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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.

Contents

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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

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

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

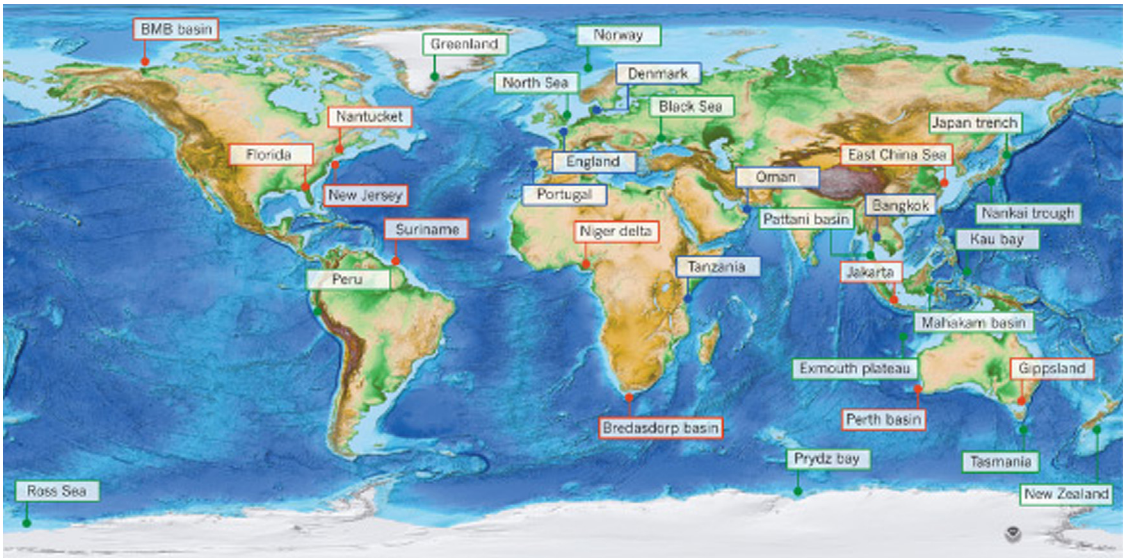

Fig. 1. World map of freshwater (in green) reserves [1]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Classification of waters by total dissolved solids [2,3].

Type of water	EC (dS/m)	TDS (g/l)	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

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 15–20 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.

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 NaCl salts, the TDS of 1 g/l is the same as 1000 ppm.). Observe from 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.

2.3.1. Classification of waters by salinity

Brackish water is water with salinity between that of fresh water and seawater (in the range of approx. 5000–35,0000 ppm, but typically approx. 10,000–15,000 ppm), and constitutes approximately 23% of the world's water. The salinity of seawater ranges between 35,000 and 45,000 ppm, and constitutes approximately 58% of the world's water. Other water consists of wastewater (approximately 5%), and river water (approximately 7%), and other sources. 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.

The first issue is the situation of the saline and brackish water. Fig. 2 above gives a world map of situations of saline water reserves, with Basin (red), Sedimentary-Basin (yellow), Mountain (green), volcanic (blue) [4].

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. Fig. 3 above gives a world map of brackish water

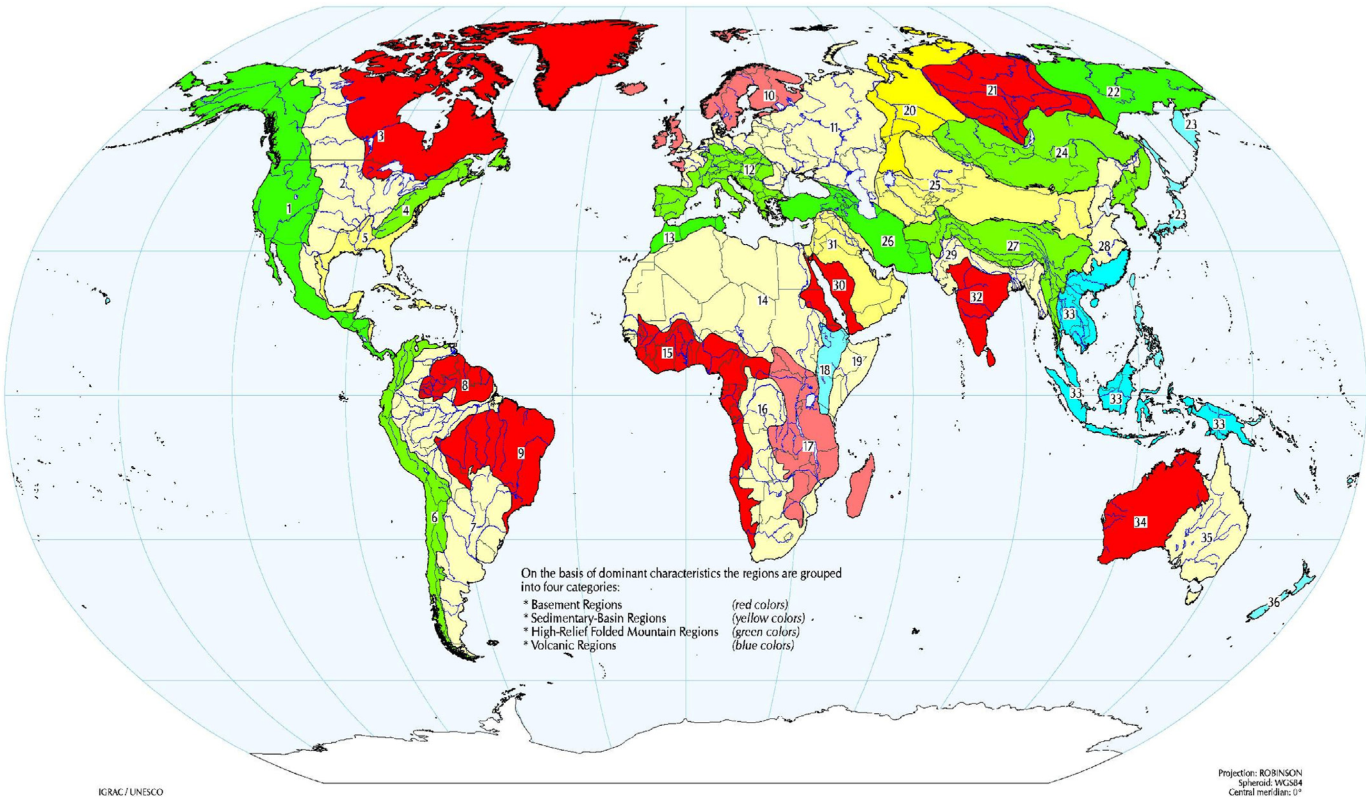

Fig. 2. World map of situation of saline water reserves [4]. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

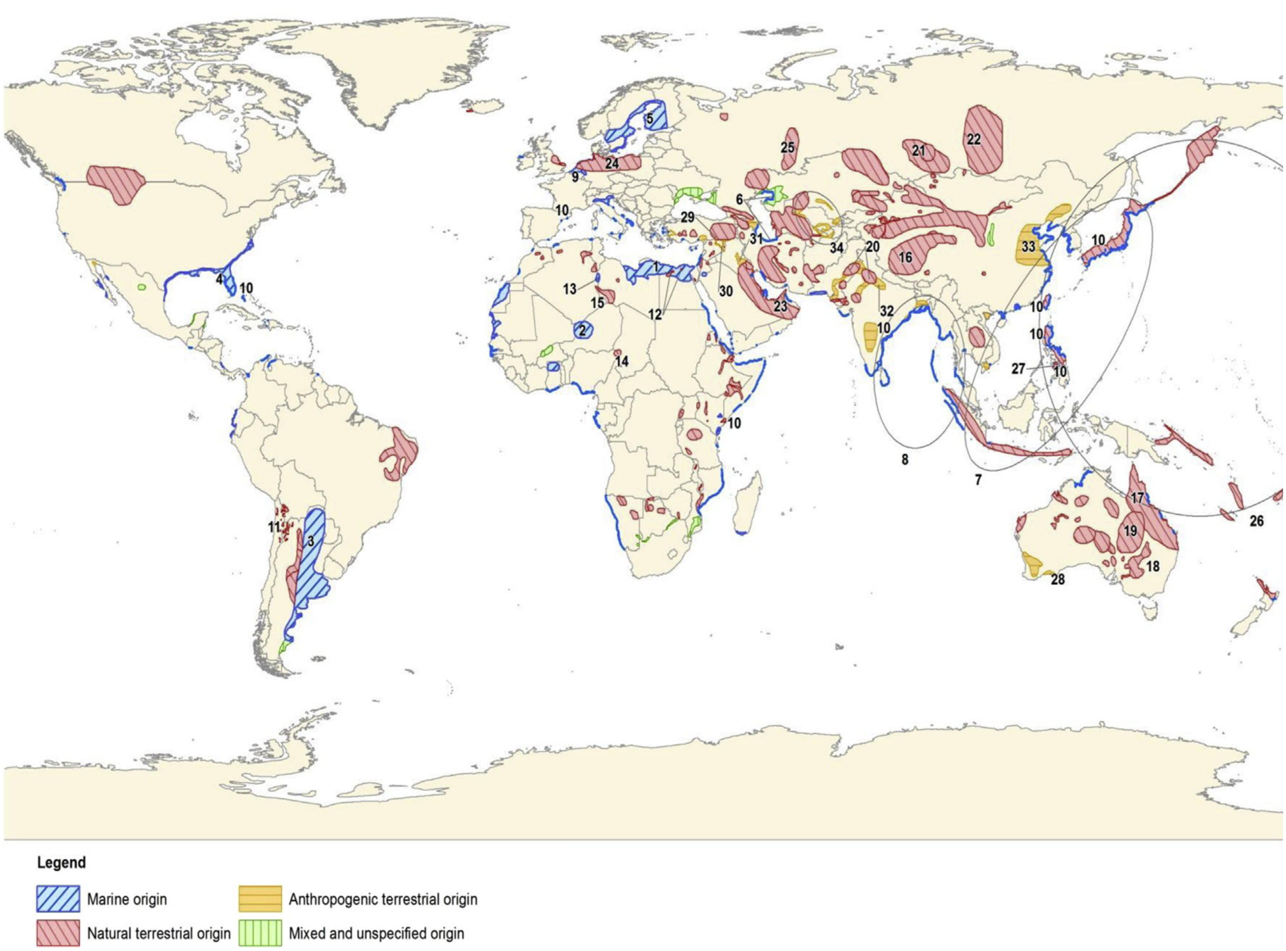

Fig. 3. World map of brackish water reserves [5]. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

reserves [5] and in Figs. 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 [16], 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

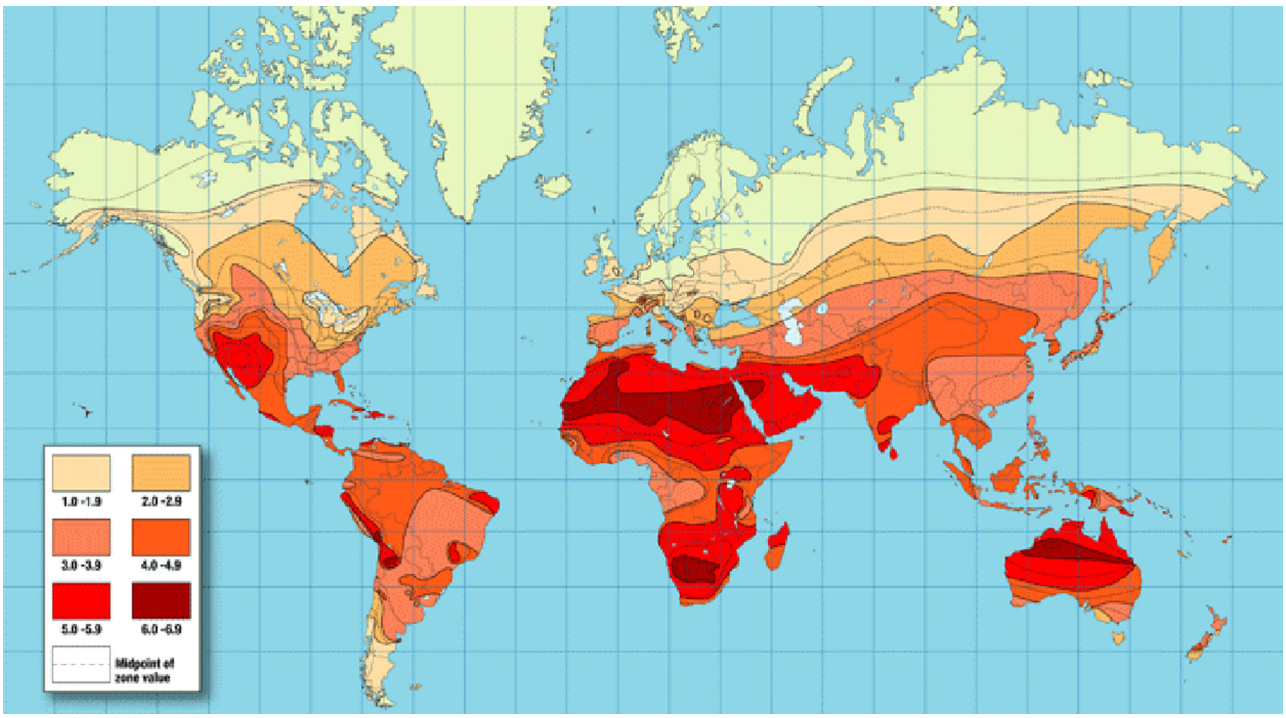

Fig. 4. World insolation map: (from www.applied-solar.info). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

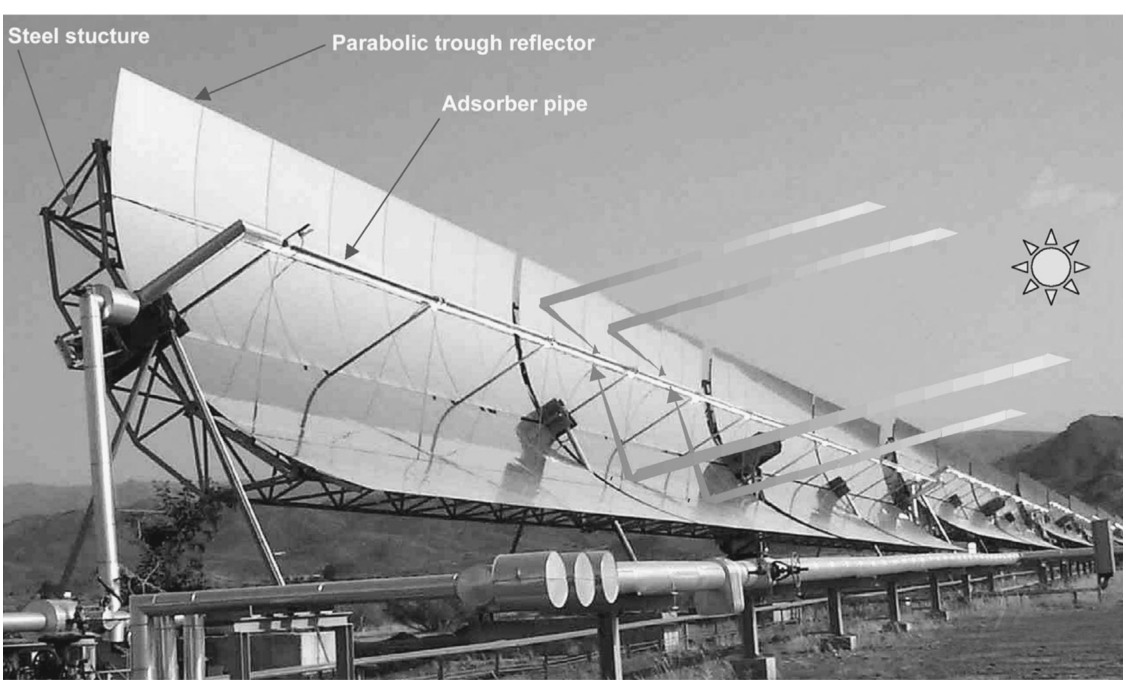

Fig. 5. Parabolic solar trough concentrator (from *Plataforma Solar de Almeria* (*PSA*)).

power transport, but it does indicate some of the potential of solar power.

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 5–7 kW h of solar insolation each solar day. By most estimates, these regions yearly receive approx. 1.7–2.2 MW h/m^2 per year (this is megawatt hours of solar power available per square meter per year). Unfortunately, it has been estimated [87] 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 [7]). 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 [17], and more recent reviews include [8] and [14].

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.

3.2.1. 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/kW h, which is two to three times of the current US commercial market price of electricity (per kW h). 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

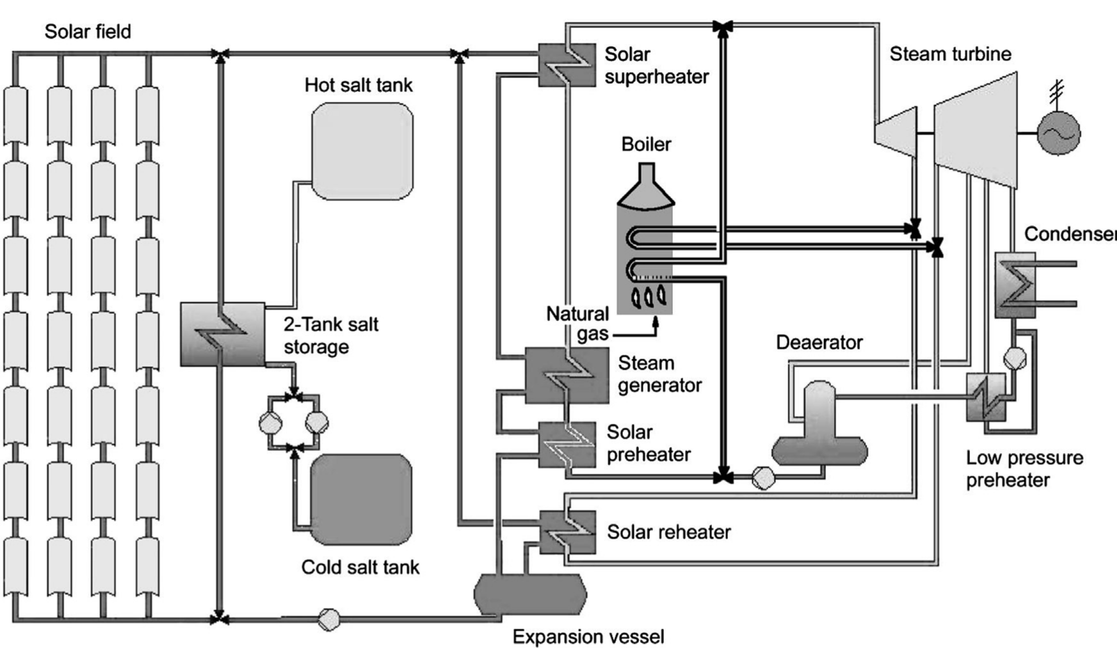

Fig. 6. Flow schematic of parabolic solar trough concentrator (from [19]).

generally have even shorter life periods non-concentrating PV systems before they significantly degrade.

3.2.2. 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 [6,9,12,14,18,17,16,19,22–24,25,17] provides one of the most extensive surveys, but [14] is more current).

In contrast, we will mostly discuss the use of solar concentrating systems instead for powering desalination. Unfortunately, it has been estimated [87] that only approximately 0.02% of desalination capacity is using solar power or any other renewable power source.

3.2.3. 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: Fig. 5; Fig. 6.

The principal solar trough concentrators are:

- *parabolic solar trough concentrators* (see [6,15,10–12,17,20,21,16,22], and [23] and a
- *linear Fresnel concentrators* (see [14,26]).

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 which 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 60:1–80:1, 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 [13]) 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.

3.2.3.1. Cost-effectiveness of solar concentrators. The *primary concen trators* 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 that 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 [17] 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 15–25 years. Similar payback period estimates were subsequently made in [8] for solar-thermal systems (and even higher estimates for payback period can be inferred from the cost and performance [7] 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 [33] 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 kW h m^{-3} for conversion of seawater with saline content of 34,500 ppm at a temperature of 25 °C [33]. The cost for desalination has considerably reduced in recent years, and in the US is approximately \$0.5–1 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 desa lination 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 [32,35,34,35,41,43].
- Seawater desalination is described in [29,30,28,39,33].
- Case studies for given locations include: Saudia Arabia [28,27], Kuwait [37], and California [36].
- Study of the environmental costs of desalination is given in [42].
- Industrial status reports for extant desalination plants are given in [33,38,40].

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 [87–89,91, 93,92,95,96,99,101–105,108,110].
- PV-powered desalination is described in [80,81,82,94], RO [97,98,106,107,111].
- Solar-concentrator-powered desalination is described in [83,84–86,90], and [109].
- Studies of desalination systems in Saudi Arabia and their feasibility for solar powering these plants are given in [81,82,115,30,28,36, 91,92,94] and [99]. A study of an experimental implementation of a solar-concentrator-powered desalination system in Saudi Arabia is given in [100].

4.3. Electrodialysis

Another related membrane-base desalination process is known as Electrodialysis (ED) (see [48,49,46]. 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

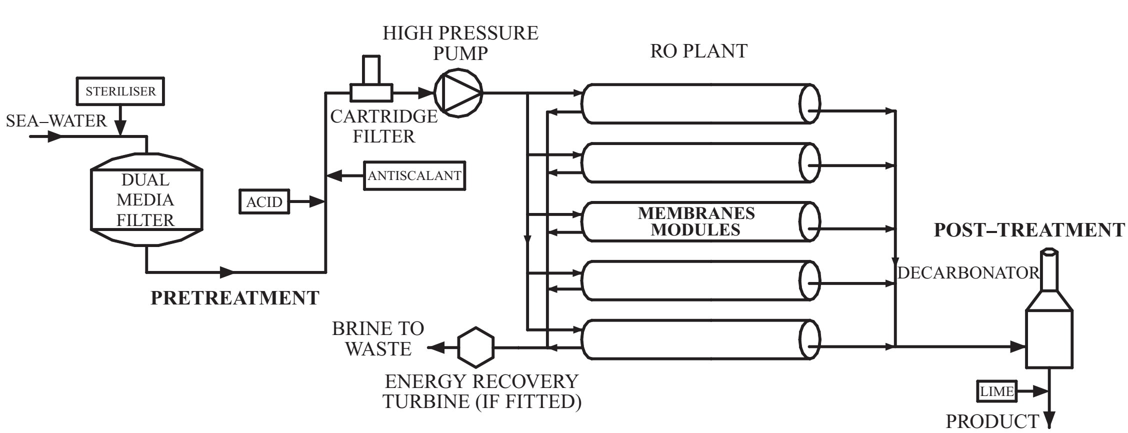

Fig. 7. Reverse osmosis (RO) filtration (from [99]).

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

Currently RO is one of the most efficient technologies for desalination and is used in approximately 59% of all desalination systems worldwide [76], Fig. 7.

The energy use for RO distillation of seawater is 3–5.5 kW h m^{-3} [33]. This method makes use of pressure to force the salt water through reverse osmosis filtration systems ([31,50]). 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 [76].
- [75] gives a handbook on membrane filtration, including RO.
- Energy analysis for RO desalination is given in [72].
- RO systems in various locations are described and analyzed for Saudi Arabia [55,53,56] and Egypt [61].
- Studies of experimental system in Saudi Arabia are given in [58,63].

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 [54,57,59,60,62,64–71,73,74,77,78,79].

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 [45,51], and

- A feasibility study of brackish water desalination using PV is is given in [47].
- A demonstration study for Jordan is given in [44].

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 and 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 kW h 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 CO_2 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 [52] 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 15:1–20:1. 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. 60:1–75:1 to produce very highly pressurized steam to drive high performance steam turbines).

4.6. Multi-effect desalination (MED) and multi-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 Fig. 8.

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 kW h m^{-3} [33]. 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 Fig. 9.

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 kW h m^{-3} [33], 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 kW h m^{-3} [33]. 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 [144,112,119, 121,123,125,127,134,137,139,142,143].
- In more advanced systems, sorbents (see [117,128–131,146]) are used to facilitate the cycle of capturing the condensation, and then to releasing the condensation.
- Reviews of solar still technology are given in [120,132,133, 140,141,145].

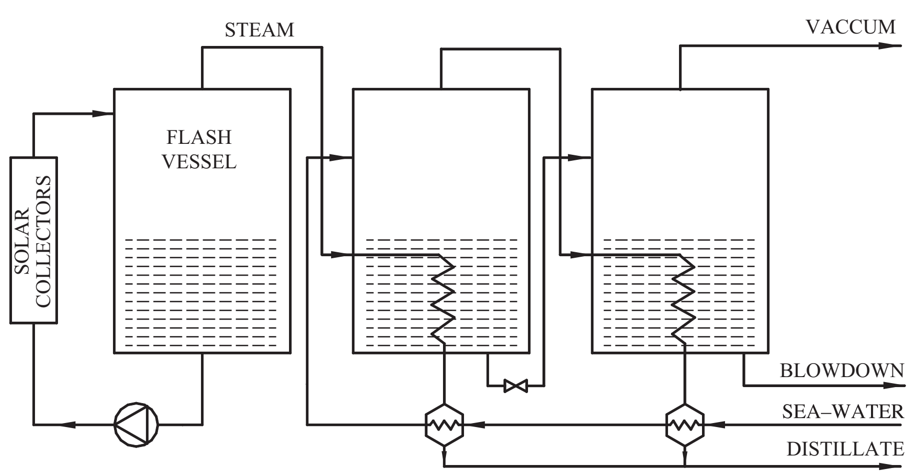

Fig. 8. Design for MED desalination system using boilers (from [99]).

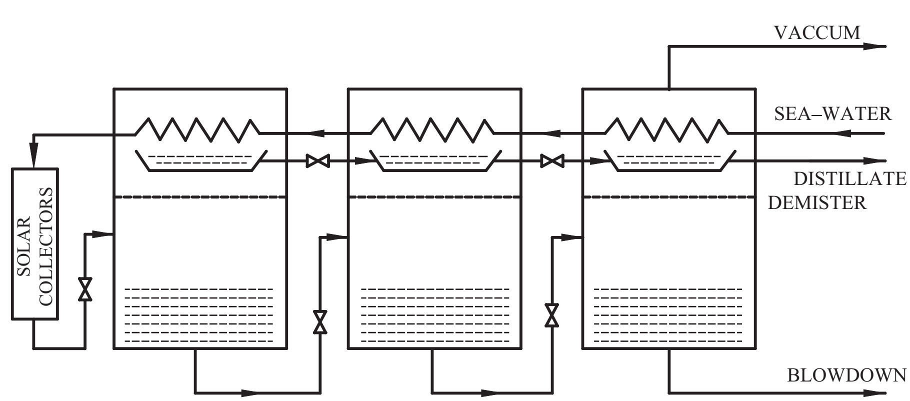

Fig. 9. Design for MSF desalination system (from [99]).

- Experiments, demonstrations, performance analysis are described in [113–116,122,124,135,136,138]. Modeling of solar stills is given in [118,126].

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.

4.9. Application of solar-powered desalination

4.9.1. The attractive opportunity of using solar energy to power reverse osmosis filtration pressurization

Recall from above that approx. 2.5 kW h 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 MW h/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 MW h/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 1000 mx1000 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.

5.2.1. 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.

5.2.2. 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.

5.2.3. 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. [93] 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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