Review Article

Solar-Thermal Powered Desalination: Its Significant Challenges and Potential

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Abstract

Throughout the world, there are regions of vast extent that have many favorable features, but whose development is principally limited by the lack of fresh water. In arid areas where large-scale development has already occurred, e.g. parts of the Middle East and North Africa, the extraction of fresh water via desalination plants requires very large energy consumption. This motivates the development of *solar-desalination* systems, which are desalination systems that are powered by solar energy. With the goal of identifying key technical challenges and potential opportunities solar-desalination, we review a variety of solar energy technologies used for capturing and concentrating heat energy, and also review various technologies for desalination systems including advanced techniques for energy-recovery. Existing solar-powered desalination plants have generally been *indirect solar-desalination* systems that first (i) transform solar energy into electrical energy and then (ii) employ the resulting electrical energy to drive desalination systems. Other, potentially more efficient *direct solar-desalination* systems directly convert the solar energy to pressure and/or heat, and use these to directly power the desalination process. We compare the cost-effectiveness, energy-efficiency, and other relevant quantities of these potential technologies for solar-desalination systems. We conclude that the direct solar-desalination systems using solar-thermal collectors appear to be most attractive for optimization of the energy-efficiency of solar-desalination systems. Further, we consider the economics and other practical issues associated with employing solar-desalination systems to provide for economic water sources for urban and agricultural areas. We consider factors that have significant impact to the use of solar-desalination systems: including location, climate, the type of water source (ocean water or brackish water sources), as well as land-use and ecological issues. We observe that the most favorable locations are those with high solar irradiance, lack of fresh water, but access to large brackish water sources and/or proximate seawater. We review the known locations of global brackish water reserves and areas with proximate seawater. Finally, we determine what appear to be the most favorable candidate locations for solar-desalination systems, which include considerable sections of North and East Africa, the Middle East, Southern Europe, Western South America, Australia, Northern Mexico, and South-West USA. We conclude that the development of cost-effective and energy-efficient solar-desalination systems may in the immediate future the key to a future "terraforming" of otherwise desert and near-desert regions of the world, providing a "greening" of these regions.

Keywords – *solar energy; desalination, solar-desalination, brackish water*

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1 Introduction

1.1 A Historical Prospective: Prior Greening of the World at the End of the Pleistocene

Interestingly, many areas such as the Middle East and North Africa were not always arid. At the end of the Pleistocene, roughly 12,000 years ago, the melting of glacier ice allowed many such areas have considerable fresh water. These conditions persisted to a degree even up to the Classic period 2000 years ago, and in those times for example certain areas that are now deserts in North Africa were a significant source of grains for Rome.

1.2 Green Terraforming

We use the term "Green Terraforming" to describe the goal of transforming now arid areas of the world (e.g., sections of North and East Africa, the Middle East, Southern Europe, Western South America, Australia's interior, and South-West USA) to areas with considerable available fresh water. We will be discussing technology that with further improvement and the overcoming of some considerable technical challenges may lead to such as "Green Terraforming" of arid regions.

1.3 Goals and Organization of Paper

It should be noted that there is a very extensive existing literature (which we shall cite) both for desalination technologies and for solar powered technologies, and it our goal to provide a brief introduction and overview of those technologies sufficient to discuss them in conjunction.

In this section 1 we have motivated our survey paper on solar-powered desalination. In section 2 we briefly discuss known solar technologies, as well as their cost-efficiency, energy-efficiency, and technological challenges, and in particular how to best adapt these solar technologies to provide power for desalination. In section 3 we discuss known desalination technologies, as well as their cost-efficiency, energy-efficiency, and technological challenges: in particular, the challenge of adapting desalination technologies to best utilize the power supplied by solar energy. In section 4 we conclude the paper with a discussion of future challenges.

2 The Rapidly Increasing Need for Desalination

2.1 Freshwater Reserves

<see figures>
Figure 1: World map of freshwater (in green) reserves [Gleeson, 2012]

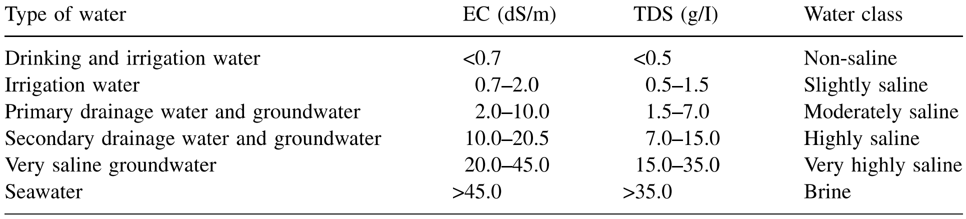
We will use the term *fresh water* to denote water with no more than approx. 500 to 100 ppm salinity; fresh water constitutes only 3%-5% of the world's water [ADA, 2002]. To determine the areas where desalination is of use, see the above Figure 1, which provides a world map of freshwater water reserves [Gleeson, 2012].

2.2 Rapidly Diminishing Accessible Freshwater Reserves

The high rate of population growth and climate change presents increased need for freshwater, and in the next decades many further areas of the world are expected also to require substantial use of desalination. Agriculture currently uses approximately 70% of fresh water, and overall agricultural water use will increase substantially with population growth, perhaps by 50% within 15 to 20 years. Agriculture use of fresh water competes with the industrial (approx. 20%) and household (approx. 10%) use of freshwater. A number of arid areas (e.g., much of the Middle East) already completely utilize all available sources of fresh water, and need to rely on desalination. In the future, with demand for fresh water approx. doubling every twenty years, many more regions will need to rely on desalination for a growing proportion of their fresh water needs.

2.3 Classification of Waters

A key issue for desalination is the source volume, salinity, and other dissolved solids of the feed water used for desalination.



Type of water	EC (dS/m)	TDS (g/I)	Water class
Drinking and irrigation water	<0.7	<0.5	Non-saline
Irrigation water	0.7–2.0	0.5–1.5	Slightly saline
Primary drainage water and groundwater	2.0–10.0	1.5–7.0	Moderately saline
Secondary drainage water and groundwater	10.0–20.5	7.0–15.0	Highly saline
Very saline groundwater	20.0–45.0	15.0–35.0	Very highly saline
Seawater	>45.0	>35.0	Brine

Table 1: Classification of waters by total dissolved solids [Rhoades, 1992]

The above Table 1 gives Total Dissolved Solids (TDS) in grams per liter (g/l), as well as electrical conductivity (EC), expressed in units of deciSiemen per meter (dS/m). (Note that for TDS consisting only of Na Cl salts, the TDS of 1 gram per liter (g/l) is the same as 1,000 ppm.) Observe from the Table 1 that irrigation water can, depending on the crop, be up to approximately three times the TDS of drinking water. Also, ground water has a wide variation of TDS, depending on the drainage and topsoil.

Classification of waters by salinity: *Brackish water* is water with salinity between that of fresh water and seawater (in the range of approx. 5,000-35,0000 ppm, but typically approx. 10,000-15,000 ppm), and constitutes approximately 23% of the world's water [ADA, 2002]. The salinity of seawater ranges between 35,000 to 45,000 ppm, and constitutes approximately 58% of the world's water [ADA, 2002]. Other water consists of wastewater (approximately 5%), and river water (approximately 7%), and other sources [ADA, 2002]. Unfortunately, a large proportion of wastewater of developing nations is released directly into rivers, thus further limiting sources of fresh water.

2.4 Saline and Brackish Water Reserves

The salinity and composition of the input feed to any desalination system is critical, and so it is essential to know the accessible sources, saline concentration of nearby saline and brackish water.

<see figures>

Figure 2: World map of situation of saline water reserves [Weert, 2009]

The first issue is the situation of the saline and brackish water. The Figure 2 above gives a world map of situations of saline water reserves, with Basin (red), Sedimentary-Basin (yellow), Mountain (green), volcanic (blue) [Weert, 2009].

<see figures>

Figure 3: World map of brackish water reserves [Weert, 2012]

Note that brackish water often results from freshwater sources that are in contact with saline sediments or seawater seepage. Furthermore, brackish water can be found often near salt domes, and so collocated near deposits of oil or natural gas.

The next issue is the geographic locations of the saline and brackish water. Figure 3 above gives a world map of brackish water reserves [Weert, 2012] and in Figures 4 and 5 maps are also given for brackish water reserves in the Middle East and North Africa, respectively. Observe the extent of brackish water with partial marine origin (in blue), e.g., those ringing much of Africa, and particularly evident in North Africa. Also, observe the large brackish water reserves of natural terrestrial origin (in red) in eastern Saudi Arabia, which may be associated with salt domes.

3. Solar Energy Technologies: Their Cost-Effectiveness, Energy-Efficiency, and Challenges

3.1 Solar Energy, the Underutilized Energy Resource

Although solar energy until recently has been considerably underutilized as an energy source, it is now emerging as one of the most promising sustainable energy sources. According to [Pilkington, 1996], the entire world can theoretically be supplied with its current needs for electricity from solar power stations covering only 1% of the semi-arid or arid lands on earth. This may be an over estimate, and does not account for the limits of electrical power transport, but it does indicate some of the potential of solar power.

<see figures>

Figure 4: World Insolation Map: (from www.applied-solar.info)

Solar irradiation is the radiation from the sun. *Solar Insolation* is a measure of incident solar irradiation energy received on a given surface area over a given time. It is convenient that many of the areas of the world with most need for desalination have an abundance of solar energy. Many of the arid areas of the world are ideally suited for solar energy harvesting; for example each square meter of land in many sections of the Middle East and North Africa receive 5 to 7 kWh of solar insolation each solar day. By most estimates, these regions yearly receive approx. 1.7-2.2 MWh/m^2 per year (this is megawatt hours of solar power available per square meter per year).

Unfortunately, it has been estimated [Delyannis, 2003] that only approximately 0.02% of desalination capacity is using solar power or any other renewable power source.

3.2 Solar Power systems

Here we give a brief overview of Solar Power systems to provide the context and motivation for solar-powered desalination. We consider two major classes of solar power systems:

(1) *Solar photovoltaic (PV) systems,* which collect solar power and transform this energy into electrical power (see [Chaabane, 2013]). The transformation into electrical energy via conventional steam turbines entails an approximately 45% efficiency loss.

(2) Solar thermal systems, which collect solar power and transfer this to heat energy (perhaps the most extensive surveys on solar thermal systems is [NREL, 2003], and more recent reviews include [Charles, 2005] and [Morin, 2012])

We will argue that solar thermal systems are better suited for application to power desalination, in part because most desalination systems can directly utilize thermal energy with little or no transformation into electrical energy.

3.2a Solar Photovoltaic (PV) Systems

Solar photovoltaic (PV) plants make use of photovoltaic (PV) cells to generate electricity. Many of the most efficient PV plants make use of concentrated solar radiation primarily in the ultraviolet (UV) and visual (VIS) ranges.

High-performance PV arrays (used for example by satellites and other high-value systems) are currently relatively costly per square meter compared to solar thermal systems. Also, compared to solar thermal systems, PV plants generally degrade more rapidly, making them at this time a significantly less preferable choice for large-scale solar power systems than solar-thermal plants.

In certain circumstances PV plants have distinct advantages, such as their capability to provide electrical power in very remote areas far from conventional electrical power sources, and their potential portability.

There are number of negative issues associated with PV plants

(i) A major issue is their **cost-effectiveness**: The National Renewable Energy Laboratory (NREL) of the US Dept. of Energy (DOE) has made a number of cost analyses of PV systems, and concluded that with current PV technology, it was not feasible to ever get a payback period for construction and repair cost within the PV unit's expected functional lifetime. This is because currently operating PV systems produce electricity at a cost (including finance costs for construction and repair) of roughly \$0.12/ kWh, which is two to three times of the current US commercial market price of electricity (per kWh). That implies that a PV system never produces enough electrical energy (priced at competitive commercial rates) to pay for both their initial construction and subsequent repair. *This also implies that the use of PV system to power desalination would be more costly that the use of a conventional electrical source.*

(ii) Another major issue, particularly with respect for use to power desalination, is the issue of **energy storage**: The use of batteries significantly further degrades the cost-effectiveness of PV plants.

Certain Photovoltaic (PV) systems known as *concentrating PV* systems are designed to take concentrated solar energy that is concentrated by a solar concentrating system (see below), and so potentially their cost per meter of incoming solar energy is reduced, but in addition to the *issue of energy storage,* these generally have even shorter life periods non-concentrating PV systems before they significantly degrade.

3.2b Solar Concentrating Systems

A *solar concentrating system* concentrates solar irradiance for conversion into other forms of usable energy; it directs solar irradiance from a relatively large collection field and concentrates it to a smaller receiver area. The concentration ratio is the ratio of the area of the collection field to the receiver area.

A *concentrating solar energy plant* is a solar plant composed of two major parts: a *solar concentrating system*, and a *power-block*, which converts concentrated solar radiation to energy and/or useful products.

Most solar concentrating systems are used for a *solar-thermal-electrical power systems*, which are power systems that collect and concentrate solar thermal energy, and then convert the thermal energy to electrical energy via steam turbines. *Concentrated solar thermal-electrical plants* are solar power plants that make use of solar radiation (primarily in the infrared (IR) range) to generate electricity. Reviews of solar-thermal technology are given in [Becker, 2000], [Elsayed, 1994], [Jackson, 2008], [Morin, 2012], [NREL, 1994], [NREL, 2003], [Pilkington, 1996], [Pitz-Paal, 2012], [Reddy, 1987], [Sargent, 2003], [Thirugnanasambandam, 2010], [Xi, 2012] ([NREL, 2003] provides one of the most extensive surveys, but [Morin, 2012] is more current).

In contrast, we will mostly discuss the use of solar concentrating systems instead for powering desalination. Unfortunately, it has been estimated [Delyannis, 2003] that only approximately 0.02% of desalination capacity is using solar power or any other renewable power source.

3.2b Solar troughs, linear Fresnel concentrators and solar towers

Most of the prior designs for solar concentrating systems in current use make use of solar troughs, linear Fresnel concentrators or solar towers:

<see figures>

Figure 5: Parabolic solar trough concentrator (from Plataforma* Solar *de Almeria (*PSA*))

<see figures>

Figure 6: Flow Schematic of parabolic solar trough concentrator (from [Price, 2002])

The principal solar trough concentrators are:

- *parabolic solar trough concentrators* (see [Becker, 2000], [Elsayed, 1994], [Fernández-García, 2010], [Giostri, 2002], [Jackson, 2008], [NREL, 2003], [NREL, 2004], [Price, 2002], [Price, 2003], [Pilkington, 1996], [Reddy, 1987], and [Sargent, 2003]) and a

- *linear Fresnel concentrators* (see [Morin, 2012] [Xie, 2011).

These are similar: they both consist of a long reflector, which acts as the only concentrator, aligned on a north-south axis with a collector tube running along its length. In a parabolic solar trough concentrator, the cross-section of the reflector is parabolic, whereas in a linear Fresnel concentrator the reflector has Fresnel shape (it is a continuous surface of a parabolic cross-section of the same curvature, with stepwise discontinuities between them). One advantage of these systems is the tracking is primarily only in one dimension. The reflector is rotated to track the sun's movement, and its reflected solar energy is concentrated along a focal line and is captured by its receiver tube, containing a heat absorbing fluid that absorbs the concentrated heat. These systems generally provide a solar concentration ratio that is at most 60:1 to 80:1, which is somewhat of a disadvantage for electrical generation (which is most efficient at the highest thermal concentration ratios) compared to Solar Tower and Dish Designs that generally provide a concentration ratio of 100:1 or higher. However, such a high solar concentration ratio is not a critical issue for powering desalination via heat or pressure, as we discuss below.

- *Solar Tower Designs* consist of multiple *heliostats*, which are moving mirrors that track and concentrate the solar energy so as to continuously focus and concentrate the incoming solar energy upon a centralized collector tower.
- *Solar Dish Designs* (see [Kongtragool, 2003]) utilize parabolic reflectors that concentrate the solar energy to a focus at a Stirling engine that uses the concentrated solar thermal energy to expand and contract a fluid.

Cost-Effectiveness of Solar Concentrators: The *primary concentrators* of a solar concentrator system are those parts that first receive the solar irradiation, and first concentrate it. The majority of the surface area and materials comprising a solar concentrator are generally in its primary concentrators. Since the *primary concentrators* are the parts that collect the solar energy directly, they are far the largest part of any solar concentrating system, and hence the properties of the primary concentrator are key the cost-effectiveness and durability of the solar concentrating systems. It is very important that the primary concentrator be constructed of materials that are not costly. Also, the primary concentrator needs to be very durable and not exposed to horizontal winds if possible. In most designs, the primary concentrator is required to move or track with the movement of the sun.

While solar concentrating systems are a well developed technology, the have a number of technical challenges, some of which increase their cost and limit their durability:

- They require support structures for their *primary concentrators* that are exposed to the weather.
- Their *primary concentrators need to be actively mechanically moved* over each day to track the movement of the sun.
- The *materials composing the primary concentrators need to be relatively high-cost material* that is lightweight enough to be mechanically moved each day and yet strong enough to withstand high winds. In particular, for these prior solar concentrating systems it is not feasible to use very low-cost material for the primary concentrator such as concrete due to its high weight.

Studies of Cost-Performance Analysis of Prior Concentrating Solar Concentrating Systems: A report [NREL, 2003] of the National Renewable Energy Laboratory of the US Dept. of Energy (DOE) made a detailed amortized cost analysis of these current solar concentrating systems when used for electrical generation, which implies a payback period (taking into account costs for construction, finance, and repair) of roughly 15 to 25 years. Similar payback period estimates were subsequently made in [Charles, 2005] for solar-thermal systems (and even higher estimates for payback period can be inferred from the cost and performance [Chaabane, 2013] for concentrating solar photovoltaic systems).

Challenges: *There are a number of challenges for the widespread use of solar concentrating systems to power desalination:*

(1) For deployment in many arid areas these prior solar concentrating systems need to withstand many difficult environmental conditions that are especially challenging: these include high temperatures, high winds and sand storms. The solar concentrating systems developed in the US and Europe were generally not designed for the high winds and sand storms of desert regions in North Africa and the Middle East, and hence would require higher construction and/or repair costs.

(2) The existing solar concentrating systems have primarily been designed for use with steam-turbine electrical generation rather than for desalination systems. The diverse desalination systems described in the next section have various needs to power them ranging from purely pressure, purely heat, or combinations of these over various ranges. Hence the existing solar concentrating systems need to be redesigned for the particular desalination system to be powered. We are not aware of detailed amortized cost analysis for solar concentrating systems when used for powering desalination, and this needs to be done.

4 Desalination Technologies: Their Cost-Effectiveness, Energy-Efficiency, and Challenges

This section provides a brief overview of desalination systems (of which [DESWARE, 2014] is perhaps the most extensive review of desalination technology and extant desalination plants) to provide the context and motivation for solar-powered desalination.

4.1 Overview of Desalination

Desalination is the process of removing salt and other minerals from saline water (e.g., separating the salt content of converting from salt water). The desalination *recovery ratio* is the ratio of the desalinated water volume to the seawater volume.

The energy cost is 0.86 kWh m^{-3} for conversion of seawater with saline content of 34,500 ppm at a temperature of 25^0C [DESWARE, 2014]. The cost for desalination has considerably reduced in recent years, and in the US is approximately \$0.5 m^{-3} to \$1 m^{-3}.

As stated above, many of the countries in the Middle East make extensive use of desalination for fresh water. For example, the Kingdom of Saudi Arabia and the Gulf States are currently almost completely dependent on desalination for much of its water needs, and this incurs considerable use of nonrenewable energy. The Shoaiba Desalination Plant in Saudi Arabia constructed in 2003 was at the time the world's largest desalination plant with a capacity of 150 million m^3/year. This desalination plant uses non-renewable power is from oil-fired turbines, and also makes use of the resulting heat to power seawater distillers.

This illustrates the challenge for oil and natural gas producing countries in the Middle East, which are dependent on: their energy reserves are being squandered by their need for very energy-costly desalination. This motivates their need for solar-powered desalination. As a side effect of this need for desalination, the countries in the Middle East have considerable academic and industrial expertise in desalination, including solar-powered desalination, as will be evident from our papers references.

Desalination (using nonrenewable power) is described in the following:

- Principals of desalination are given in [Crittenden, 2000], [El-Dessouki, 2002], [El-Dessouki, 2008], [Shanmugam, 2004], [Watson, 2003], [Trussell, 2005].
- Seawater desalination is described in [Al-sofi, 2011], [Alawaji, 2007], [Al-Sahlawi, 1999], [Mickols, 2005], [Elimelech, 2011].
- Case studies for given locations include: Saudia Arabia [Al-Sahlawi, 1999], [Abdul Azis, 2000], Kuwait [Finan, 2003], California [Erik, 2011].
- Study of the environmental costs of desalination is given in [Purnamaa, 2005]
- Industrial status reports for extant desalination plants are given in [DESWARE, 2014], [Fried, 2011], [NRC, 2008]

We will now overview the most important classes of large-scale desalination systems (intentionally ignoring solar stills, since they are much smaller scale), and noting the challenges associate with powering these with solar power.

4.2 Solar-Thermal Desalination Systems

Concentrated solar thermal-desalination plants are solar power plants that make use of solar radiation primarily in the infrared (IR) range to power the desalination of salt water to fresh water. The most modern solar-thermal desalination systems generally produce concentrated heat energy, which is used to create pressurized steam, which is used to power reverse osmosis desalination systems. This is the process our proposed solar thermal-desalination system will use.

The use of concentrated solar thermal-desalination plants provides an exciting opportunity to construct in future much larger and more efficient desalination plants. Hence the design of energy-efficient, low-cost solar concentrating systems is of potentially critical importance.

Solar-powered desalination is described in the following:

- Reviews of Solar-powered desalination are given in [Delyannis, 2003], [Delyannis, 1987], [Delyannis, 2000], [Eltawil, 2008], [Garcia-Rodriguez, 2002], [Eltawil, 2009], [Goosena, 2000], [Gude, 2010], [Kalogirou, 2005], [Mathioulakis, 2007], [MED-CSD, 2010], [MED-CSD, 2010], [Mu̇ller-Holst, 1998], [Qiblawey, 2008], [Schillings, 2007], [Sethi, 2012].

- PV-powered desalination is described in [Alawaji, 1995]. [Al-Karaghouli, 2010], [Al-Karaghouli, 2011], [Ghermandi, 2009], RO [Gwillim, 1996], [Hasnain, 1998], [Peterson, 2012], [Poovanaesvaran, 2011], [Thomson, 2003].

- Solar-concentrator-powered desalination is described in [Bardi, 2008], [Blanco, 2003], [Chafik, 2003], [Chaouchi, 2007], [El-Nashar, 1992], and [Scrivani, 2007].

- Studies of desalination systems in Saudi Arabia and their feasibility for solar powering these plants are given in [Al-Karaghouli, 2004, 2010, 2011], [Alawaji, 2007], [Al-Sahlawi, 1999], [l-Dessouki, 2008], [Eltawil, 2008, 2009], [Ghermandi, 2009], and [Kalogirou, 2005]. A study of an experimental implementation of a solar-concentrator-powered desalination system in Saudi Arabia is given in [l-Harbi, 2011].

4.3 Electrodialysis: Another related membrane-base desalination process is known as Electrodialysis (ED) (see [Strathmann,1992], [Strathmann, 2004], [Sata, 2004],. It works by setting an electrical potential difference between two *ion-exchange* membranes in contact with the feed water, which causes the transfer of salt ions from the feed water through the membranes (the negatively charged chlorine ions go through the membrane to a positively charged chamber and the positively charged sodium ions go through the membrane to a negatively charged chamber). However, this process requires electrical power, and hence is less efficient for use with solar concentrators that would have to generate electrical power from the heat energy they harvest.

4.4 Overview of Reverse Osmosis Desalination Systems

<see figures>

Figure 7: Reverse Osmosis (RO) Filtration (from [Kalogirou, 2005])

Currently RO is one of the most efficient technologies for desalination and is used in approximately 59% of all desalination systems worldwide [Widiasa, 2009].

The energy use for RO distillation of seawater is 3-5.5 kWh m^{-3} [DESWARE, 2014]. This method makes use of pressure to force the salt water through reverse osmosis filtration systems ([Crittenden, 2005]). It requires application of a pressure in excess of the osmotic pressure (seawater that has salinity of 35 g/kg has an osmotic pressure of about 25 bar), which forces the pure water component of saline water through a semipermeable membrane: the membrane generally contains a polymer matrix which excludes the flow of salt and other minerals but allows the flow of pure water. RO filtration technology is highly developed, and is generally considered at this time the most efficient method for desalination. Highly efficient RO filtration systems for desalination are commercial available.

Description of RO desalination without use of renewable power are given in:

- A review of RO desalination is given in [Widiasa, 2009].

- [Wagner, 2002] gives a handbook on membrane filtration, including RO.

- Energy analysis for RO desalination is given in [Song, 2011].

- RO systems in various locations are described and analyzed for Saudi Arabia ([Almudaiheem, 1998], [Alawaji, 2007], [Al-Mutaz, 2006]) and Egypt ([Hafez, 2002]).

- Studies of experimental system in Saudi Arabia are given in [Baig, 1998], [Khawaji, 2007].

In many of these modern systems, up to 98% energy recovery of pressurization energy is made by use of isobaric energy recovery systems which pre-pressurize the input, by placing the concentrate reject and input (seawater or brackish water) in contact together in isobaric chambers. Energy recovery systems for RO desalination are given in [Al-Hawaj, 2003], [Andrews, 2001], [Farooque, 2004], [Farooque, 2008], [Harris, 1999], [Leandro, 2008], [MacHarg, 2003], [Migliorini, 2004], [Pen˜ateB, 2011], [Oklejas, 2007], [Rahman, 2011], [Rayana, 2002], [Rybar, 2010], [Stover, 2007], [Stover, 2007], [Wilf, 2005], [William, 2001], [Zhou, 2004].

Prior to the osmosis filtration, seawater preparation may be required involving preliminary filtration steps to eliminate for example organic matter in the seawater, which are reduced for lower recovery ratios. A low recovery ratio increases the desalination efficiency, whereas a high recovery ratio increases seawater preparation efficiency. Hence the recovery ratio is set to optimize the energy for these two tasks. In the case of variable pressurization (as in the case of pressurization from a solar concentrator with variable insolation), the recovery ratio may have to be reset dynamically.

RO desalination can be driven either by PV electrical generators or by pressurization energy from solar-thermal concentrator systems. Reviews are given in [Sampathkumar, 2010], [Verdier, 2011], and

- A feasibility study of brackish water desalination using PVis is given in [Schmid, 2002].
- A demonstration study for Jordan is given in [Mohsena, 1999].

In the case where a solar concentrator system is used to provide the power for a reverse osmosis desalination system, there are various considerations:

(1) Only Moderate Pressure (approximately 55 bar) is Required for Reverse Osmosis Filtration: Pressurization energy on the high concentration side of the membrane is required to power reverse osmosis desalination: this pressure is for seawater is approx. 55 bar, and for brackish water can range between 10 to 15 bar. (Recall that a bar is a unit of pressure that is approximately the atmospheric pressure at sea level, or about 15 psi.) This 55 bar for seawater is much less pressure than required for driving high-performance steam turbines used for electrical generation, which require pressure ranging from at least 75 bar to 120 bar. *This implies that a solar concentrator system (that powers the Reverse Osmosis Filtration) needs a much lower concentration ratio (only approximately 15-20) than would be the case where the solar concentrator was used for steam turbines used for electrical generation.*

(2) ***Energy Required for Reverse Osmosis Filtration Pressurization:*** In high efficiency reverse osmosis systems energy recovery and pressure conversion devices are used, resulting in approximate pressurization energy requirement of approx. 2.5 kWh/m^3 for seawater desalination. *The pressurization energy required by even the most efficient reverse osmosis filtration system is therefore considerable, and this motivates the goal of use of solar energy for this task, rather than valuable non-renewable energy reserves.*

Note: Various types of filtration (including microfiltration, ultrafiltration and nanofiltration) are applied for pretreatment of seawater or brackish water prior to reverse osmosis desalination, and post-treatment after typically involves (i) adding Ca or Na salts to stabilize the pH, (ii) removal of dissolved CO2 and other gases. These pretreatment filtrations can use the pressurization provided by a solar-thermal concentrating system. The post-treatment consume much less energy compared to the desalination process, but so can cost-effectively use conventional energy sources.

4.5 Solar-Thermal to Steam Pressurization Technology

The *power block* of a solar energy system converts concentrated solar energy into forms of usable energy, which may include electrical energy, but it the context of this paper is pressurization, providing energy for desalination of seawater or brackish water (conversion to pure water). In the context of this paper work, where the goal is solar desalination, the power block provides for heat energy and/or pressurization.

Steam pressurization systems using heat energy: The technology for producing pressurization from heat energy is very well established due to their use many prior industrial applications. For example, in a steam engine, the pressure vessel [Steingress, 2003] of the steam engine boiler is heated from externally applied heat energy and as a consequence, the steam within the pressure vessel is pressurized (in the case of a steam engine, this pressurized steam is subsequently released to generate mechanical energy). As another example, for solar-thermal-electrical generators, the pressure vessel is heated from heat energy obtained from a solar concentrator, and the resulting pressurized steam is harnessed to drive a steam turbine electrical generator (note that there can be very high pressure requirements to drive high-performance steam turbine electrical generators, and so they often operate as ultra-pressurization systems, where the entire pressurization cycle is in the steam state, rather than water to steam). Both of these example steam pressurization systems also include a cooling cycle to cool and return the steam.

In contrast, for solar-desalination applications of interest here, the pressurization to drive desalination can make use of a pressure vessel that is heated using heat energy obtained from a solar concentrator; the pressurized steam is then released to drive the (reverse osmosis) desalination process. Again, system also needs to include a cooling cycle to cool and return the steam.

As noted above, saltwater reverse osmosis desalination requires only moderate pressure of approximately 55 bar, and such use of conventional heated pressure vessels can be used to achieve this pressure (without necessary needing ultra-pressurization technology).

Lower Solar Concentration Ratios needed for solar-desalination applications: Since the application of solar-desalination requires only moderate pressure of approximately 55 bar to drive the reverse-osmosis process, and so the solar concentrator needs a considerably lower concentration ratio of in the range of approximately 15:1 to 20:1. It is important to note that this solar concentration ratio is much less than needed for solar-thermal-electrical applications (which use very high solar concentration ratios of approx. 60:1 to 75:1 to produce very highly pressurized steam to drive high performance steam turbines).

4.6 Multi-Effect Desalination (MED) and Mult-Stage Flash (MSF) Desalination

In both Multi-Effect Desalination (MED) and Multi-Stage Flash (MSF) Desalination methods, the high saline feed water is sent through a series of evaporator tubes with decreasing heat and pressure.

<see figures>

Figure 8: Design for MED desalination system using boilers (from [Kalogirou,2005])

In the MED method (also known as MEB for its use of boilers), each of the evaporator tubes is heated (by the solar thermal energy in our applications) to produce steam, which is condensed by the following evaporator, where steam also is produced, until reaching the final condenser where the steam is cooled by the incoming seawater or brackish water. The energy use for MED of seawater is 6.5-11 kWh m^{-3} [DESWARE, 2014]. In very large desalination systems, MED may be competitive to reverse-osmosis desalination, and may be appropriate for large-scale deployments of solar-powered desalination systems.

<see figures>

Figure 9: Design for MSF desalination system (from [Kalogirou, 2005])

In the MSF method, the chambers are evacuated to produce vapor. Either method can be nearly as efficient as reverse-osmosis desalination, and together are used in approximately 40% of all large-scale distillation systems. The energy use for MSF distillation of seawater is 13.5-25.5 kWh m^{-3} [DESWARE, 2014], which is far above the more efficient implementations of RO and MED.

4.7 Vapor Compression (VP) Desalination

In Vapor Compression (VP) desalination the saline water feed is vaporized, and condensed with via mechanical or pressure means. The energy use for VP desalination of seawater is 7-12 kWh m^{-3} [DESWARE, 2014]. VP desalination is limited in scale due to limits in the size and cost of large vapor chambers, so not discussed here in detail.

4.8 Solar Stills

Solar stills convert the humidity in the air into fresh water, using solar energy.

- Techniques for solar stills are described in [Tygarinov, 1947], [Abualhamayel, 1997], [Bar, 2004], [Beckmann, 2005], [Beckman, 1999], [EL-Sharkawy, 2000], [Gad, 2001], [Habeebullah, 2009], [Kabeel, 2007], [Kobayashi, 1981], [Sofrata, 1981], [Sultan, 2004].
- In more advanced systems, sorbents (see [Aristov, 1999], [Gordeeva, 1998], [Hamed, 2000a], [Hamed, 2000b], [Hamed, 2003], [Wang, 2007]) are used to facilitate the cycle of capturing the condensation, and then to releasing the condensation.
- Reviews of solar still technology are given in [Bourouni, 2001], [Hamed, 2010], [Hamed, 2011], [Prakash, 2010], [Roland, 2001], [Wahlgren, 2001].
- Experiments, demonstrations, performance analysis are described in [Al-hassan, 2009], [Al-Hallaj, 1998], [Al-Karaghouli, 2004a], [Al-Karaghouli, 2004b], [Ben-Bacha, 2003], [Elsarrag, 2011], [Jacobs, 2008], [Kabeel, 2006], [Khalil, 1993]. Modeling of solar stills is given in [Bacha, 1999], [Farid, 2002].

Unfortunately, current designs for solar stills do not scale well to large systems, and it remains a challenge to redesign them for large scale solar-powered desalination system.

4.8 Application of Solar-Powered Desalination

The Attractive Opportunity of Using Solar Energy to Power Reverse Osmosis Filtration Pressurization: Recall from above that approx. 2.5 kWh m^{-3} is required for the most efficient RO distillation. Recall that the other counties of the Middle East and North Africa receive approx. 2 MWh/m^2 insolation per year. A system for converting this solar energy to pressurization energy, even with relatively low conversion efficiency of say 25%, would provide approximately 0.5 MWh/m^2 pressurization energy per year, which would result in the production of approximately 250 m^3 of desalinated water per m^2 of solar collection area per year.

Hence a mega-size solar-desalination system with solar collection area of area 1,000 m x 1,000 m =1,000,000 m^2 and efficiency of 25% would provide the production of approx. 250,000,000 m^3 of desalinated water of solar collection area per year without expenditure of nonrenewable energy sources.

Cultivation of crops such as wheat requires an annual water budget of approx. 60 cm of water per year, which is a volume of 0.6 m^3 water per m^2 of land area per year. *This implies that only a small proportion 0.6/250 = 0.24% of the land area needs to be devoted to harvesting solar energy to be able to convert the land to productive croplands.*

5. Conclusions and Technical Challenges to Solar-Powered Desalination

5.1 Conclusions.

In this paper we compared the cost-effectiveness, energy-efficiency, and other relevant quantities of these potential solar-desalination systems, and concluded that the direct solar-desalination systems using solar-thermal collectors appear to be most attractive for highly energy-efficient solar-desalination systems, although there are significant technical challenges remaining. Further, we overviewed the economics and practical issues associated with employing cost-effective solar-desalination systems to provide for economic water sources for urban and also agricultural areas. We considered factors that have significant impact to these solar-desalination systems: including location, climate, and access to ocean water or brackish water sources, as well as land-use and ecological issues. We observe that the most favorable locations are those with high solar irradiance, lack of fresh water but access to large brackish water sources and/or seawater. The most favorable locations appear to include considerable sections of North and East Africa, the Middle East, Southern Europe, Western South America, Australia, Northern Mexico, and South-West USA; each has particular issues and challenges unique to their location. Nevertheless, we conclude that the development of cost-effective and energy-efficient solar-desalination systems may well be key to a future “terraforming” of otherwise desert and near-desert regions of the world, providing a “greening” of these regions.

5.2 Technical Challenges to Solar-Powered Desalination

There are many technical challenges to obtaining cost-effective and energy-efficient solar-powered desalination systems.

5.2a Need to tailor solar power technologies to powering desalination:

One major issue is that solar power technologies were not originally developed with powering desalination, and instead generally were developed with the goal of providing electrical energy. For example, photovoltaic (PV) systems by definition convert solar power to electrical energy. Also, solar-thermal systems generally harvest heat energy, and convert this heat energy to electrical energy via steam turbines, and this conversion electrical energy entails an approximately 40% loss. However, many desalination systems can be powered by pressure or heat energy directly, without major use of electrical energy. As a result, there are considerable technical challenges to adapting solar energy systems to power desalination systems.

5.2b Need to avoid hyperbole and face the challenges: Another challenge to the proper development of cost-effective and energy-efficient Solar-Powered Desalination systems is not so much technical as it is intellectual. The issue is that promoters (e.g., some private solar power corporations) of solar-technologies have sometimes optimistically overstated the efficiencies and cost-efficiency of solar technologies, and also of solar-powered desalination systems. As a result, there is an under-appreciation of the technical challenges involved to insure the systems are cost-effective and energy-efficient. Evidence of this disconnect is the deployment of some large systems of desalination systems powered by PV systems, which are neither cost-efficient nor energy-efficient. To its credit, the National Renewable Energy Lab (NREL) of the US Department of Energy (DOE) has been quite forthright on cost and energy-efficiency analysis of solar-powered systems.

Also, the deployment of Solar-Powered Desalination systems in remote arid regions entails some considerable risk, requiring considerable further R&D.

5.3c Need for better determination of saline and brackish water reserves: Finally, although there is excellent knowledge of the geographical location in the world with high solar insolation, desalination systems also require adequate sources of seawater, or better still brackish water with a lower saline content. [Garcia-Rodriguez, 2002] has estimated the energy costs of conventional desalination of seawater, where as desalination of brackish water entails considerably lower energy cost for desalination. Hence, there is a need for more knowledge of brackish water reserves; what is needed is a detailed world map of brackish water reserves. Unfortunately, since certain brackish water reserves can also be associated (via salt domes and other geological features) with petroleum and natural gas reserves, the maps of brackish water reserves are sometimes made proprietary.

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6. References

The references have been separated into distinct topics, as listed below:

6.1 References for Solar-Thermal Technology

[AbKadir, 2010] AbKadir MZA, Rafeeu Y, Adam NM. Prospective scenarios for the full solar energy development in Malaysia. Renewable and Sustainable Energy Reviews 2010;14:3023–31.

[Alawaji, 1999] Alawaji SH, Hasanain SM. Role of solar energy research in transferring of technology to Saudi Arabia. Energy Sources 1999;21(934):923.

[Alawaji, 2001] Alawaji SH. Evaluation of solar energy research and its applications in Saudi Arabia—20 years of experience. Renewable and Sustainable Energy Reviews 2001;5:59–77.

[Al-Abbadi, 2002] Al-Abbadi NM, Alawaji SH, Bin Mahfoodh MY, Myers DR, Anderberg M. Saudi Arabian solar radiation network operation data collection and quality assessment. Renewable Energy 2002;25:219–34.

[Becker, 2000] M. Becker, W. Meinecke, M. Geyer, F. Trieb, M. Blanco, M. Romero, and A. Ferrière, Solar Thermal Power Plants, EUREC-Agency, May 03, 2000.

[Chaabane, 2013] Monia Chaabane, Wael Charfi, Hatem Mhiri, Philippe Bournot, Performance evaluation of concentrating solar photovoltaic and photovoltaic/thermal systems, Solar Energy 98 (2013) 315–321.

[Charles, 2005] Robert P. Charles, Kenneth W. Davis, Joseph L. Smith, “Assessment of Concentrating Solar Power Technology Cost and Performance Forecasts”, Presented at Electric Power 2005, April 5-7, 2005.

[Elsayed, 1994] Elsayed, Moustafa M. Ibrahim S. Taba, and Jaffar A. Sabbagh, Design of Solar Thermal Systems, Scientific Publishing Center, King Abdulaziz University, Saudi Arabia, 1994 AD (1414 AH) ISBN : 2-001-06-9960

[Fernández-García, 2010] A. Fernández-García, E. Zarza, L. Valenzuela, M. Pérez-García, Parabolic-trough solar collectors and their applications, Renewable and Sustainable Energy Reviews (Impact Factor: 5.63). 09/2010; 14(7):1695–1721. DOI:10.1016/j.rser.2010.03.012

[Giostri, 2002] Andrea Giostri, Marco Binotti, Marco Astolfi, Paolo Silva, Ennio Macchi, Giampaolo Manzolini, Comparison of different solar plants based on parabolic trough technology, Solar Energy, Volume 86, Issue 5,, Pages 1208-1221 (May 2012).

[Jackson, 2008] S. Jackson. Overview of Solar Thermal Technologies. US Department of Energy (DOE). DOE/EPRI Technology Characterization. Global Solar Thermal Energy Council, (2008). Web address of document: http://www.solarthermalworld.org/node/30

[Kongtragool, 2003] Bancha Kongtragool, Somchai Wongwises, A review of solar-powered Stirling engines and low temperature differential Stirling engine, Renewable and Sustainable Energy Reviews, Volume 7, Issue 2, Pages 131-154 (April 2003).

[Morin, 2012] Gabriel Morin, Jürgen Dersch, Werner Platzer, Markus Eck, Andreas Häberle, Comparison of Linear Fresnel and Parabolic Trough Collector power plants, Solar Energy, Volume 86, Issue 1, Pages 1-12 (January 2012).

[Moustafa, 1994] Moustafa M. Elsayed, Ibrahim S. Taba, and Jaffar A. Sabbagh, Design of Solar Thermal Systems, Scientific Publishing Center, King Abdulaziz University, Saudi Arabia, 1994 AD (1414 AH) ISBN : 2-001-06-9960

[Pilkington, 1996] Pilkington. Status Report on Solar Trough Power Plants. Cologne, Germany, Chapter 3.1, (1996).

[NREL, 2003] National Renewable Energy Laboratory(NREL) staff members, Concentrated Solar Power (CSP) Resource Potential, Figure 12, US Department of Energy (DOE), National Renewable Energy Laboratory(NREL). (Apr 29 2003). Web address of document: http://www.eia.doe.gov/cneaf/solar.renewables/ilands/fig12.html

[NREL, 1994] National Renewable Energy Laboratory(NREL) staff members, Concentrated Solar Power (CSP) Resource Potential, Figure 12, US Department of Energy (DOE), National Renewable Energy Laboratory(NREL). (Apr 29 2003). Web address of document: http://www.eia.doe.gov/cneaf/solar.renewables/ilands/fig12.html

[Pilkington, 1996] Pilkington. Status Report on Solar Trough Power Plants. Cologne, Germany, Chapter 3.1, (1996).

[Pitz-Paal, 2012] Robert Pitz-Paal et al., Concentrating Solar Power in Europe, the Middle East and North Africa: A Review of Development Issues and Potential to 2050, Journal of Solar Energy Engineering. 134, 024501 (2012).

[Price, 2002] Hank Price, Eckhard Lu¨pfert, David Kearney, Eduardo Zarza, Gilbert Cohen Randy Gee, Rod Mahoney, Advances in Parabolic Trough Solar Power Technology, Journal of Solar Energy Engineering, MAY 2002, Vol. 124, pp 109-126. DOI: 10.1115/1.1467922

[Price, 2003] H. Price, D. Kearney, Reducing the Cost of Energy from Parabolic Trough Solar Power Plants, ISES 2003: International Solar Energy Conference Hawaii Island, Hawaii, March 16–18, 2003.
[Pilkington,1996] Pilkington. Status Report on Solar Trough Power Plants. Cologne, Germany, Chapter 3.1, (1996).

[Reddy, 1987] Reddy, T. Agami,The Design and Sizing of Active Solar Thermal Systems, Oxford University Press, USA (September 3, 1987) ISBN-10: 0198590164 | ISBN-13: 978-0198590163 |

[Sargent, 2003] Sargent and Lundy LLC Consulting Group, Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts. National Renewable Energy Laboratory, Chicago, Illinois, (October 2003).

[Thirugnanasambandam, 2010] Mirunalini Thirugnanasambandam, S. Iniyan, Ranko Goic, A review of solar thermal technologies, Renewable and Sustainable Energy Reviews, Volume 14, Issue 1, Pages 312-322 (January 2010).

[Ummel, 2008] Ummel K, Wheeler D. Desert power: the economics of solar thermal electricity For Europe. North Africa, and the Middle East Center for Global Development; 2008.

[Xi, 2012] Hongxia Xi, Lingai Luo, Gilles Fraisse, Development and applications of solar-based thermoelectric technologies, Renewable and Sustainable Energy Reviews, Volume 11, Issue 5, Pages 923-936 (June 2007).

[Xie, 2011] W.T. Xie, Y.J. Dai, R.Z. Wang, K. Sumathy, Concentrated solar energy applications using Fresnel lenses: A review, Renewable and Sustainable Energy Reviews, Volume 15, Issue 6, Pages 2588-2606 (August 2011).

6.2 References for Desalination (using Nonrenewable Power):

[Abdul Azis, 2000] P. K. Abdul Azis, Ibrahim Al-Tisan, Mohammad Al-Daili, Troy N. Green, Abdul, Ghani I. Dalvi and M. A. Javeed. Effects of Environment on Source Water for Desalination Plants on the Eastern Coast of Saudi Arabia. Desalination 132 (2000) 29-40

[Al-Sahlawi, 1999] Al-Sahlawi MA. Sea water desalination in Saudia Arabia: economic review and demand projection. Elsever Desalination 1999;123:143–7.

[Al-sofi, 2011] Al-sofi MAK. Sea water desalination—SWCC experience and vision. Desalination 2001;135:121–39. El-Sadek A. Water desalination: an imperative measure for water security in Egypt. Elsever Desalination 2010;250:876–84.

[Alawaji, 2007] Alawaji SH, Kutubkhanah IK, Wie JM. Advances in seawater desalination technologies. Desalination 2007;221:47–69.

[Al-Sahlawi, 1999] Al-Sahlawi MA. Sea water desalination in Saudia Arabia: economic review and demand projection. Elsever desalination 1999;123(143):147.

[Crittenden, 2000] Crittenden, John; Trussell, Rhodes; Hand, David; Howe, Kerry and Tchobanoglous, George. Water Treatment Principles and Design, Edition 2. John Wiley and Sons. New Jersey. 2005 ISBN 0471110183

[DESWARE, 2014] Encyclopedia of Desalination and Water Resources (DESWARE), Energy requirements of desalination processes, www.desware.net/desa4.aspx

[Elimelech, 2011] Menachem Elimelech, William A. Phillip. The Future of Seawater Desalination: Energy, Technology, and the Environment. DOI: 10.1126/science.1200488, Science 333, 712 (2011);

[El-Dessouki, 2002] El-Dessouki HT, Ettouney HM. Fundamentals of salt water desalination. Elsevier Science B.V.; 2002.

[El-Dessouki, 2008] El-Dessouki HT, Ettouney HM. Fundamentals of salt water desalination. Elsevier Science B.V; 2002. Desalination: a national perspective. Committee on Advancing Desalination Technology, Water Science and Technology Board, Division on Earth and Life Studies, National Research Council of the National Academies; 2008.

[Erik, 2011] Erik D, Juan MP. A case study: energy use and process design considerations for four desalination projects in California. In: IDA World Congress – Perth Convention and Exhibition Centre (PCEC). 2011.

[Finan, 2003] Ashley Finan, Mujid S. Kazimi. Potential Benefits of Innovative desalination Technology Development in Kuwait, manuscripts, 2003.

[Fried, 2011] Fried A. Water industry segment report desalination. The World Trade Center San Diego; 2011. /www.wtcsd.orgS.

[Mickols, 2005] Mickols WE, Busch M, Maeda Y, Tonner J. A novel design approach for seawater plants. In: Proceedings of the International Desalination Association World Congress. 2005. EPP-SWRO Desalination Plant Operation Manual.

[NRC, 2008] National Research Council (NRC) of the national academies, Water Science and Technology Board, Division on Earth and Life Studies. Desalination: a national perspective, committee on advancing desalination technology.; 2008.

[Shanmugam, 2004] Shanmugam, G, Jawahar, GS, Ravindran, S. Review on the uses of appropriate techniques for arid environment. International Conference on Water Resources and Arid Environment, 2004. .

[Purnamaa, 2005] Anton Purnamaa, H. H. Al-Barwania, Ronald Smithb. Calculating the environmental cost of seawater desalination in the Arabian marginal seas. Conference on Desalination and the Environment, Santa Margherita, Italy, 22–26 May 2005. European Desalination Society.

[Watson, 2003] Watson IC, Morin PO, Henthorne JPL. Desalting handbook for planners. Desalination research and development program report no. 72. 3rd edition 2003.

[Mohsena, 1999] Mousa S. Mohsena, Odeh R. Al-Jayyousib. Brackish water desalination: an alternative for water supply enhancement in Jordan, Desalination 124 (1999) 163–174

[Sampathkumar, 2010] K. Sampathkumar, T.V. Arjunan, P. Pitchandi, P. Senthilkumar, Active solar distillation—A detailed review, Renewable and Sustainable Energy Reviews, Volume 14, Issue 6, Pages 1503-1526 (August 2010).

[Sata, 2004] Sata, T., Ion Exchange Membranes: Preparation, Characterization, Modification and Application, Royal Society of Chemistry, London, 2004.

[Schmid, 2002] Ahmad G, Schmid J. Feasibility study of brackish water desalination in the Egyptian deserts and rural regions using PV systems. Energy Conversion and Management 2002;43(2002):2641–9.

[Strathmann,1992] Strathmann, H., "Electrodialysis", in Membrane Handbook, W.S.W. Ho and K.K. Sirkar, eds., Van Nostrand Reinhold, New York, 1992.

[Strathmann,2004] Strathmann, H., Ion-Exchange Membrane Separation Processes, Elsevier, New York, 2004.

[Trussell, 2005] Crittenden, John; Trussell, Rhodes; Hand, David; Howe, Kerry and Tchobanoglous, George. Water Treatment Principles and Design, Edition 2. John Wiley and Sons. New Jersey. 2005 ISBN 0471110183

[Verdier, 2011] Verdier F. MENA Regional Water Outlook. Part II desalination using renewable energy. Task-1–Desalination Potential Fichtener; 2011. http://www. Fichtner. deS.

6.3 References for Reverse Osmosis Water Desalination (using Nonrenewable Power):

[Alawaji, 2007] Alawaji AD, Kutubkhanah IK, Wie JM. A 13.3 MGD seawater RO desalination plant for Yanbu Industrial City. Desalination 2007;203:176–88.

[Al-Hawaj, 2003] Al-Hawaj OM. The work exchanger for reverse osmosis plants. Desalination 2003;157:23–7.

[Almudaiheem, 1998] Almudaiheem RS, Alyousef SO, Sharif T, Amirul Islam AKM. Performance evaluation of ten years operation experience of brackish water RO desalination in Manfouha plants, Riyadh. Desalination 1998;120:115–20, Elsevier.

[Al-Mutaz, 2006] Al-Mutaz Ibrahim S, Al-Khudhiri Abdullah I. Optimal design of hybrid MSF/RO desalination plant. Master of Science in Chemical Engineering. Kingdom of Saudi Arabia: College of Engineering, King Saud University; 2006.

[Andrews, 2001] Andrews W T,Laker D S. A twelve-year history of large scale application of work- exchanger energy recovery technology. Desalination 2001;138:201–6.

[Baig, 1998] Baig MB, Al Kutbi AA. Design features of a 20 migd SWRO desalination plant, Al Jubail, Saudi Arabia. Desalination 1998;118:5–12.

[Farooque, 2004] Farooque AM, Jamaluddin ATM, Al-Reweli AR. Comparative Study of Various Energy Recovery Devices used in SWRO Process. Saline Water Desalination Research Institute, Saline Water Conversion Corporation (SWCC), 2004

[Farooque, 2008] Farooque A. Parametric analyses of energy consumption and losses in SWCC SWRO plants utilizing energy recovery devices. Desalination 2008;219:137–59.

[Hafez, 2002] Hafez A, El-Manharawy S. Economics of seawater RO desalination in the Red Sea region, Egypt. Part 1. A case study. Desalination 2002;153:335–47.

[Harris, 1999] Harris C. Energy recovery for membrane desalination. Desalination 1999;125:173–80.

[Khawaji, 2007] I. .Khawaji AD, Kutubkhanah IK, Wie JM. A 13.3 MGD seawater RO desalination plant for Yanbu Industrial City. Desalination 2007;203:176–88.

[Leandro, 2008] Leandro S. Performance Curves, Positive Displacement, Pressure Exchangers, PX-220. Doolittle, CA, USA: Energy Recovery Inc. (ERI); 2008.

[MacHarg, 2003] MacHarg JP. Retro-fitting existing SWRO systems with a new energy recovery device. Desalination 2003;153:253–64.

[Migliorini, 2004] Migliorini G, Luzzo E. Seawater reverse osmosis plant using the pressure exchanger for energy recovery: a calculation model. Desalination 2004;165:289–98.

[Pen˜ateB, 2011] Pen˜ateB, García-Rodríguez L .Energy optimization of existing SWRO (seawater reverse osmosis) plants with ERT (energy recovery turbines): technical and thermo-economic assessment. Energy 2011;36:613–26.

[Oklejas, 2007] Oklejas Jr E, Kadaj E. An integrated feed pump–recovery turbine reduces energy consumption and capital costs of brackish water RO systems. In: Proceedings of the American Membrane Technology Association Conference and Exposition. 2007.

[Rahman, 2011] M.M. Rahman, C. Lusk, M.J. Guirguis, Energy Recovery Devices in Seawater Reverse Osmosis Desalination Plants with Emphasis on Efficiency and Economical Analysis of Isobaric versus Centrifugal Devices, Master Degree of Science, University of South Florida, 2011.

[Rayana, 2002] Rayana MA, Khaled I. Seawater desalination by reverse osmosis (case study). Desalination 2002;153:245–325.

[Rybar, 2010] Rybar S, Boda R, Bartels C. Split partial second pass design for SWRO plants. Desalination and Water Treatment 2010;13:186–94.

[Song, 2011] Song L. Energy analysis and efficiency assessment of reverse osmosis desalination process. Desalination 2011;276:352–8.

[Stover, 2007] Stover RL. Sea water reverse osmosis with energy recovery devices. Desalination 2007;203:168–75.

[Stover, 2007] Stover RL. Energy Recovery Inc., Energy Recovery Device Performance Analysis, Water Middle East, 2005. Water Middle East, Bahrain. Plant Design and Performance with PX Pressure Exchanger Technology. Water Middle East, Bahrain: The New Qidfa and Al Zawrah SWRO Plants; 2007.

[Wagner, 2002] Wagner J. Membrane filtration handbook: practical tips and hints. Osmonics, Inc.; 2001 FILMITEC reverse osmosis membranes technical manual. Dow Water & Process Solutions.

[Widiasa, 2009] Widiasa N, Paramita V, Kusumayanti H. BWRO desalination for potable water supply enhancement in coastal regions. Journal of Coastal Development 2009;12(2):81–8.

[Wilf, 2005] Mark Wilf, Craig Bartels. Optimization of seawater RO systems design
Desalination, 2005

[William, 2001] William T, Andrews DSL. A twelve-year history of large scale application of work-exchanger energy recovery technology. Desalination 2001;138:201–6.

[Zhou, 2004] Yuan Zhou, Richard S.J. Tol Evaluating the costs of desalination and water transport

6.4 References for Solar-Powered Desalination:

[Alawaji, 1995] Alawaji S, Smiai MS, Rafique S. PV-powered water pumping and desalination plant for remote areas in Saudi Arabia. Applied Energy 1995;52:283–9, Elsevier.

[Al-Karaghouli, 2010] Al-Karaghouli A, Kazmerski LL. Economic analysis of a Brackish Water Photovoltaic-Operated (BWRO-PV) desalination system. Colorado 80401, USA: National Renewable Energy Laboratory Golden; 2010.

[Al-Karaghouli, 2011] Al-Karaghouli A, Kazmerski LL. Renewable energy Opportunities in water desalination. Golden, Colorado, 80401, USA: National Renewable Energy Laboratory (NREL); 2011.

[Bardi, 2008] Bardi U. Fresh water production by means of solar concentration: the AQUASOLIS project. Desalination 2008;220:588–91.

[Beysens, 2000] Beysens D, Milimouk I. The case for alternative fresh water sources pour les ressources alternatives en eau. Se´ cheresse 2000;11:4.

[Blanco, 2003] Julián Blanco, Diego Alarcón, Bernardo Sánchez, Sixto Malato, Manuel I. Maldonado, Astrid Hublitz, Markus Spinnler, Technical Comparison of Different Solar Assisted Heat Supply Systems for a multi-effect Seawater distillation unit, June, 14-19, 2003, ISES Solar World Congress 2003 Göteborg, Sweden, Solar Energy for a Sustainable Future

[Chafik, 2003] Chafik E. A new type of seawater desalination plants using solar energy. Desalination 2003;156:333–48.

[Chaouchi, 2007] Béchir Chaouchi, Adel Zrelli, Slimane Gabsi, Desalination of brackish water by means of a parabolic solar concentrator, Desalination 217 (2007) 118–126.

[Delyannis, 2003] E. Delyannis, Historic background of desalination and renewable energies, Solar Energy 75 (2003) 357–366

[Delyannis, 1987] E. Delyannis, Status of solar-assisted desalination: a review, Desalination 67 (1987) 3-19.

[Delyannis, 2000] E. Delyannis and Belessiotis, V., The story of renewable energies for water desalination, Desalination 128 (2000) 147-159.

[El-Nashar, 1992] El-Nashar AM. Optimising the operating parameters of a solar desalination plant. Solar Energy 1992;48(4):207–13.

[Eltawil, 2008] Eltawil, Mohamed A., Zhao Zhengming and Liqiang Yuan, Renewable Energy Powered Desalination Systems: Technologies and Economics-State of the Art, (2008), Twelfth International Water Technology Conference, IWTC12 2008, Alexandria, Egypt 1099 -1137

[Eltawil, 2009] Eltawil MA, Zhengming Z, Yuan L. A review of renewable energy technologies integrated with desalination systems. Renewable and Sustainable Energy Review 2009;13:2245–62.

[Garcia-Rodriguez, 2002] Lourdes Garcia-Rodriguez, Seawater desalination driven by renewable energies: a review, Desalination 143 (2002) 103-l 13

[Ghermandi, 2009] Ghermandi A, Messalem R. Solar-driven desalination with reverse osmosis: the state of the art. Desalination and Water Treatment 2009;7:285–96. Desalination units powered by renewable energy systems. Opportunities and challenges. Organized by INRGREF. In: Proceedings of the international seminar held in Hammamet, Tunisia; 2005.

[Goosena, 2000] Mattheus F.A. Goosena, Shyam S. Sablanib, Walid H. Shayyab, Charles Paton, Hilal A1-Hinai, Thermodynamic and economic considerations in solar desalination,,Desalination 129, pp. 63-89 (2000)

[Gude, 2010] Veera Gnaneswar Gude, Nagamany Nirmalakhandan a, Shuguang Deng Desalination using solar energy: Towards sustainability, Energy, pp. 1-8 (2010)

[Gwillim, 1996] Gwillim, Jo. Village scale photovoltaic powered reverse osmosis. Machynlleth, Wales: Dulas Limited; 1996.

[Hasnain, 1998] Hasnain SM, Alajlan S. Coupling of PV-powered RO brackish water desalination plant with solar stills. Renewable Energy 1998;14(1–4):281–6.

[Kalogirou, 2005] Kalogirou SA. Seawater desalination using renewable energy sources. Progress in Energy and Combustion Science 2005;31:242–81.

[l-Harbi, 2011] l-Harbi O, Lehnert K. Al-Khafji solar water desalination. The Saudi International Water Technology Conference; 2011.

[Mathioulakis, 2007] Mathioulakis, E., Belessiotis, V., and E. Delyannis. Desalination by using alternative energy: review and state-of-the-art, Desalination 203 (2007) 346-365.

[MED-CSD, 2010] MED-CSD, Action Plan for the Development of combined solar power and desalination, OMDD (Mediterranean Observatory for Sustainable evelopment), 2010.

[MED-CSD, 2010] MED-CSD, Combined solar power and desalination plants, 2010.

[Mu¨ller-Holst, 1998] Mu¨ller-Holst H, Engelhardt M, Herve M, Scholkopf W. Solar thermal seawater desalination systems for decentralized use. Renewable Energy 1998;14(1–4):311–8.

[Qiblawey, 2008] Hazim Mohameed Qiblawey, Fawzi Banat, Solar thermal desalination technologies, Desalination 220 (2008) 633–644

[Peterson, 2012] Peterson, Eric L and Stephen Gray, Effectiveness of desalination powered by a tracking solar array to treat saline bore water, Desalination Volume 293, 1 May 2012, Pages 94–103.

[Poovanaesvaran, 2011] Poovanaesvaran P, Alghoul MA, Sopian K, Amin N, Fadhel MI, Yahya M. Design aspects of small-scale photovoltaic brackish water reverse osmosis (PV-BWRO) system. Desalination and Water Treatment 2011;27:210–23.

[Schillings, 2007] Trieb F, Schillings C, Viebahn P, Paul C, Altowaie H, Sufian T, Alnaser W, Kabariti M, Shahin W, Bennouna A, Nokraschy H, Kern J, Knies G, El Bassam N, Hasairi I, Haddouche A, Glade H, Aliewi A. Concentrating solar power for seawater desalination, Center (DLR). Study for the German Ministry of Environment. Nature Conversation and Nuclear Safety, Stuttgart; 2007, /www.dlr.de/tt/aqua-cspS.

[Scrivani, 2007] A. Scrivani, El Asmarb, U. Bardi, Solar trough concentration for fresh water production and waste water treatment, Desalination 206 (2007) 485–493.

[Sethi, 2012] V.K.Sethi, E, Mukesh Pandey' Priti Shukla, Concentrating Solar Power, Seawater Desalination, Parabolic Troughs, Fresnel Systems, International Journal of Advanced Renewable Energy Research, 2012, Vol. 1, Issue. 3, pp. 167-171.

[Thomson, 2003] A.M. Thomson, Reverse-Osmosis Desalination of Seawater Powered by Photo-voltaics Without Batteries, A Doctoral Thesis, Loughborough University, 2003.

References for Solar Still Desalination (humidification and dehumidification of air)

[Abualhamayel, 1997] Abualhamayel HI, Gandhidasan P. A method of obtaining fresh water from the humid atmosphere. Desalination 1997;113:51–63.

[Al-hassan, 2009] Al-hassan GA. Fog water collection evaluation in Asia region-Saudi Arabia. Water Resources Management 2009;23:2805–13.

[Al-Hallaj, 1998] Al-Hallaj S, Farid MM, Tamimi AR. Solar desalination with humidification-dehumidification cycle: performance of the unit. Desalination 1998;120: 273–80.

[Al-Karaghouli, 2004] Al-Karaghouli AA, Alnaser WE. Experimental comparative study of the performances of single and double basin solar stills. Applied Energy 2004;77(3):317–25.

[Al-Karaghouli, 2004] Al-Karaghouli AA, Alnaser WE. Performances of single and double basin solar-stills. Applied Energy 2004 2004;78(3):347–54.

[Aristov, 1999] Aristov YUI, Tokarev MM, Gordeeva LG, Snytnikov VN, Parmon VN. New composite sorbents for solar-driven technology of fresh water production from the atmosphere. Solar Energy 1999;66(2):165–8.

[Bacha, 1999] Ben Bacha H, Bouzguenda M, Abid MS, Maalej AY. Modeling and simulation of a water desalination station with solar multiple condensation evaporation cycle technique. Renewable Energy 1999;18:349–65.

[Bar, 2004] Etan Bar. Extraction of water from air an alternative solution for water supply. Desalination 2004;165:335.

[Bourouni, 2001] Bourouni K, Chaibi MT, Tadrist L. Water desalination by humidification and dehumidification of air: state of the art. Desalination 2001;37:167–76.

[Beckmann, 2005] Beckmann, JR. Method and apparatus for simultaneous heat and mass transfer utilizing a carrier gas, 2005 US Patent no. 6,911,121.

[Ben-Bacha, 2003] Ben-Bacha H, Damak T, Bouzguenda M. Experimental validation of the distillation module of a desalination station using the SMCEC principle. Renewable Energy 2003;28:2335–54.

[Beckman, 1999] Beckman, JR. Innovative atmospheric pressure desalination, 1999. Final Report 98-FC-81-0049.

[Elsarrag, 2011] Elsarrag, E, Al Horr,Y. Experimental investigation on water recovery from the atmosphere in arid humid regions CIBSE Technical Symposium, DeMontfort University, Leicestern UK—6th and 7th September 2011.

[EL-Sharkawy, 2000] EL-Sharkawy I. Production of water by extraction of atmospheric moisture using solar energy, 2000 M.Sc. Thesis, Mansoura University.

[Farid, 2002] Farid MM, Parekh S, Selman JR, Al-Hallaj S. Solar desalination with a humidification-dehumidification cycle: mathematical modeling of the unit. Desalination 2002;151:153–63.

[Gad, 2001] Gad HE, Hamed AM, El-sharkawy II. Application of solar desiccant/collector system for water recovery from atmospheric air. Renewable Energy 2001;22: 541–56.

[Gordeeva, 1998] Gordeeva LG, Tokarev MM, Parmon VN, Aristov YI. Selective water sorbents for multiple application, fresh water production from the atmosphere. Elseveir

[Hamed, 2000a] Hamed AM. Parametric study of the adsorption-desorption system producing water from ambient air. International Journal of Renewable Energy Engineering 2000;2:244–52.

[Hamed, 2000b] Hamed AM. Absorption-regeneration cycle for production of water from air—theoretical approach. Renewable Energy 2000;19:625–35.

[Hamed, 2003] Hamed AM. Experimental investigation on the natural absorption on the surface of sandy layer impregnated with liquid desiccant. Renewable Energy 2003;28:1587–96.

[Hamed, 2010] Hamed AM, Kabeel AE, E-Shafei Zedin Ayman Aly A. Technical review on the extraction water from atomospheric air in arid zones. Journal of Heat and Mass Transfer 2010;4(3):213–28.

[Hamed, 2011] Hamed AM, Aly AA, Zeidan EB. Application of solar energy for recovery of water from atmospheric air in climatic zones of Saudi Arabia. Natural Resources 2011;2:8–17.

[Habeebullah, 2009] Habeebullah BA. Potential use of evaporator coils for water extraction in hot and humid areas. Desalination 2009;237:330–45.

[Jacobs, 2008] Jacobs AFG, Heusinkveld BG, Berkowicz SM. Passive dew collection in a grassland area, The Netherlands. Atmospheric Research 2008;87:377–85.

[Kabeel, 2006] Kabeel AE. Application of sandy bed solar collector system for water extraction from air. International Journal of Energy Research 2006;30: 381–94**.**

[Kabeel, 2007] Kabeel A. Water production from air using multi shelves solar glass pyramid system. Renewable energy 2007;32(1):157–72.

[Khalil, 1993] Khalil A. Dehumidification of atmospheric air as a potential source of fresh water in the UAE. Desalination 1993;93:587–96.

[Kobayashi, 1981] Kobayashi M. A method of obtaining water in arid land. Solar Energy 1963;7:93–9.

[Prakash, 2010] Prakash G, Narayan, Sharqawy MH, Summers EK, John H. The potential of solar-driven humidification-dehumidification desalination for small-scale decentralized water production. Elsevier; 2010.

[Roland, 2001] Roland V, Wahlgre N. Atmospheric water vapour processor designs for potable water production: a review. Water Research 2001;35(1):1–22. .

[Sofrata, 1981] Sofrata H. Non-conventional system for water collection. Proc. of Solar Desalination Workshop, 1981, 71–87.

[Sultan, 2004] Sultan A. Absorption/regeneration non-conventional system for water extraction from atmospheric air. Renewable Energy 2004;29:1515–35.

[Tygarinov, 1947] Tygarinov VV. An equipment for collecting water from air, 1947, Patent no. 69751, Russia.

[Wahlgren, 2001] Wahlgren RV. Atmospheric water vapor processor designs for potable water production: a review. Water Resources Management 2001;35:1–22.

[Wang, 2007] Wang G, Ji RZ, Li LX. New composite adsorbent for solar-driven fresh water production from the atmosphere. Desalination 2007;212:176–82.