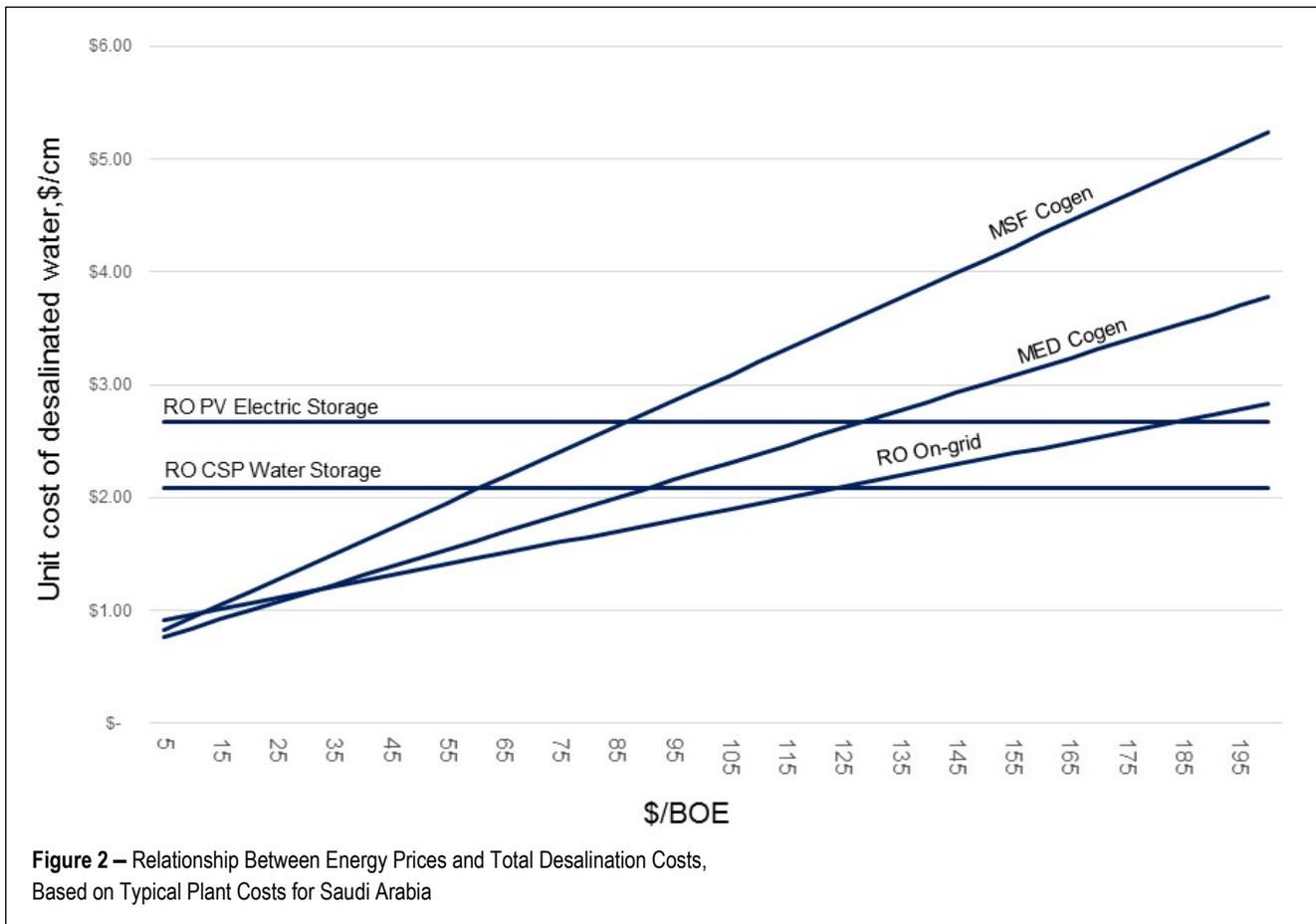


Figure 1 – Costs of Desalination Under Different Pricing Schemes, Based on Saudi Arabian Fuel And Electricity Tariffs



- As would be expected, the total cost of desalination powered completely from solar energy (either PV or CSP) does not vary with changes in fossil fuel prices.
- Given that thermal technologies use the most energy for desalination, the costs of MSF cogeneration and MED cogeneration vary most with changes in energy prices. When energy prices are below \$30/BOE, MED cogeneration offers the cheapest option for desalination. MSF and MED cogeneration quickly become more expensive than solar powered RO scenarios, exceeding the least expensive solar options once fuel prices rise above \$60/BOE and \$90/BOE respectively.
- Even when accounting for opportunity costs of fuels, the cheapest option for desalinating water

when fuel prices are between \$35/BOE and \$125/BOE, which brackets the range of consensus on long term international fuel prices, is Grid Powered RO. Thus, solar desalination currently represents a higher cost option than RO technology, even when the opportunity costs of fuels are considered.

Both Figures 1 and 2 show that electricity storage, using sodium sulfur flow batteries (RO Solar PV with Electric Storage), is more expensive than oversizing the RO facility and storing excess water produced during daylight hours (RO Solar PV with Electric Storage). The precision of this calculation should not lead to overconfidence in the accuracy of the input data (particularly regarding the reliability of operating a membrane plant intermittently). Valid data is likely to be available only when such plants have been tested over long periods of operation.



## Possible Future Cost Reductions

Additional breakeven analyses for solar desalination demonstrate how technological innovation in energy storage, spare desalination capacity and solar power can improve the competitiveness of solar desalination. First, consider the tradeoff between desalination powered by solar PV using either electric storage or excess desalination capacity with water storage. The breakeven conditions between these two scenarios are shown in Figure 3, including the levelized cost of electricity and cost of spare desalination capacity.

As previously noted, electricity storage using sodium sulfur flow batteries is simply too expensive relative to typical capital costs of RO facilities, \$900-1200/cubic meters per day (cmd). The capital cost of NaS batteries would have to drop below \$4,500/kW to compete with water storage, providing a levelized cost of electricity storage well below \$250/MWh. At the current capital cost of \$6,100/kW the levelized cost is about \$350/MWh. An alternative energy storage system is CAE, which has been achieved with a levelized cost of electricity storage below \$150/MWh (Sandia 2013).

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 the capital cost of battery storage (vertical axis), fuel cost (horizontal axis) and the capital cost of solar power (colored area). The shaded area indicates where the unit cost of water is lower for the solar option. The figure shows that for current capital costs of sodium sulfur flow batteries (\$6,100/kW) and Solar PV costs in the range of \$2,000/kW, fuel costs would have to exceed \$150/BOE for solar to break even. However, that breakeven oil price drops into the \$70/BOE range if the capital cost of battery storage falls to one quarter (\$1,500/kW) of what it was.

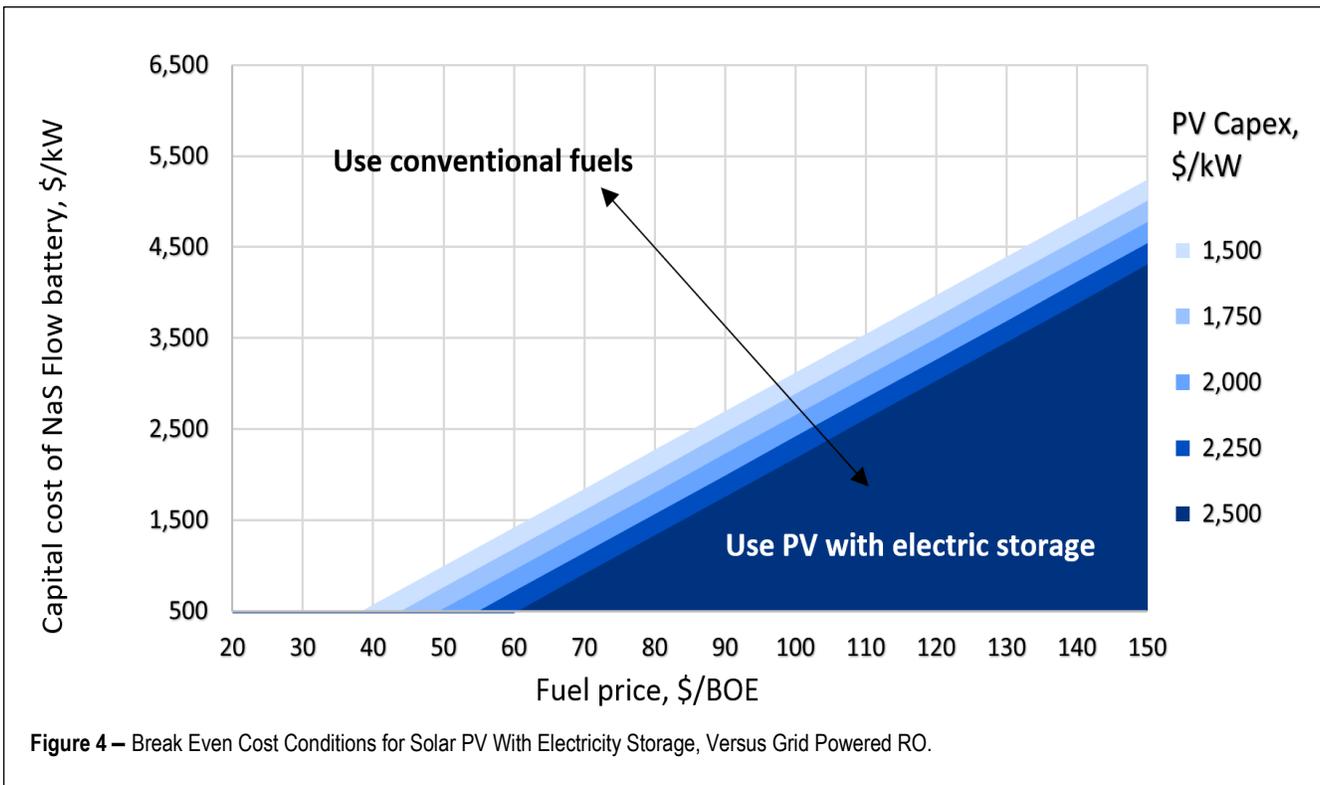
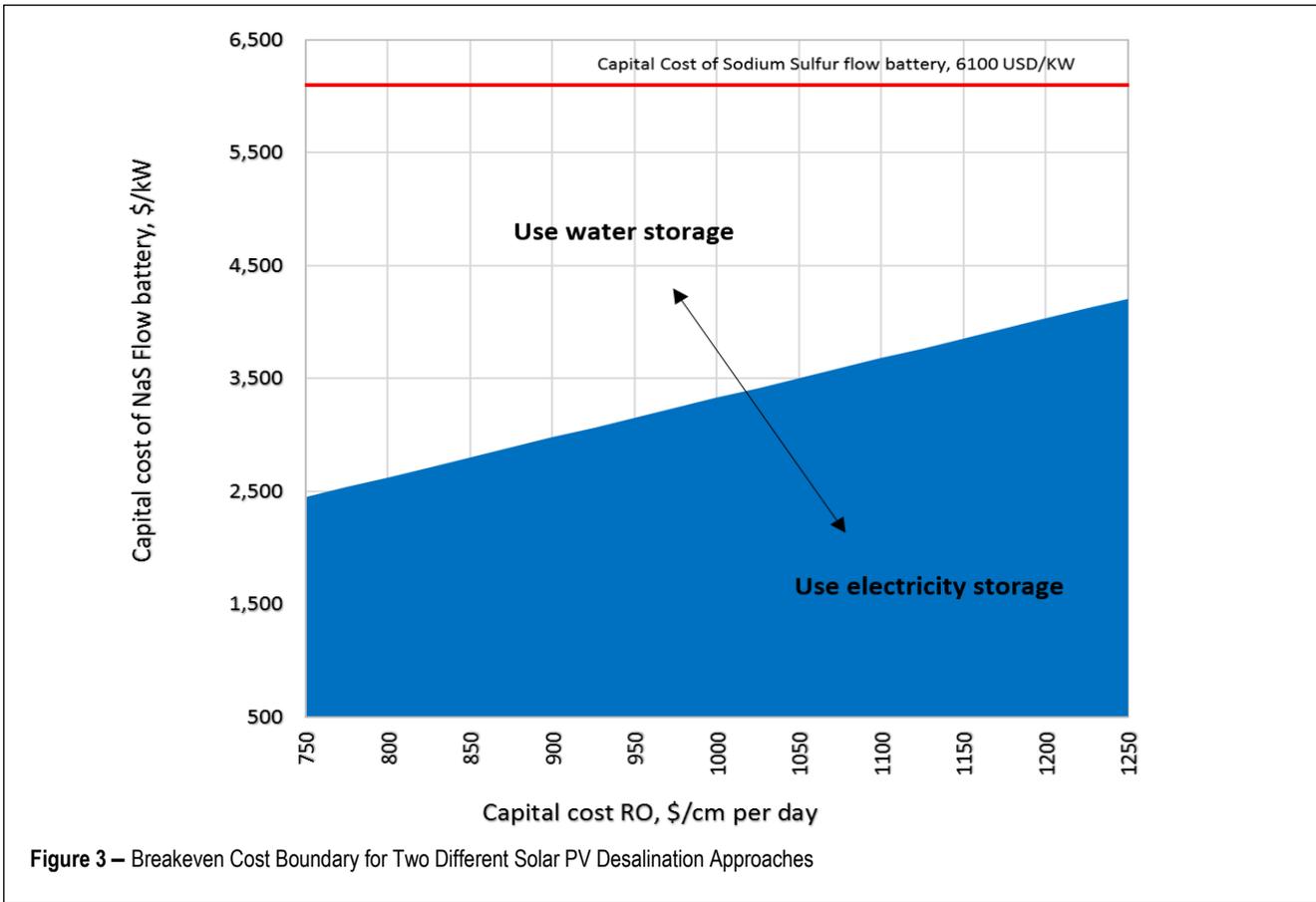
Figure 5 delineates the conditions in which Scenario 3 (RO Solar PV with water storage) could compete with conventional RO. The capital cost of battery storage in Figure 4 is replaced with the capital cost of spare desalination capacity. Water storage costs represent less than 3 percent of total costs, and therefore do not play a major role in the relative economics. The figure shows that with innovation in the capital cost of RO and PV, solar desalination could start to make economic sense when fuel costs exceed \$100/BOE. Assuming a total capital cost of \$2000/MW for a PV plant and \$800/cmd for the RO plant, solar desalination with water storage becomes cost competitive at roughly \$100/BOE.

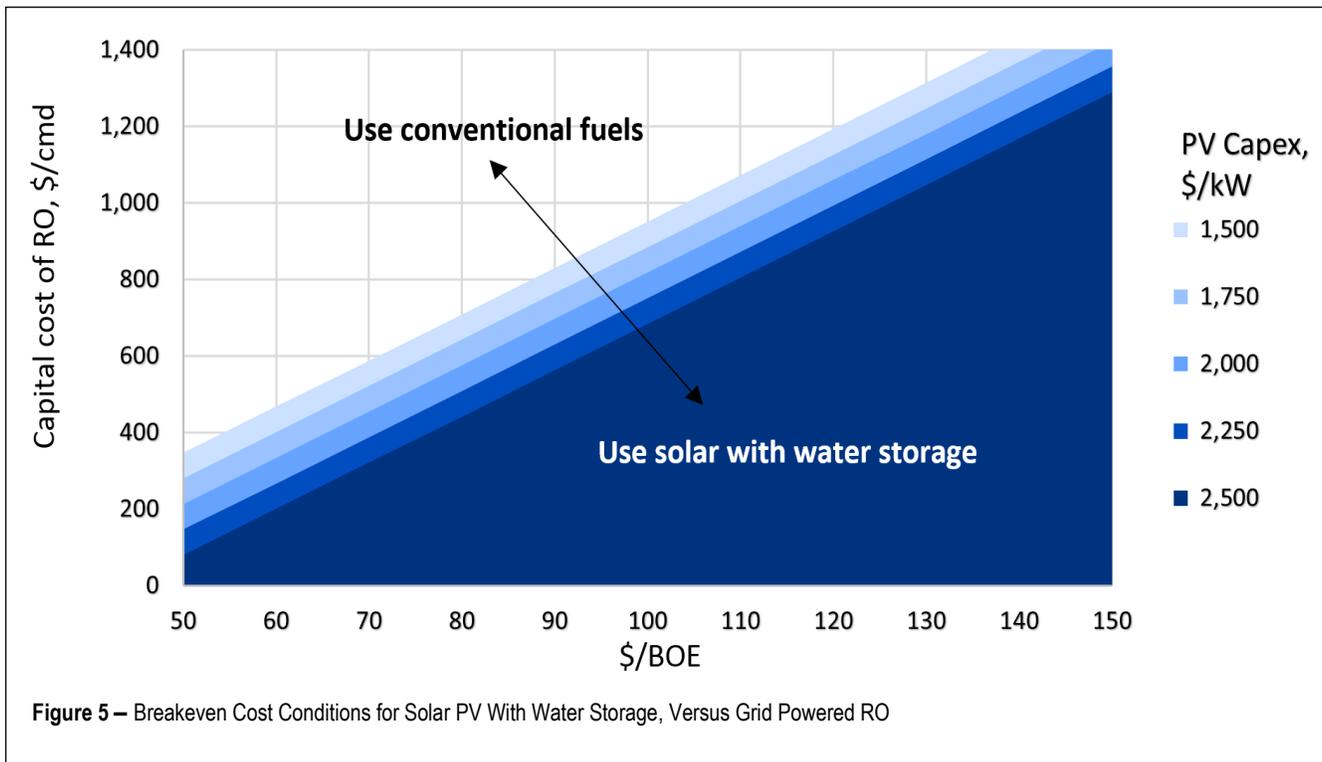
The analysis is based on an electricity consumption rate for RO of 5 kWh/cm. The breakeven line will shift up and to the left in the case of more energy intensive membrane treatments. This can be the case for the high salinity of the Red Sea and Arabian Gulf waters and reduces the breakeven fuel price at which solar desalination becomes viable.

## Conclusions and Policy Implications

We have examined the costs of different renewable desalination technologies using current state of the art solar energy systems. We defined solar desalination as a unique integrated water energy system that combines both energy and water conversion and storage technologies in a closed system. In this way we were able to restrict the analysis to issues relevant for desalination applications, rather than more general renewable grid power or heat production.

The results explain why Saudi Arabia's current use of thermal technologies for desalination is appropriate in light of the current administered prices of fuels. Raising fuel prices to global market levels would incentivize a shift to more energy efficient RO technologies, reducing the total primary energy consumed for desalination.





The integration of solar power, membrane desalination and energy and water storage systems is being tested in Saudi Arabia. For example, a pilot solar desalination plant is being constructed in the town of Al-Khafji in the northeast of Saudi Arabia, designed to provide 60,000 cmd of desalinated water using reverse osmosis, with a solar photovoltaic plant capable of supplying the power for the desalination process (Abengoa 2015).

At current domestic fuel prices, thermal desalination technologies are by far the most cost-competitive technology for water utilities in Saudi Arabia. This promotes a highly energy intensive domestic water supply industry. Using representative data for The Kingdom, the costs of producing 1 cm of desalinated water from MED, MSF and conventional RO under administered fuel prices are \$0.78/cm, \$0.85/cm and \$0.92/cm respectively. A fuel price of above \$40/BOE provides the necessary incentive to switch from

energy intensive thermal cogeneration to more efficient RO.

Comparing the pure solar powered desalination options presented in this paper, water storage with spare desalination capacity is currently more competitive than power storage using bulk flow batteries. A major technical issue may prove to be the integration and operation of spare RO capacity with a variable power supply. If these technological issues can be resolved, investment in R&D to reduce solar powered desalination costs will continue to improve its competitiveness against incumbent technologies. The current breakeven opportunity cost of avoided fuel consumption is \$60/BOE, but further innovation may reduce this to a figure that better reflects the actual value of a barrel of oil saved in Saudi Arabia or other countries that have spare production capacity.



## Appendix 1

Water scarcity is a major challenge in Saudi Arabia, a country endowed with enormous energy resources but few other natural resources and which 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 \$780 to \$25,850 between 1968 and 2013 (World Bank 2014b).

Similarly, and in part because of the growth in agricultural production, Saudi Arabia's water use has increased alongside the growth in its population and wealth. In 1975, Saudi Arabia used roughly 1,750 cm of water. By 2006, that annual consumption figure had risen to 23,670 cm (FAO 2014). Importantly, roughly 70 percent of the water used in Saudi Arabia comes from non-renewable fossil aquifers located deep within the earth. At current consumption trends, Saudi Arabia's renewable water resources per capita are depleting by 2 percent per year (Giansiracusa 2010). In 2011, roughly 1,500 cm 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 and Electricity 2012).

Saudi Arabia has a long history of desalination. In 1938, the world's first large scale desalination plant was established in Jeddah, Western Region. Despite this, it was not until the 1970s, when windfall profits from oil exports made the process financially viable on a large scale, that the country fully adopted desalination as a method for meeting national water demand. In 2010, desalination technologies provided roughly 50 percent of the water used by the municipalities in Saudi Arabia. A majority of this water was provided by nine large MSF and MED cogeneration plants, and eight large RO plants. In addition to these, there are a number of smaller plants used by industry as well as commercial and residential buildings. In total, there are 1,595 desalination plants operating in Saudi Arabia. Today, 57 percent of the installed capacity for desalination comes from thermal technologies, namely multi stage flash (46.8 percent) and multi effect distillation (10.3 percent), with RO accounting for 40 percent. The remaining 3 percent comes from advanced desalination technologies such as nano-filtration and membrane bioreactors (KAPSARC calculations, data from Desalination Database 2014).

The reasons for the dominance of thermal technology in Saudi Arabia are three-fold.

- Thermal technologies use the simple process of distillation to separate fresh water from salt and other impurities and so it has historically been a more reliable method for large scale desalination (Bernat et al. 2010), particularly in the high salinity of the Gulf waters, where the salt content is roughly 45,000 ppm compared with global averages of 35,000 ppm.
- Thermal desalination can use waste heat from cogeneration power plants, thus allowing water and energy needs to be met simultaneously from one utility.
- Thermal technologies, which are more energy intensive but less capital and labor intensive, produce water more cheaply than membrane technologies like RO when energy prices are very low. 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).



While desalination has helped Saudi Arabia combat water scarcity, this has come at a significant financial cost, particularly given the dominance of energy intensive thermal technologies.

Desalination technologies are capital and energy intensive, increasing the direct spending needed to supply an essential natural resource. It can also increase demand for conventional fuels. Saudi Arabia used roughly 28 MBOED to desalinate all the water distributed to municipal and industrial water networks in 2011 (Matar et al. 2014). As the price of oil and natural gas sold domestically is set at administered prices much lower than their international market values, the true cost of the desalination is hidden. There is an opportunity cost borne by Saudi Arabia because the choices of technologies and processes are optimized for these administered domestic prices rather than for the values that can be put on oil and gas if they are allocated to their highest value uses (including exports).

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 percent annually, resulting in a nine-fold increase. This has made Saudi Arabia the sixth largest consumer of oil globally, trailing only the (much larger) economies of the U.S., China, India, Japan, and Russia (Gately 2011). 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 and El Baltaji 2012).



**Appendix 2: Capital and operating costs of solar desalination technology options**

		RO Solar PV with Electric Storage	RO Solar PV with Water Storage	RO Solar CSP with Water Storage	MED Solar
	Capacity	100,000	100,000	100,000	1,000,000
	Capacity factor (percent)	22	22	40	40
$L_D$	Plant lifetime	25	25	25	30
$K_D$	Plant capital cost (\$/cm)	1100	1100	1100	1250
$V_D$	Plant capital cost (\$/cm)	1100	1100	1100	1250
<b>Solar Technology Costs</b>					
$S_{K,V}$	Solar Technology Costs				
$K_S$	Capital cost (\$/kW)	2500	2500	7700	n/a
$V_S$	Variable O&M cost (\$/kWh)	0.0034	0.0034	0.011	n/a
$L_S$	Technology lifetime	25	25	25	n/a
CF	Capacity factor (percent)	22	22	40	n/a
<b>Electricity storage costs</b>					
$B_{K,V}$	Electricity storage costs				
$K_B$	Battery capital cost (\$/kW)	6100	-	-	-
$V_B$	Battery O&M cost (\$/kWh)	0.01	-	-	-
$L_B$	Lifetime	15	-	-	-
$\epsilon$	Battery charge discharge efficiency (percent)	86	-	-	-
$\tau$	Discharge period (hours)	7.2	-	-	-
N	Discharge cycles (over lifetime)	4500	-	-	-
<b>Water Storage Costs</b>					
$W_{K,V}$	Water Storage Costs		-	-	-
$K_W$	Capital Costs (\$/cm)	-	200	200	-
$V_W$	Variable O&M costs (\$/cm)	-	0.02	0.02	-
$L_W$	Lifetime	-	30	30	-

**Sources** – Capital costs of thermal desalination plants UNESCO (2008). Capital cost of RO plants come from a project statement for the Shuaiba Expansion Project, ACWA (2014). Operating costs of all plants were taken from Thyne (2010). Solar PV and CSP plant costs and average yearly capacity factors were taken from World Energy Outlook 2013 (IEA 2014b) for Middle Eastern countries. Electricity storage cost is derived for sodium sulfur (NaS) flow batteries (Sandia 2014). Capital cost of water storage is taken from online news article (*Arab News 2014*). All costs have been adjusted to 2014 real U.S. dollars.

Other variables		Sources:	
$i$	Discount rate of capital and operation costs Administered Fuel Prices for Saudi Arabia	6 percent	Matar et al. (2014)
$C_f$	Crude oil price for water and power utilities (2011 value) Gas price for utilities	\$4.24/barrel \$0.75/MMBtu ~ \$0.0025/kWh	ECRA, personal comm. (2014)
$C_e$	Industrial electricity tariff set by Saudi Electricity Company (annual average over summer and winter periods)	\$3.84/kWh	ECRA (2013)
eff	Fuel consumption efficiency for the Saudi electric grid	32 percent	Derived from IEA (2012)



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## Notes

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