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A Review of Solar-geothermal Hybrid Systems for Water Desalination

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ABSTRACT

Water plays an important role in all our day to day activities and its consumption is increasing day by day because of increased living standards of mankind. The existence of human population in many areas around the world strongly depends on the availability of fresh water. Around 97% of water on earth is not directly available for consumption due to high water salinity and that only 3% is fresh and used for consumption as potable water. It would be feasible to address the water-shortage problem with seawater desalination; however, the separation of salts from seawater requires large amounts of energy which, when produced from fossil fuels, can cause harm to the environment. Therefore, Energy intensive production of potable water develops a need to use renewable energy technologies for seawater desalination. Much research has been directed at addressing the challenges in using renewable energy to meet the energy needs for desalination plants.

As for desalination, different technologies are considered affordable and sustainable if the energy requirements are met by renewable and waste heat sources such as solar, geothermal and wind energy sources and low grade process waste heat sources to deal with freshwater scarcity by desalting seawater or brackish water. Harvesting of geothermal energy to power desalination systems has a considerable advantage over renewable energy sources that can produce energy over part of a 24-h daily cycle. A geothermal energy system can provide ‘‘base-load’’ power on a continuous basis and can do so for continuous, long-term time periods if properly designed. Using combined geothermal energy systems with solar power for desalination of seawater has been proposed to provide simultaneously electricity, space heating and cooling and desalinized water and also to eliminate the necessity to develop thermal storage for nighttime operation of a purely solar-powered desalination system and to allow geothermal heat source regeneration. In this paper the technical and economic feasibility of using a hybrid solar-geothermal energy source in different desalination systems is investigated and also is presented that coupling a geothermal energy source with electric power generation and desalination can produce the highest efficiency use of the resource.

1. INTRODUCTION

Global demand for water continues to increase whilst freshwater sources are becoming more scarce due to increasing demand for natural resources and the impacts of climate change, particularly in semi-arid and coastal areas (Renewable & Agency, 2012). The United Nations World Water Assessment Programme (WWAP) estimates that by 2030, in a business as usual scenario, only 60% of the global water demand can be met (UN-WWAP, 2015). The OECD expects that, in a business as usual scenario, by 2050, the global fresh water withdrawals will increase by 55%. Consequently, by the end of this period, 40% of the global population will be living in water-stressed regions. (WWAP, 2014). Figure. 1, illustrates the regions in a global water stress map for the 2030 optimistic scenario. According to figure 1, the most water stressed regions in the world will be in North and South Africa, and Central and South Asia. These regions have high or extremely high water stress in 2030 and more than 40% of the renewable water resources are being withdrawn (Luck, Landis, & Gassert, 2015).

The only possible way to tackle the water-shortage problem would be desalinating the inexhaustible sources of water in oceans which can properly supply all human needs (Kalogirou, 2004). Desalination of seawater and brackish water is growing so fast globally particularly in parts of the world where water availability is low and can be used to augment the increasing demand for fresh water supplies (Renewable & Agency, 2012). Figure 2 shows the percentages of desalination plants for each geographical area. As it can be perceived from Figure 2, middle east has the biggest number of desalination plants in the world, followed by the Mediterranean, the Americas, and Asia (House, Listons, & Road, 2015). The global capacity of desalination plants, including renewable desalination, is expected to grow at an annual rate of more than 9% between 2010 and 2016. The market is set to grow in both developed and emerging countries such as the United States, China, Saudi Arabia and the United Arab Emirates, as shown in Figure 3. A very significant potential also exists in rural and remote areas, as well as in islands (Figure 2, rest of world (ROW)), where grid electricity or fossil fuels to generate energy may not be available at affordable costs. About 54% of the global growth is expected to occur in the Middle East and North Africa region (Isaka, 2012).

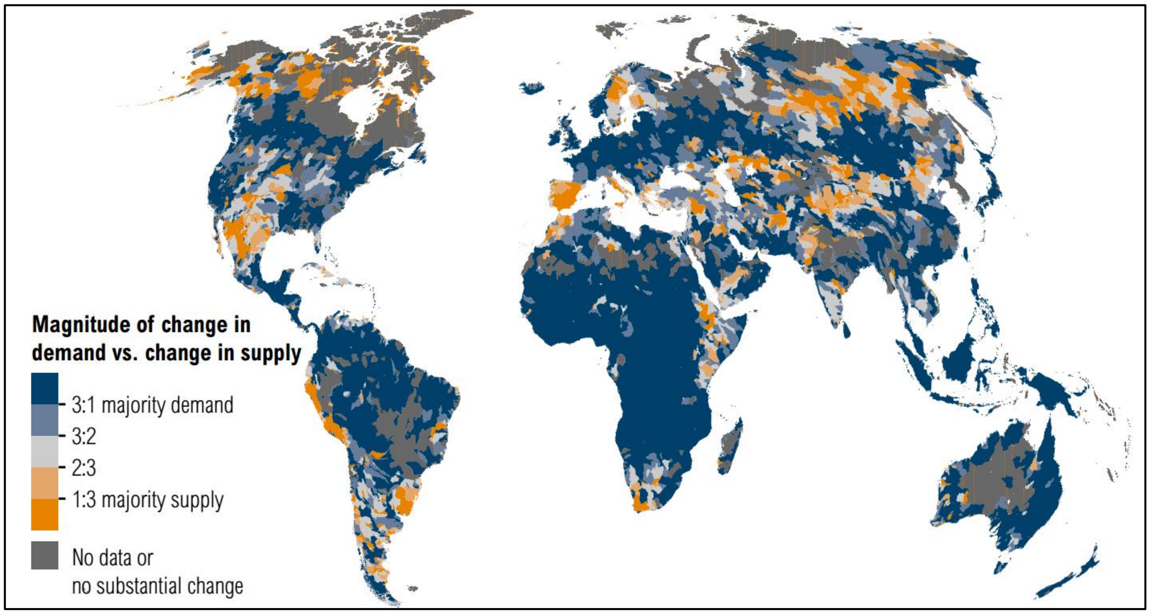

Figure 1. Projected water stress for the 2030 optimistic scenario. The water stress is the ratio of the total water demand in the region to the annual renewable water resources available in that region (Luck et al., 2015).

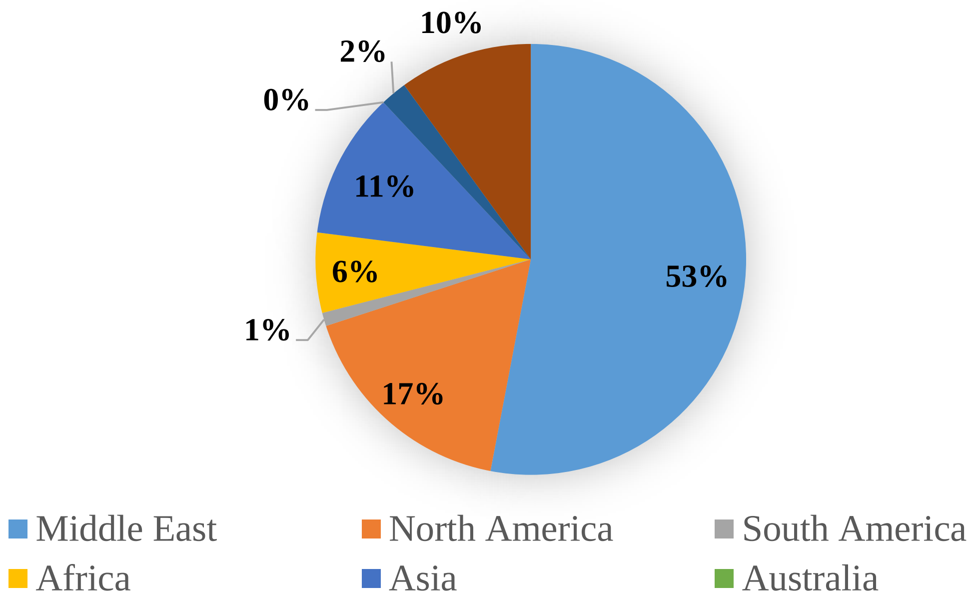

Figure 2. World desalination plants per geographical area (%). Adapted from [one-10].

As shown in Figure 3, many of the countries in the Middle East make extensive use of desalination for fresh water. For example, the Kingdom of Saudi Arabia (KSA) 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. Water desalination has been one of the most expensive ways of producing drinking water at the commercial scale due to the high capital and energy costs. This illustrates the challenge for oil and natural gas producing countries in the Middle East, which are dependent on their energy reserves. However, desalination is increasingly recognized as a needed and viable option due to the rapid increase of the world population (Reif & Alhalabi, 2015).

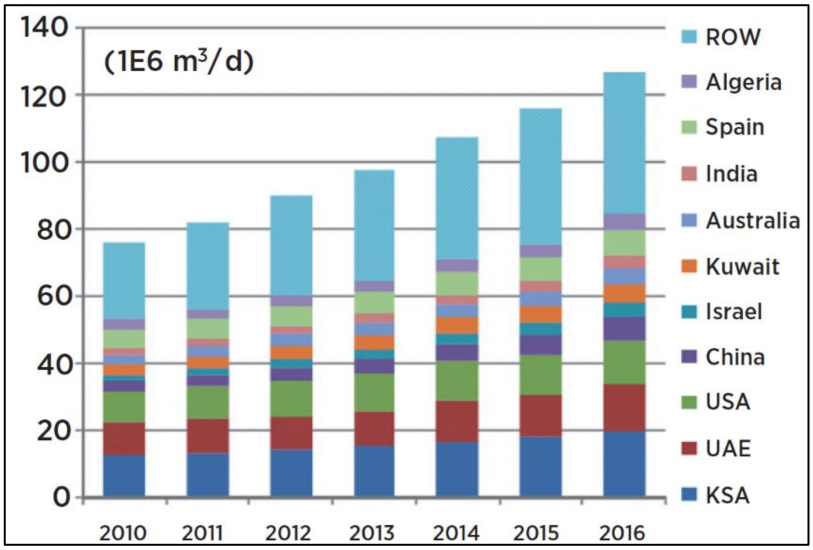

Figure 3. Global installed desalination capacity, 2010–2016. Adapted from (Isaka, 2012).

2. WATER DESALINATION TECHNOLOGIES

There are two major types of technologies that are commonly for desalination in the world that can be broadly classified as either thermal or membrane. Both technologies need energy to operate and produce fresh water. Within these two broad types, there are sub-processes using different techniques. The major desalination processes are identified in Table 1 (Ali, Fath, & Armstrong, 2011; Awerbuch, 1961; Kalogirou, 2004). Thermal desalination involves distillation processes where saline feed-water is heated to vaporize, causing fresh water to evaporate and leave behind a highly saline solution, namely the brine. Freshwater is then obtained from vapor cooling and condensation (Renewable & Agency, 2012).

In the membrane processes, electricity is used either for driving high pressure pumps or for ionization of salts contained in the sea water (Kalogirou, 2004). Figure 4 presents the total amount of water produced by membrane desalination plants and thermal desalination. As it can be seen from figure 4, membrane desalination is projected to increase exponentially in following years whereas the growth of thermal desalination remained almost unchanged (Misdan, Lau, & Ismail, 2012).

Thermal separation processes include multi stage flash (MSF), multi effect evaporation (MEE)/multi effect distillation (MED), vapor compression (VC) and solar desalination. Membrane separation processes include reverses osmosis (RO) and electro-dialysis (ED). Reverses osmosis desalination will become increasingly more competitive with thermal desalination processes in the next decade (Goosen, Mahmoudi, & Ghaffour, 2010).

Table 1. Major desalination technologies (Kalogirou, 2004)

Phase-change processes	Membrane processes
(1) Multistage flash (MSF)	(1) Reverse osmosis (RO)
(2) Multi effect boiling (MEB)	RO without energy
(3) Vapor compression (VC)	Recovery
(4) Freezing	RO with energy
(5) Humidification/dehumidification	Recovery (ER-RO)
(6) Solar stills	(2) Electrodialysis (ED)
Conventional stills	
Special stills	
Wick-type stills	
Multiple-wick-type stills	

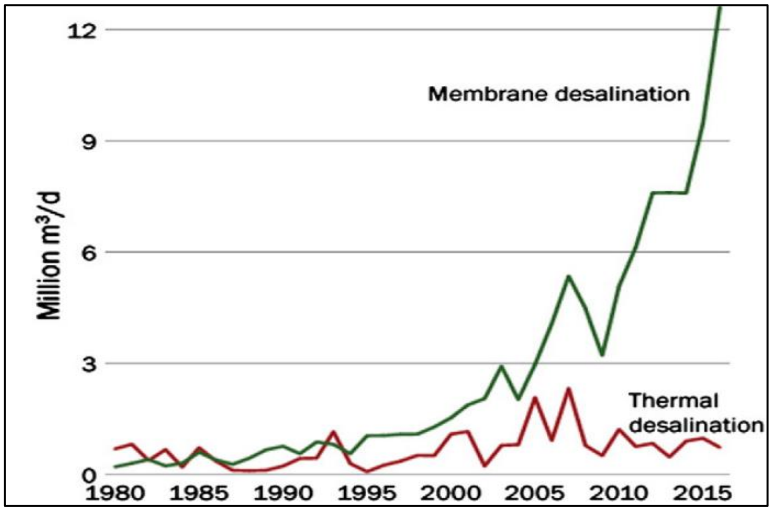

Figure 4. Comparison between membrane desalination capacity and thermal desalination capacity from 1980 to 2016 (Misdan et al., 2012).

It should be noted that the dominant desalination processes are based on Reverse Osmosis (RO) and Multi Stage Flash (MSF) which constitute 60.0% and 26.8% of the worldwide capacity, respectively. The feasibility of each technology depends on specific conditions such as energy price, water quality and the technical resources of the region (Renewable & Agency, 2012).

3. WATER DESALINATION USING RENEWABLE ENERGIES

Energy intensive production of potable water develops a need to use renewable energy (RE) technologies for seawater desalination which their costs are quickly decreasing. Much research has been directed at addressing the challenges in using renewable energy to meet the energy needs for desalination plants. Only about 1% of total desalinated water is currently based on energy from renewable sources. However, as renewables are becoming increasingly main stream and technology prices continue to decline, there is a large market potential for RE-powered desalination systems worldwide. Renewable technologies that are suited to desalination include solar thermal and photovoltaic (PV), wind, and geothermal energy. As electricity storage is still a challenge, combining power generation and water desalination can also be a cost-effective option for electricity storage when generation exceeds demand (Renewable & Agency, 2012).

There have been performed various researches over seawater desalination processes that include an evaluation of various systems that use RE sources for desalination. Table 2 shows the distribution of renewable energy powered desalination technologies and it can be noticed from the Table 2 that the most suitable desalination combinations are MED and MSF for solar power and RO and ED for PV power (i.e. indirect solar), in addition to RO and VC for wind power. It can be argued that solar direct and indirect energy is the most suitable for installed desalination capacity (Ghaffour, Bundschuh, Mahmoudi, & Goosen, 2015).

Table 2. Distribution of renewable energy powered desalination technology (Ghaffour et al., 2015)

Renewable energy-desalination system combination	Installed capacity (%)
Photovoltaic-reverse osmosis (PV-RO)	32
Photovoltaic-electrodialysis (PV-ED)	6
Solar-multiple-effect distillation (solar-MED)	13
Solar-multi-stage flash (solar-MSF)	6
Wind-reverse osmosis (wind-RO)	19
Wind-vapor compression (wind-VC)	5
Others	19
Total	100

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It should also be noted that RO is the most prevalent desalination technology which is powered by renewable energy in the world and after that MSF and MED are the second and third most used desalination technologies around the world. Table 3 shows the total global renewable energy installed desalination capacity by different technologies in the world.

Table 3. Global renewable energy (RE) installed desalination capacity by technology (Ghaffour et al., 2015)

Desalination technology powered by renewable energy	Global RE installed capacity (%)
Reverse osmosis (RO)	62
Multi-stage flash (MSF)	10
Multiple-effect distillation (MED)	14
Vapor compression distillation (VCD)	5
Electrodialysis (ED)	5
Other	4
Total	100

The combination of renewable energies, such as wind, solar and geothermal, with desalination systems holds immense promise for improving potable water supplies in arid regions. It can be argued that an efficient combination of these technologies will allow nations to deal with water shortage problems with a domestic energy source that does not produce air pollution or contribute to the global crisis of climate change (Goosen et al., 2010).
While a system may be technically very efficient it may not be economic (i.e. the cost of water production may be too high). Therefore, both efficiency and economics need to be considered when choosing a solar desalination scheme (Lund, 2007).

3.1 Solar desalination technologies

Desalination processes require significant quantities of thermal and/or electrical energy to achieve separation (Kalogirou, 2004). On a global scale, seawater desalination is an energy intensive and also one of the most expensive processes normally requiring high tonnage plants that utilize non-renewable fossil fuels to produce drinking water at the commercial scale, which in turn contribute to global warming and air pollution (Borsani & Rebagliati, 2005; Sommariva, Hogg, & Callister, 2003).

However, desalination is increasingly recognized as a needed and viable option due to the rapid increase of the world population. It is estimated that about 8.78 million tons of oil per year is required to produce by desalination 1million/m3/day of fresh water, which indicates the importance of finding suitable alternative energy resources for the desalination systems (Li, Goswami, & Stefanakos, 2013). Therefore, in recent years, much attention has been paid to renewable energies for their environmentally friendly nature over fossil fuels. Renewable energy resources like solar energy appear to be one of the most efficient and effective solutions (Ali et al., 2011).

Solar desalination process are broadly classified into two major categories, direct and indirect systems as shown in Figure 5. In direct systems like solar stills evaporation and condensation takes place in the same device. There have been many researches on solar stills and they are considered as a classical but energy intensive technology that use large land areas and are efficiently suitable for small scale , i.e. <10 m3/day (Bundschuh et al., 2015). However desalination using solar energy through PV modules or solar collectors is referred to as indirect solar desalination.

The majority of large scale applications of solar desalination use solar energy indirectly. In these systems, solar energy is harvested by using non-concentrating or concentrating solar thermal collectors or photovoltaic panels. The collected energy is used to drive thermal desalination processes such as MSF, MED, Thermal Vapor Compression (TVC) or MD or in membrane desalination methods such as RO and Electrodialysis (ED) (Kalogirou, 2004). Figure 5, demonstrates a comprehensive review of different solar desalination technologies.

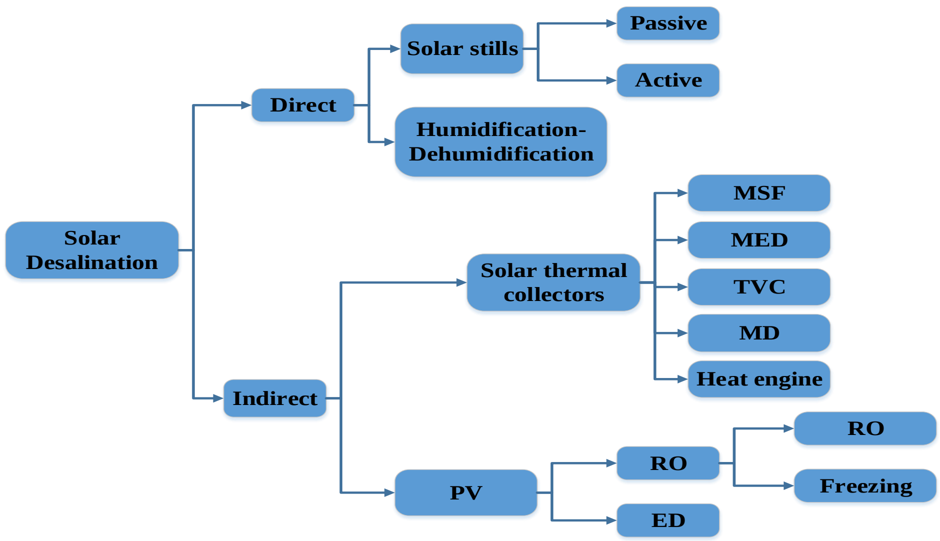

Figure 5. Solar desalination technologies

3.2 Geothermal desalination technologies

Geothermal energy is a kind of renewable technology that can be used to produce potable water in desalination plants. It is an appealing solution for water scarcity and it saves fossils fuels (Gude, Nirmalakhandan, & Deng, 2010). The use of geothermal energy in desalination plants compared with other RE sources has several advantages. It is environmentally friendly, with no emissions of air pollutants and greenhouse gases, it provides a constant stable energy, it provides a stable and reliable heat supply 24 hours a day, 365 days a year, ensuring the stability of the thermal processes of desalination and it is cost effective. Geothermal production technologies are not affected by seasonal changes and weather fluctuations and they require lower surface area or land per unit (MW) than all renewable energy sources (Gude, 2016).

Kalogirou (Kalogirou, 2005) showed that the ground temperature below a certain depth remains relatively constant throughout the year. Popiel et al. (Popiel, Wojtkowiak, & Biernacka, 2001) reported on the temperature distribution measured in the ground during a two-year period. They concluded that one can distinguish three ground zones; surface, shallow and deep. Hence, geothermal energy sources can be classified in terms of their measured temperatures as low (<100 8C), medium (100–150 8C) and high (>150 8C). Geothermal wells deeper than 100 m can be employed to power desalination plants (Kalogirou, 2005). The geothermal energy would be used to heat the saline water and or it could be used to generate electricity for operating reverse osmosis units. Typical geothermal source temperatures are in the range of 70–90 °C in most parts of the world, which are ideal for low- temperature MED desalination. High grade sources above 100°C can be used for power generation and other process heat applications (Gude, 2016). Figure 6 shows numerous possible suggestions for using geothermal heat at small to medium size for desalination of brackish/saline groundwater but very few downsized pilot or demonstration units exist (Bundschuh et al., 2015).

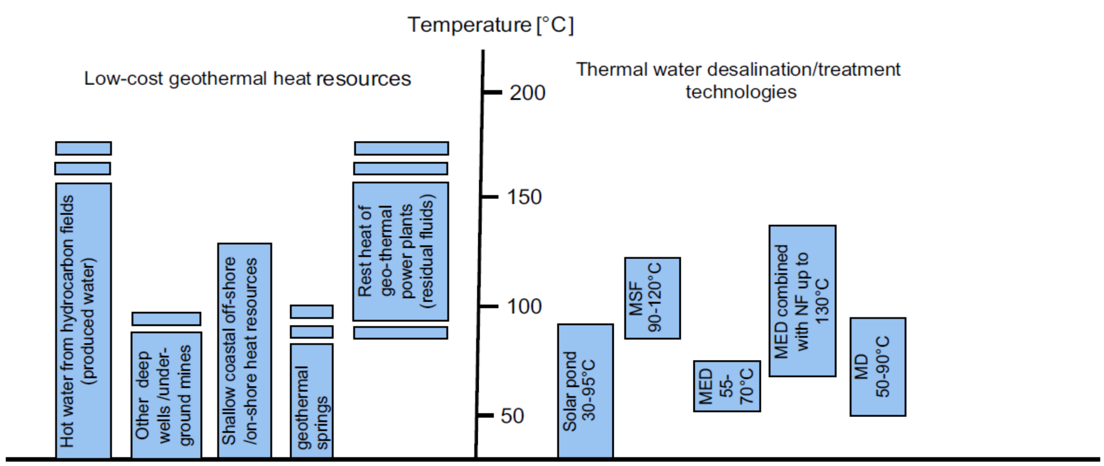

Figure 6. Thermal-based desalination technologies powered by low-cost geothermal heat sources with common temperature

3.3 Solar-Geothermal hybrid desalination technologies

Use of solely a single renewable source of heat to allow thermal desalination of seawater has presented some difficult issues when attempts are made to "scale up" such systems to capacities required to meet water demands of large users. Solar systems providing heated water can do so only during daylight hours, and diminished heat production also occurs on cloudy or rainy days or seasonally. Therefore, heat storage is required to allow continuous operation of thermal desalination facilities using solar-produced heat (Taylor et al., 2012). In addition while a system may be technically very efficient it may not be economic (i.e. the cost of water production may be too high) (Fath, 1998).

Therefore, both efficiency and economics need to be considered when choosing a solar desalination scheme. Therefore many possible combinations can be envisaged between renewable energy sources such as wind, solar and geothermal, and desalination technologies (Mahmoudi et al., 2010). Hybrid desalination systems, which are used to combine desalination technologies, are suitable for big installations in order to accomplish scale economies that reduce the production cost (Zotalis, Dialynas, Mamassis, & Angelakis, 2014). The coupling of solar and geothermal energy with desalination systems holds great promise for increasing water supplies in arid regions. An effective integration of these technologies will allow countries to address water shortage problems with a domestic energy source that does not produce air pollution or contribute to the global problem of climate change (Mahmoudi et al., 2010).

A combined-cycle solar and geothermal powered desalination process can provide the most effective use of RE without the need for energy storage (Ghaffour et al., 2015). Missimer et al. (Taylor et al., 2012) explored an innovative hybrid approach which would combine solar and geothermal energy using an alternating 12-hour cycle to reduce the probability of depleting the heat source within the geothermal reservoir. This amalgamation provides one of the most effective uses of RE without the need for energy storage. Figure 7, shows the coupled solar and geothermal energy source to power thermally driven adsorption desalination processes.

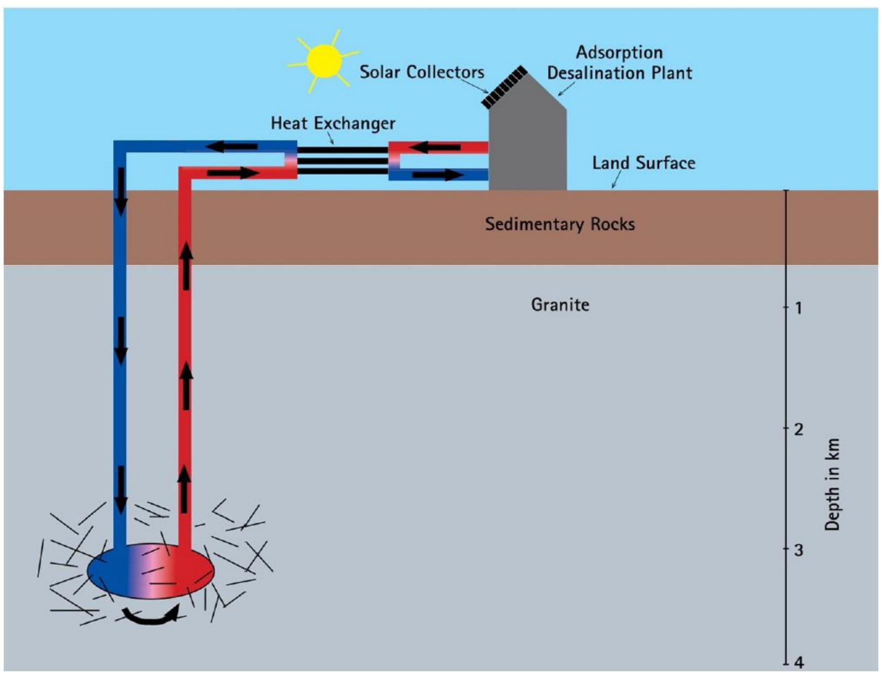

Figure 7. Coupled solar and geothermal energy source to power thermally driven desalination processes (Taylor et al., 2012)

Solar heating can provide raw water with a temperature of between 55 and 90°C and a low-grade geothermal system can provide water or water heated in exchangers from a dry subsurface heat source with a temperature range of 60–120°C. Raw water or steam temperatures in these ranges can be used in combination with adsorption desalination (AD) to produce high volumes of freshwater from seawater and chilled water simultaneously. The combination of cycled solar and geothermal heat sources with AD and possibly with multiple-effect distillation would also allow scale-up to virtually any capacity water treatment system desired (Taylor et al., 2012).

Vanoli et al. (Calise, Dentice d'Accadia, Macaluso, Vanoli, & Piacentino, 2016) investigated a novel solar-geothermal polygeneration system powered by solar and geothermal sources which supplies a small community with electricity, desalinated water and space heating and cooling. In this system the attained heat after driving organic rankine cycle loop and providing heating (in winter) and cooling (in summer) finally drives a MED system, where seawater is converted into freshwater. The results showed that the novel system is highly flexible and efficient. And the system is economically profitable only when the majority of the energy available for heating and cooling purposes is actually used. Besides, it was also demonstrated that the exergoeconomic cost of a desalinated water varies between 0.5695–0.6023 €/kW h_{ex} (Calise, D'Accadia, MacAluso, Piacentino, & Vanoli, 2016).

Duccio et al. (Tempesti & Fiaschi, 2013) conducted a thermo-economic analysis for a 50kWe heat and power (CHP) plant supplied by solar and geothermal sources. It was realized that R245fa allows the lowest price of electricity production and the lowest overall cost of the CHP plant. Elminshawy et al. techno-economically investigated a hybrid solar-geothermal energy in a humidification-dehumidification desalination system. Daytime experimental accumulated productivity up to 104 L/m^2 and the cost of fresh water produced using the presented desalination system is 0.003 USD/L (Elminshawy, Siddiqui, & Addas, 2016).

4. CONCLUSION

Fossil fuels have been used for many years as the main energy sources for the desalination technologies. The continued increase in the demand for desalinated water has resulted in rising greenhouse gas emissions and threat to available fuel reserves. Consequently, most commercial desalination processes powered by fossil fuels have significantly contributed to environmental pollution. Therefore renewable energies come into the picture as an environmental friendly options in order to minimize the use of fossil fuels. In this paper, a review on the use of renewable energy in recent desalination processes has been carried out, with a focus on solar and geothermal energy.

Hybrid solar and geothermal desalination systems hold great promises for increasing water supplies in arid regions. In addition, an effective integration of these technologies will allow countries to address water shortage problems with a domestic energy sources with low costs and without air pollution. However the coupling of RE technologies with desalination systems will require significant additional R&D. This will help to facilitate market launch and market penetration with mass production at low cost. In addition, technical enhancement and development of innovative and energy-efficient desalination technologies such as AD and MD, which are more suitable for RE use, will help to establish new frontiers in the application of RE technology.

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