Seawater desalination using renewable energy: solar, geothermal, and wind

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Abstract

Globally, the Kingdom of Saudi Arabia (KSA) desalinates the largest capacity of seawater but through energy-intensive thermal processes such as multi-stage flash (MSF) distillation (>10 kWh per m^{3}of desalinated water). In other regions where fossil energy is more expensive and not subsidized, seawater reverse osmosis (SWRO) is the most common desalination technology but it is still energy-intensive (3-4 kWh/m^3). Both processes therefore lead to the emission of significant amounts of greenhouse gases (GHGs). Moreover, MSF and SWRO technologies are most often used for large desalination facilities serving urban centers with centralized water distribution systems and power grids. While renewable energy (RE) sources could be used to serve centralized systems in urban centers and thus provide an opportunity to make desalination greener, they are mostly used to serve rural communities off of the grid. In the KSA, solar and geothermal energy are of most relevance in terms of local conditions. Our group is focusing on new desalination processes, adsorption desalination (AD) and membrane distillation (MD), which can be driven by waste heat or solar energy. A demonstration solar-AD facility has been constructed and a life cycle assessment showed that a specific energy consumption of <1.5 kWh/m^3 is possible. An innovative hybrid approach has also been explored 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 and provide the most effective use of RE without the need for energy storage. This paper highlights the use of RE for desalination in KSA.

Keywords: Renewable energy-driven Desalination; Combined solar-geothermal; Innovative desalination technologies; Environment, Saudi Arabia (KSA).

1. Introduction

Globally, the Kingdom of Saudi Arabia (KSA) desalinates the largest amount of water daily but, unfortunately, through energy-intensive thermal processes such as multi-stage flash distillation (MSF) in which the specific energy consumption is of about 10-16 kWh/m^3 [1-4]. In Europe, Australia and the USA, seawater reverse osmosis (SWRO) is the most common water desalination technology but is still energy-intensive (3 to 4 kWh/m^3) compared to conventional drinking water supply sources such as surface or ground water treatment (<0.5 kWh/m^3) [4]. Due to their energy demand, these processes lead to the emission of significant amounts of greenhouse gases (GHGs) when driven by on-grid power derived from conventional energy sources (e.g., about 1.0 kg CO_2-equivalents (CO_2-e) per kWh or 3.8 kg CO_2-e per m^3 of desalinated water or 954 tons of CO_2-e per day for the Sydney SWRO desalination facility with a capacity of 250,000 m^3/day and a specific energy demand of 3.6 kWh/m^3 [5]. Moreover, because of their need for on-grid power, MSF and SWRO processes most often are limited to serving urban centers with centralized systems. While renewable energy (RE) sources such as solar, geothermal, and wind can still serve centralized systems in urban centers, they also provide an opportunity to make desalination *greener* and serve rural communities off of the grid or provide decentralized systems in urban areas, all with no *direct* GHG emissions. Australia has developed a national policy on requiring *energy compensation* for new desalination plants. For example, while the new Sydney SWRO plant takes its power from the grid, the energy demand of the facility is compensated by a newly developed wind farm in an offsite location with 67 turbines producing 132 MW of power. Presently, there are no large desalination plants being driven directly by RE, however, there are some small, stand-alone systems [2, 6-9]. In the KSA, solar and possibly geothermal energy are of most relevance in terms of local conditions.

Solar energy (SE) can be used for powering SWRO through photovoltaic (PV) cells which harness solar radiation. Alternatively, solar heat can be harvested by collectors, either concentrating (e.g., parabolic mirrors) or non-concentrating (e.g., solar ponds), for powering distillation [6]. The simplest approach is where the PV power generation and the desalination process are interfaced but not integrated; here, the problem is the variable diurnal pattern of sunlight. An integrated system requires an energy (heat) storage component for powering desalination during periods of low or no sunlight.

The King Abdulaziz City for Science and Technology (KACST) has a joint initiative with IBM, the National Initiative for Solar Desalination, in which 30,000 m^3/day is being desalinated by 10 MW of SE (Al-Lhafji plant); new improved PV cells from KACST are being coupled with SWRO membranes with improved materials from IBM [10, 11]. The Al-Lhafji solar water desalination plant will be, worldwide, the first high volume SWRO desalination plant powered by SE. To be most efficient, the plant design will profit from latest KACST/IBM UHCPV and Nanomembrane R&D results [10, 11].

Our group has developed a new low-energy desalination process, adsorption desalination (AD), which can be driven by waste heat or SE. A demonstration AD facility has been constructed on the KAUST campus, coupled with SE, and a life cycle assessment has been performed showing that a specific energy consumption of <1.5 kWh/m^3 is possible, with no *direct* GHG emissions. The inherent component of the AD process is silica gel, a very hydroscopic material, which adsorbs water from seawater which is then desorbed at a low temperature (55 to 85 °C) provided by SE, and later condensed free of salts. We are also performing research on solar-driven membrane distillation (MD) in which only water vapor from seawater is transported through a hydrophobic membrane by a temperature gradient as low as 40 °C, which can be provided by SE. A recent breakthrough by our group has been the development of a new generation of MD membranes, opening the possibility of even lower temperature gradients. Details of these emerging technologies are presented in Section 6.

In the KSA, subsurface geothermal energy sources can potentially be tapped for powering desalination processes, suitable for AD, MD and multi-effect distillation (MED) (< 100 °C), and possibly even for MSF (> 100 °C). Geothermal energy can be harvested as wet or dry, and a heat exchanger can be used within a closed loop system. The WDRC is exploring 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 and provide the most effective use of RE without the need for energy storage.

This paper highlights the use of RE mainly solar, geothermal and wind energies for conventional and the innovative desalination technologies described with an emphasis on application in KSA.

2. Desalination capacity and market in KSA

KSA is the world’s largest producer of desalinated water, accounting for 18 % of total global output and 41 % of the total production capacity of the Gulf Corporation Council (GCC) states [12]. The desalination capacity in KSA is approaching a daily water production of 10 million cubic meters per day (Mm^3/d) (Table 1) [12]. In addition to the existing capacity of 9.8 Mm^3/d, a further 1.6 Mm^3/d is under consideration [12, 13]. Most of the desalinated water in the KSA is still produced by thermal-based desalination processes, mainly the MSF process (5.6 Mm^3/d), but less energy-intensive processes such as MED and reverse osmosis (RO) are gaining ground.

3. Desalination and energy

The energy demand of desalination depends on a range of factors including recovery, pretreatment design (e.g., conventional vs. membrane filtration), the type of distillation process (e.g., MSF vs. MED) or SWRO membranes used (e.g., low energy membranes), the efficiency of pumps and motors, the type and efficiency of the energy recovery system installed (if any), and environmental conditions (e.g., feed water temperature). Energy demand also depends on the product water specifications. For example, employing a second SWRO pass for boron removal will increase the energy demand of the process [14]. Table 2 [15-18] summarizes the typical energy requirements of the main desalination processes and compares them to other water supply options [1, 5].

Modern SWRO plants can achieve a specific energy demand of <2.5 kWh/m^3 and a total energy demand of <3.5 kWh/m^3 by using state of the art equipment (such as pressure exchangers, variable frequency pumps and low-pressure membranes) and under favorable conditions (i.e., a low fouling potential, a temperature > 15 °C, a salinity < 35,000 ppm). The real energy demand may be higher under less favorable conditions. For example, the calculated specific energy demand of a state-of-the-art facility with a feed water salinity of 40,000 ppm and a temperature of 20 °C (typical for Eastern Mediterranean seawater), a total recovery of 41 %, and equipped with the most efficient energy recovery system, is approximately 3.8 kWh/m^3 [15]. An additional 0.2-0.8 kWh/m^3 is required for pretreatment, waste water and sludge treatment (depending on the feed water quality), administration buildings and laboratories, post-treatment and drinking water pumping to supply network, which leads to a total energy consumption of about 4-4.6 kWh/m^3 [19]. Ghaffour et al. [1] reported real data from two SWRO plants, using state of the art equipment, located in different sites. The total power consumption (including pretreatment and post-treatment) of a first one-pass SWRO plant (salinity = 35,000 ppm) is 3.8 kWh/m^3, whereas a second two-pass SWRO plant (salinity = 39,000 ppm) consumes 4.25 kWh/m^3. For example, the Spanish National Hydrological Plan assumes a total energy value of 4 kWh/m^3 under the assumption that plants are equipped with state of the art technologies [20], which is similar to the energy demands reported for other large SWRO projects around the world. Older or smaller SWRO plants without energy recovery may use up to 7 kWh/m^3 [15].

As the treatment and distribution of water by conventional means also require energy, the relative increase in energy demand should be considered in addition to the total demand of the process. The electrical energy demand of treating local surface water is typically between 0.2 and 0.4 kWh/m^3, compared to a specific energy demand of a modern SWRO plant of 3.5 kWh/m^3 under favorable conditions, resulting in the best case in a relative increase of 3.1–3.3 kWh/m^3 for seawater desalination. In locations where the water is transported over long distances, the relative increase of a local desalination plant may be much smaller – or even the best option as in the Perth example.

MSF distillation plants, which have an operating temperature up to 120°C, require about 250-330 MJ of thermal energy and 3-5 kWh of electrical energy for the production of one cubic meter of water (Table 2) [15]. MED plants, which operate at temperatures below 70°C, require 145-390 MJ of thermal and 1.5-2.5 kWh of electrical energy per m^3 of water [15]. Although distillation processes require more energy than SWRO, they are still the first choice in countries of the Middle East (cf. section 2) for political, technical and economic reasons, such as difficult feed water conditions for SWRO plants (e.g., red tide events) and the availability of low cost energy. Dual-purpose co-generation facilities predominate in the region, which integrate MSF or MED distillation with power generation [21]. Because MSF and MED are capable of using ‘low value’ and ‘waste’ heat[1], it is not straightforward to compare the total energy use of distillation with SWRO.

In a comparative life cycle assessment of different desalination processes it was concluded that the environmental impact of SWRO is one order of magnitude lower than the impact of thermal processes if they are operated with a conventional boiler, but comparable if the thermal processes are entirely driven by waste heat. MED was found to be more efficient than MSF and was also more energy efficient than RO in one evaluation under the assumption that waste heat is used. This can also be seen if only the electrical energy demand is compared (Table 2). The environmental impact of distillation processes can therefore be significantly reduced (by up to 75%) if integrated into other industrial processes [22-24].

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[1] Waste heat is defined as heat that is released to the environment, such as steam leaving a backpressure turbine that can no longer be used to produce electricity. Low value heat is defined as heat of low temperature with little value for industrial processes, such as steam extracted from a condensing turbine, that could still be used to generate electricity, but that is sometimes wasted depending on practical circumstances such as electricity demand [15].

4. Climate change and GHG emissions from desalination

As both the electrical and thermal energy used for the desalination of seawater is typically produced from fossil energy sources, a main environmental and public health concern of desalination is the release of air pollutants into the atmosphere, primarily GHGs (CO_2), acid rain gases (NO_X; SO_2), and fine particulate matter. The emissions can result directly from the process, i.e., when fossil fuels are used to provide thermal heat in the form of steam for thermal desalination processes in power and water cogeneration plants, or indirectly when electricity is taken from the electricity grid to be used in the desalination process.

GHGs and air pollutant emissions generally depend on the fuel type, the efficiency of the power plant that produces the electricity for the desalination plant as well as the installed exhaust purification equipment at that plant. CO_2 emissions can be estimated with a high degree of certainty, as they depend mainly on the carbon content of the fuel (while carbon sequestration techniques are not widely in use yet). In order to take all relevant climate-change gases into account that arise from the combustion of fossil fuels (namely CO_2, methane, nitrous oxide, perfluorocarbons, hydrofluorocarbons and sulphur hexafluoride, as specified in the Kyoto protocol), all climate change gas emissions can be expressed as CO_2-equivalents (CO_2-e), i.e., the equivalent amount of CO_2 that would have the same global warming potential as the non-CO_2 emissions. CO_2-e emission factors have been established as part of the international emission trading schemes. When electricity is taken from the grid, the energy mix of the respective grid must furthermore be taken into account. In the following, CO_2-e emission estimates for SWRO plants will be provided assuming a specific energy demand of 4 kWh/m^3.

For example, a grid average value of 1.16 kg CO_2-e per kWh was used to calculate the emissions for the Gold Coast desalination project in Queensland, Australia [25]. For the Victorian SWRO plant in Melbourne, a grid average value of 1.31 kg CO_2-e per kWh applies, which is the highest in the whole of Australia due to a high share of brown coal in the energy mix of Victoria [26].

For comparison, if one assumes an energy demand of 4 kWh/m^3 for the SWRO process, CO_2-e emissions would be 4.6 kg/m^3 of desalinated water in the Queensland case and 5.2 kg/m^3 in the Melbourne case. The emissions would be even higher if one furthermore includes the distribution of the water, construction activities as well as CO_2 emissions associated with the use of materials and chemicals into the calculation. The real energy demand of the Queensland plant including all operations and pumping within the existing water storage network is estimated to be 24.5 MW for a capacity of 125,000 m^3/d, which equates to 4.7 kWh/m^3 (4.1 kWh/m^3 for desalination alone). The indirect GHGs emissions as a result of electricity use are estimated to be approximately 679 tons of CO_2-e per day, or 5.43 kg of CO_2-e per m^3 of desalinated water, which represents a 2% increase in emissions in the Gold Coast region [25].

The real energy demand arising from the Melbourne SWRO project was estimated to be 3,239 tons of CO_2-e per day which equates to 7.45 kg of CO_2-e per m^3 of desalinated water. This value covers electricity used to drive the process and transfer the water, as well as emissions from the transportation of workforce, wastes and chemicals, from offsite waste decomposition, and embodied in the chemicals used during operation. Furthermore, if the energy used during construction of the project is added, amortized over the project life of 30 years, the energy demand amounts to 7.8 kg of CO_2-e per m^3. However, the construction process accounts for only 4% of the total project emissions [26].

For Sydney and Perth, where other large desalination projects are located, emission factors for electricity from the grid are 1.06 and 0.98 kg CO_2-e per kWh, respectively [27]. The electricity demand arising from the Sydney SWRO project with an initial capacity of 250,000 m^3/d may result in emissions of 4.24 kg of CO^2-e per m^3 or 1,060 tons of CO_2-e per day. The Perth project has the lowest grid-specific emission factor and lowest reported energy demand of the Australian projects, resulting in the lowest CO_2-e emissions of 3.43 kg/m^3 for the whole plant. The desalination-specific emissions amount to 325 t/d.

The cited examples all calculate the GHGs emissions for electricity purchased from the grid applying the grid-specific emission factor. It would also be possible to co-locate a SWRO plant next to an existing power plant, which would supply electricity ‘over-the-fence’ to avoid transmission losses. In Ashkelon, the SWRO process is driven by a natural gas-fired power plant on site, which supplies 50 MW of electricity to the desalination plant with a capacity of 330,000 m^3/d (3.6 kWh/m^3). Applying a CO_2 emission factor for natural gas of 202 g CO_2/kWh results in a very low emission factor of 0.73 kg CO_2 per m^3. However, it could be argued that the electricity for the desalination plant could also serve other end-users, so that it would be more accurate to apply the grid-specific emission factor.

A worst case example for energy demand of desalination processes and air pollutant emissions are the Gulf countries which depend heavily on desalinated seawater from co-generation plants. In Kuwait, for instance, co-generation plants produce 90% of the national water supply and are almost exclusively fired by heavy crude oils. Kuwait has the fourth largest seawater desalination capacity on a global scale after Spain and accounts for 6% of the worldwide production [5]. In 2004, the plants generated 42 million MWh of electricity and 443 million m^3 of water, using 462 million GJ of energy, which is 54% of the national fuel use. The corresponding CO_2 emission factors are 0.7 kg/kWh for electricity and 15.7 kg/m^3 for desalination. The total CO_2 emissions are approximately 19.000 t/d for 1.2 million m^3 of water per day. In Kuwait, desalination accounts for 10% of the national fuel use and hence the national emissions [28].

5. The use of renewable energy resources in desalination

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 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 [29].

5.1 Solar desalination

In the semi-arid and desert regions, solar energy is available in abundance with a typical solar irradiation of 2,200 to 2,400 kWh/m^2.year. Depending on the type of receiver devices and the application temperatures, the collectable amount of energy of the collectors may vary from 600 to 1,500 kWh/m^2.year, which corresponds to efficiencies of 25% to 60%. For example, a selectively-coated flat-plate and stationary thermal collector in an equatorial region may have a solar thermal rating of 925 kW/m^2.year with a thermal collection efficiency of 45% at 80 ^{o}C of application temperature, as compared with 1,100 to 1,200 kWh/m^2.year for the desert regions. For higher application temperatures, e.g., up to 350 ^{o}C, the single or two axis concentrators are frequently used. As solar rays are optically concentrated onto a focused tubing with fluids flowing internally (either thermal oil or pressurized water), the application temperature attained is typically up to 300 to 400 ^{o}C. At such temperatures, the heat could be used directly in a co-generation plant for both power and low temperature steam extraction to power either the MSF or the MED desalination cycles. A well-designed concentrator system could have a thermal rating of 1,300 to 1,500 kWh/m2.year. However, one inherent disadvantage factor of solar collectors in desert regions is the dust cover which may lower the thermal rating significantly if the collectors are unattended. The other drawback of a solar powered system is that it can only provide energy input during day light hours and, should a desalination facility need to operate continuously, large capacity thermal storage is needed. As a rule of thumb, a conventional silicon PV system would have an electricity rating of 110-120 kWh/m^2.year. Thus, the collector area needed to produce 1 m^3/day of water from a small RO plant (with a total specific energy consumption of 8 kWh/m^3) is 26.5 to 28 m^2 of conventional PV collectors.

5.2 *Desalination using wind energy*

Wind power based desalination can be one of the most promising options for seawater desalination, especially in coastal areas with high wind potential. The electrical and mechanical power generated by a wind turbine can be used to power desalination plants, notably RO or distillation by mechanical vapor compression (MVC). Various small wind-based desalination plants have been installed around the world. As with SE, a drawback of wind desalination is the intermittence of the energy source. Possible combinations with other RE sources, batteries or other energy storage systems can provide smoother operating conditions [29]. The ENERCON Desalination System (EDS) for instance was specifically designed for combination with a wind energy converter. In contrast to conventional SWRO plants, the EDS has a flexible production capacity that can be continuously adjusted from 12.5 to 100 % of nominal capacity, thereby allowing for easy adjustment to changing power availability as caused by fluctuating wind conditions ─ or changing water demand [30].

Besides using wind energy *directly* for desalination, the electricity grid can also serve as a means for using wind energy (or other renewables) *indirectly,* i.e., by compensating or offsetting the electricity demand by desalination by renewables produced off-site. For example, the two Perth SWRO plants and the Sydney plant in Australia compensate their electricity demand by newly erected wind farms: For the first Perth plant, an associated 82 MW wind farm with 48 turbines was erected 200 km north of the city, which will inject an expected 272 GWh of RE into the grid per year, from which the Perth plant purchases 185 GWh (68%) per year [18, 31]. The wind farm that has been purpose-built near Canberra to offset the energy use of the Sydney SWRO project will consist of 67 wind turbines and will provide 132 MW of energy to the grid, versus 42 MW required to operate the plant [32].

However, *offsetting* energy demand and GHGs emissions needs to be carefully evaluated to ensure that these projects are in fact GHGs-neutral. The key issues are additionality (is the new renewable source used to offset emissions additional to what would have been done anyway?) and allocation (the new renewable source could of course also be used to offset emissions from any other end users).

5.3 Geothermal desalination

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-hour 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. Coupling a geothermal energy source with electric power generation and desalination can produce the highest efficiency use of the resource (Figure 1). Using combined geothermal energy system with solar power for desalination of seawater has been proposed by Missimer et al. [33] 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.

There are three types of geothermal energy systems; wet rock/water flow (WR), natural dry steam, and hot dry rock (HDR). In a wet rock system, heat is extracted from either natural water flow from springs or from wells drilled into a hot-water aquifer. The cooled water is subsequently discharged to the environment or is re-injected into the groundwater system at some distance from the source to allow reheating and return into the system. It operates similar to the heat-pump systems used in building heating and cooling systems [34, 35] (Figure 2). Natural dry steam systems tend to occur near active volcanic activity where groundwater comes in contact with naturally heated rock and produces super-heated water under pressure in the subsurface. The drilling of a well into the aquifer containing the superheated water allows the harvesting of the steam with subsequent passage through a turbine electrical generation system (Figure 3). In HDR geothermal systems, heat is extracted by creating a man-made system of connected wells with artificial fractures used to connect an injected fluid from an injection well, through the fractures where heat is extracted, and ultimately to an extraction well where the superheated fluid is recovered [36-39]. The fluid used can be geothermal oil with a series of heat exchangers used at land surface to recover energy (low heat extraction) or low-salinity water can be superheated and flashed to steam at the well-head or near a turbine to generate electricity. The steam flash system is more efficient in energy recovery compared to oil/heat exchange. The steam flash system is quite useful for coupling power generation with desalination.

The goal of geothermal energy development is to produce electric energy and desalinate water at the highest level of efficiency, using virtually all of the extracted latent heat in the process. The link between electric energy production and desalination is critical in order to maximize total heat conservation. Perhaps the most efficient system that can be used includes a closed loop, multiple-well system with water injected through one or more wells that are drilled with a horizontal offset and hydraulically fractured to produce a porous media (HDR system) (Figure 4). The distilled water flows from the injection well through the labyrinth of fractures and is then pumped (or flows via natural head) into the recovery well. The water is maintained under pressure until reaching the proximity of a turbine system before which it is allowed to flash to steam, powering the production of electricity.

There are several configurations that can be used to couple geothermal energy with desalination processes. The first one is to couple geothermal energy production to MED. In this case the system can operate by using dry steam production from wells or from an HDR collection system. The steam is used to heat the raw water flowing into a standard MED unit. The second type would be to use geothermal energy to generate electrical power first and then run a stand-alone RO desalination plant. Also, a hybrid system could be developed that first generates electrical energy by using flashed steam from either a dry steam reservoir or a HDR energy extraction system. The steam vented through the turbines could be redirected for heating of the raw water going into an MED plant. The electrical energy could be used to power an onsite RO facility that combines flow with the MED plant to potable drinking water standards (Figure 5). This system would efficiently utilize the captured geothermal heat and would be particularly useful in treating high salinity waters, such as those of the Arabian Gulf and Red Sea.

6. Contribution in developing renewable energy for desalination in KSA

Our group’s contribution is developing new desalination processes which can be driven by waste heat or SE, mainly AD, MD and forward osmosis (FO) technologies targeting energy consumption below 2 kwh/m^3. An innovative hybrid approach was also explored 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 and provide the most effective use of RE. The main advantage of these more sustainable technologies is that they are simple, operate at lower temperatures and pressures, and they can function with intermittent energy supply (variable loads) without additional operating modifications and energy storage, making them suitable for RE sources without requiring connection to the electrical grid.

6.1 Adsorption desalination (AD)

AD exploits the high affinity of water vapor onto an adsorbent caused by the double-bond surface forces that exist between the porous absorbent and an adsorbate such as the silica gel and water vapor. The pore diameters of the adsorbent range from 10 to 40 nm and the total pore surface area ranges from 600 to 800 m^2/g. Figures 6 (a) and (b) show pictures of the silica gel and their typical pore distribution. The main advantage of using an adsorbent like silica gel is its ability to be re-generated by a low temperature heat source, typically from 55 to 85 ^oC (very suitable for RE use), and the high uptake rate of water vapor when exposed. When the adsorption phenomena are configured as a batch-operated cycle [40-42], an energy efficient cycle is obtained which can produce two useful effects with only one heat input, namely cooling and high-grade potable water; thus, the technology is more precisely defined as adsorption desalination with cooling (ADC). Over the past decade, Ng et al. [43-49] have successfully tested the silica gel and zeolite-based adsorption cycles (ADC), capturing low temperatures waste heat from industries as well as utilizing renewable solar and geothermal heat.

Figure 7 depicts the niche of the ADC cycle with respect to the temperature scale of heat sources. It produces both cooling and water by extracting the waste heat of exhaust or from the renewable solar and geothermal. The key point to note is that by utilizing the waste heat, it is “non-payable” because if such heat sources are untapped, they would be purged into ambient. Thus, the ADC technology is deemed to be environment-friendly and can reduce thermal and chemical pollution by re-cycling low temperature heat sources into useful effects.

A demonstration solar-AD facility has been constructed at KAUST and a life cycle assessment showed that a specific energy consumption of <1.5 kWh/m^3 is possible.

Figure 8 shows the schematic diagram of an advanced AD cycle, comprising an evaporator–condenser with stationary beds. The other major component in an ADC plant are (i) the feed water tank, (ii) two adsorber/desorber beds, (iii) the evaporator–condenser device, (iv) potable water collection tank and (v) the brine discharge tank. Each adsorber bed contains silica gels or zeolite which is packed around the tube-fin heat exchangers. During a batch-operated operation, the reactor beds can be linked to the evaporator or the condenser during the half-cycle periods via a series of valves for the control of vapor and water flows. Consequently, an ADC cycle comprises two half-cycles (intervals vary from 200 to 700 s) and a switching interval (from 20 to 40 s) in between which handles either the pre-heating or cooling of the exchangers. Based on our test experience, an ADC at a standard rating conditions ($T_{source} = 85\ ^{o}C$, $T_{cooling} = 30\ ^{o}C$ and $T_{chilled\ water} = 7\ ^{o}C$) could produce a specific cooling and water production capacities of 25 Rton and 12 m^3 per day, respectively, per ton of silica gel. The evaporator of the ADC has been proven to handle a recovery of 80 % of seawater feed, which is much higher than any other conventional method. Table 3 illustrates the schedule of an ADC operation. Further details of such an emerging technology for low life-cycle cost and low temperature ADC desalination can be found in the published literature [40-49].

6.2 Membrane distillation (MD)

MD is an emerging desalination process that has been under investigation since the 1960s but has drawn more attention in the last decade. Details on the MD process have been widely reviewed [50-55]. MD is a thermally driven process that utilizes a hydrophobic, micro-porous membrane as a contactor to achieve separation by liquid-vapor equilibrium. The feed solution, after being heated, is brought into contact with the membrane which allows only the vapor to transport through the dry pores so that it condenses on the permeate side (coolant), as shown in Figure 9. This vapor is driven across the membrane by the difference in the partial vapor pressure maintained at the two sides of the membrane. A temperature difference of $10^{o}C$ between the warm and cold streams is potentially enough to produce water [56].

MD holds high potential for several applications including water desalination application [51, 55]. It holds the potential of being efficient and cost effective separation process that can utilize low-grade waste heat or RE (typical operating temperatures of 60-70 ^{o}C) such as geothermal [57, 58] or solar [52] energies, which are widely available in the region. One of the main advantages of MD is that the process performance is not highly affected by high feed salinity, as has been proven in bench scale [51, 59] and pilot scale [55] studies.

Different flat sheet and hollow fiber modules have been designed and fabricated by our group aiming to maximize the flux (product water). In addition to process engineering development, our MD research team has locally synthesized and fabricated hydrophobic membranes made of different polymers (e.g. PVDF, PTFE, PP, fluorinated polytriazole materials) by different methods (e.g. phase inversion, electrospinning) [50, 51].

A water vapor flux of about 89 kg/m^2h was obtained at feed and permeate inlet temperatures of 80 ^oC and 20 ^oC, respectively, which is the highest reported flux obtained using real seawater as feed solution. A solar MD pilot plant is being designed using the optimized experimental data and will be tested at KAUST for long term operation using Red Sea water.

6.3 Geothermal desalination

A combined-cycle solar and geothermal powered AD process developed by our group was recently reported [33]. The major advantage of using this heat source configuration is that the daytime use of SE would not have to have a nighttime and/or cloudy period thermal energy storage component which can be quite costly to develop. Also, the development of HDR geothermal energy is less expensive because the depth of the wells can be less. The overall heat harvesting scheme can operate at lower temperatures and the heat sink will not deplete the heat reservoir because there is a recovery period each day.

Preliminary modeling conducted on the HDR system showed that the breakthrough of heat loss from an injection well to the recovery well will take greater than 8 days. This means that the HDR geothermal harvesting scheme can operate continuously for this period for the relatively shallow wells depth being considered at about 1,500 m below surface (Figure 10).

7. Conclusions

Water and energy resources are intertwined, within the water-energy nexus, and they no longer can be looked at as two separate issues and/or challenges. Both water and energy can be either non-renewable or renewable, depending on water and energy management and sources. While fossils fuels are clearly viewed as non-renewable, some water sources (e.g., fossil groundwater) can be viewed likewise. With rapid depletion of both resources at an alarming rate, there have been environmental ramifications, including GHGs, emissions causing global climate changes. Energy mixes including alternative resources, such as solar, wind and geothermal energies, should become a common practice. Their usage should become part of the energy demand, instead of fossil fuel resources; preserved for the future generations. Rather than using more energy for producing freshwater from seawater, more emphasis should be given on water reuse and recycling to minimize the stress on dwindling water supplies. Therefore, a more holistic and universal approach is needed for resolving these critical issues. This paper has addressed some of the significant progress that have been occurring in recent years to attend these important issues through scientific research and policy changes. Now, utilities of all sizes are putting more emphasis on RE, such as solar, wind, geothermal, to incorporate them in water production. Although some are have already integrated in a medium to large scale setting, these have now become prime examples for reference. With the concept of keeping the energy usage in mind, many new technologies, such as FO, MD, AD and hybrid systems are now being developed. Some of these new, innovative technologies show that not only they are energy efficient in treatment, but also in incorporation of RE will make them even more efficient. These technologies use less energy and chemicals, resulting in producing less GHGs and climate change for the future. Therefore, more energy efficient and integrated green-technologies are needed to meet growing water and energy needs.

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Figure 1

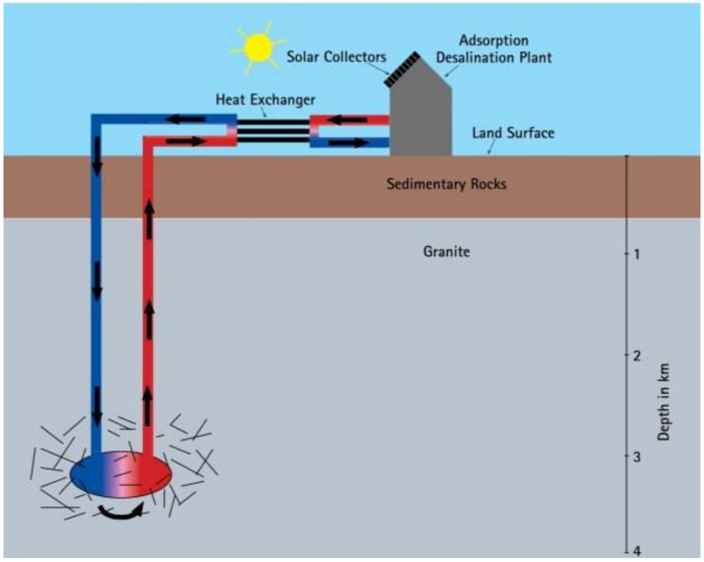

Figure 1: Combined-cycle geothermal and solar powered desalination. The system is powered by SE during daylight hours and by geothermal during nighttime and cloudy days. The combined cycle operation allows the geothermal heat source to regenerate, thereby allowing shallower, less expensive collection wells to be drilled from [33].

Figure 2

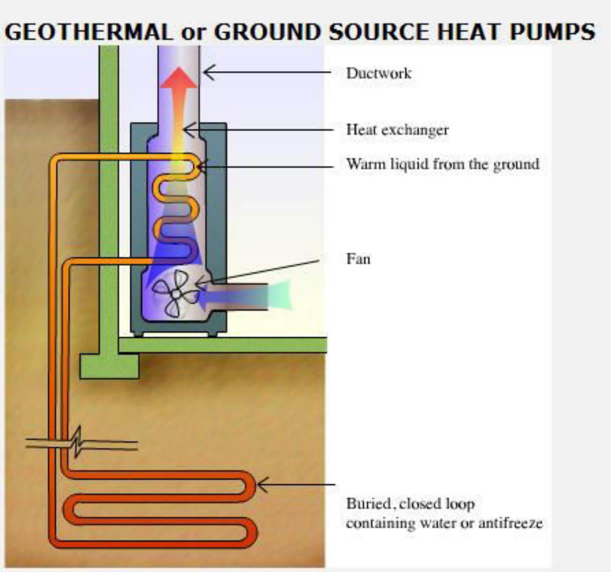

Figure 2: Geothermal heat pump system used in HVAC systems. Water can also be pumped from geothermally-heated aquifer systems.

Figure 3

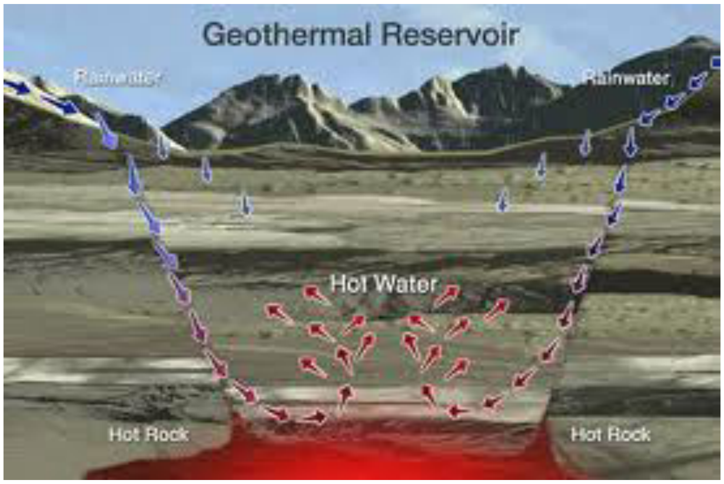

Figure 3: Dry steam can be collected by drilling a deep well into volcanically superheated water that flashed to steam at the wellhead (internet image).

Figure 4

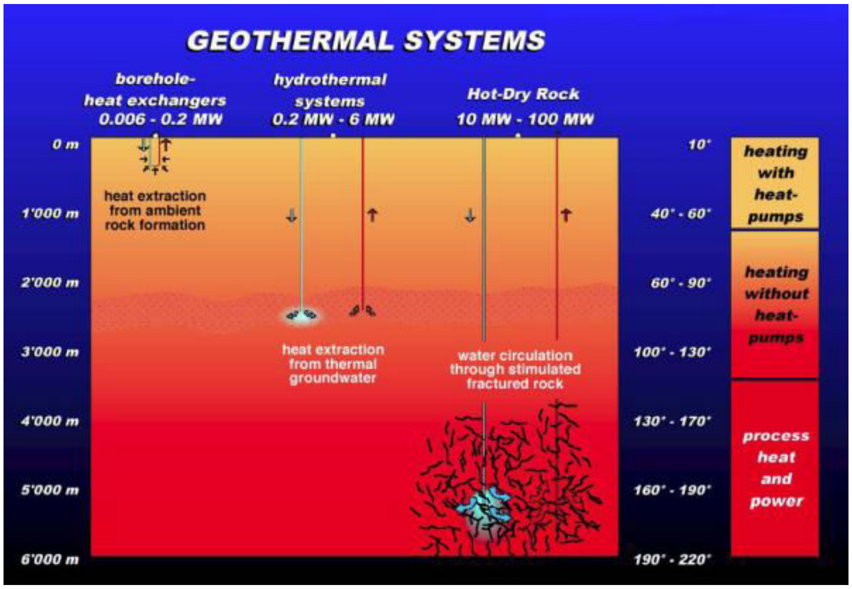

Figure 4: HDR geothermal collection systems can be engineered using hydraulic fracturing techniques to enhance fluid flow and allow better heat exchange.

Figure 5

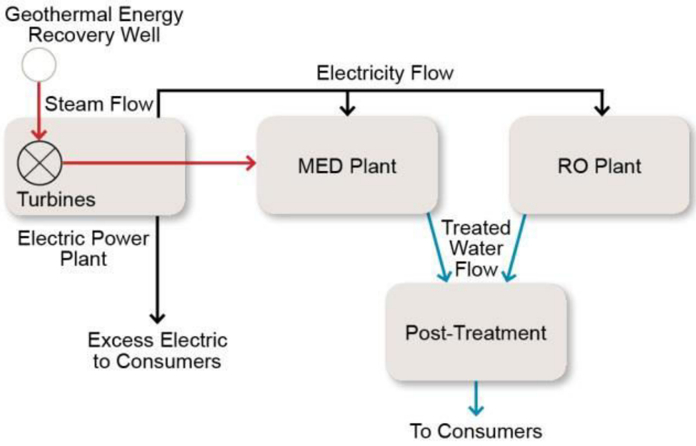

Figure 5: Coupled HDR geothermal energy collection-electric generation-desalination processes to efficiently cycle latent heat.

Figure 6

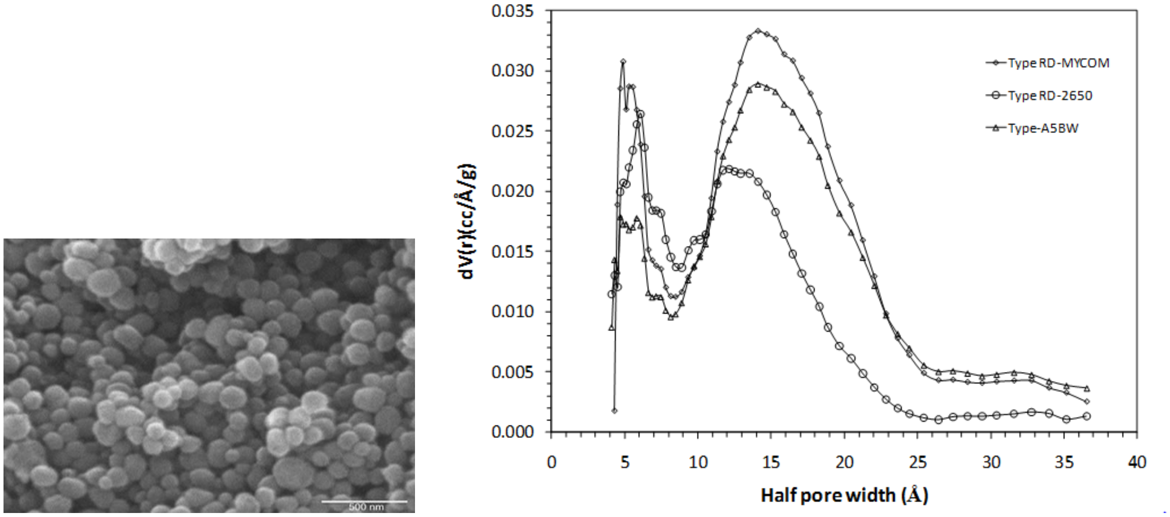

Figure 6: (a) A surface picture of the silica gel at 10,000 magnification, (b) Pore size distribution of three different parent silica gels.

Figure 7

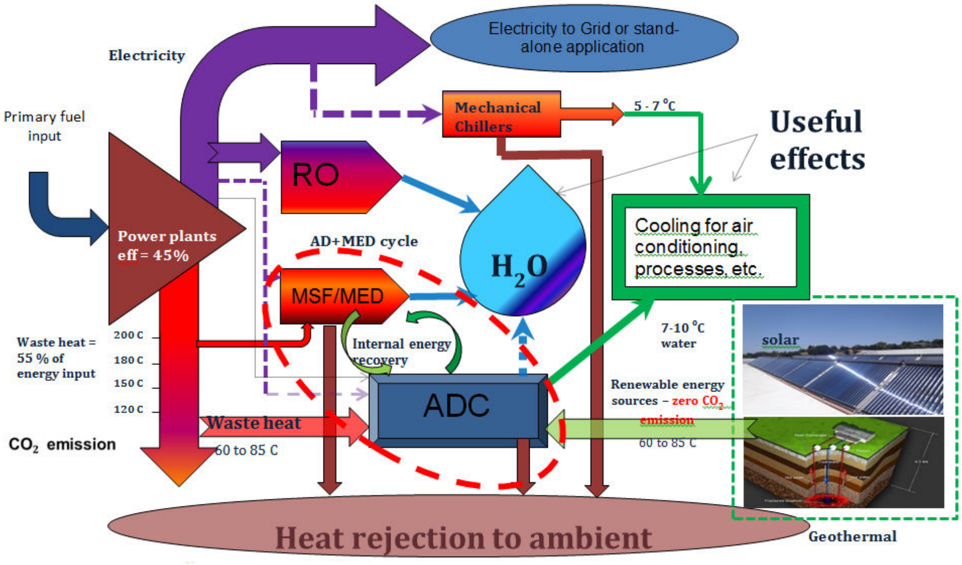

Figure 7: The niche of ADC technology for water and cooling production. It utilizes low temperature heat sources and is able to hybridize with conventional thermal desalination technologies.

Figure 8

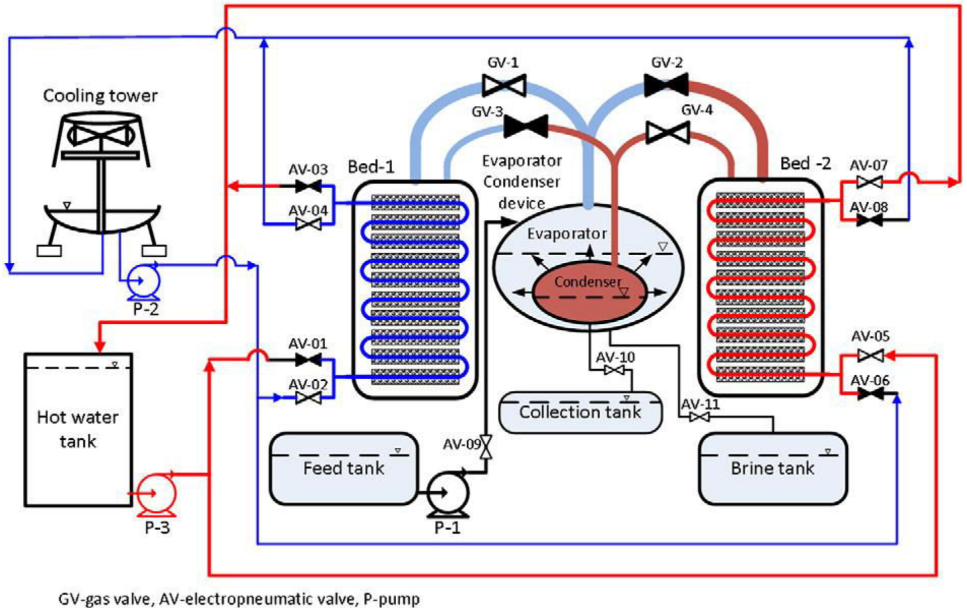

Figure 8: The schematic of an ADC with a 2-bed configuration. The specific cooling and water production capacities are 25 Rton and 12 m^3 per day, respectively, per ton of silica gel.

Figure 9

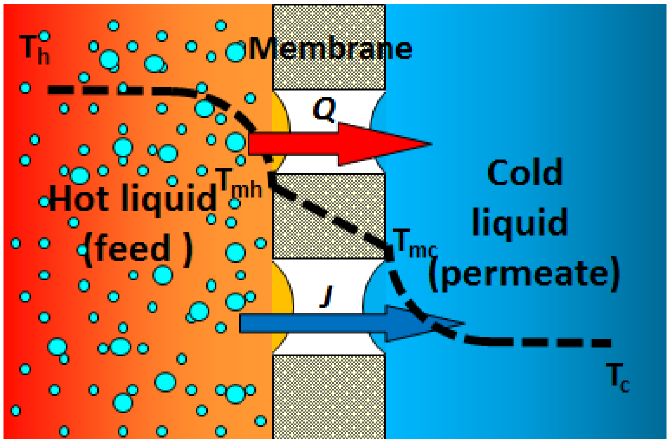

Figure 9: Principle of DCMD process.

Figure 10

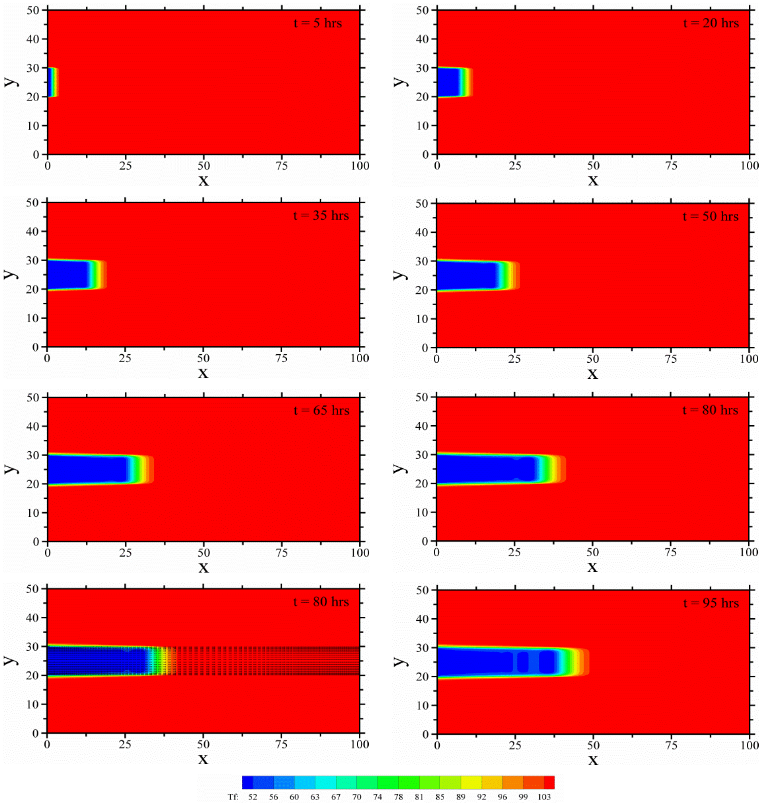

Figure 10: Model showing the migration of cool water from the injection well on the left side of the field to the recovery well on the right side of the field. The scale is in °C. Note that the cool water does not break through to the recovery well for over 95 hours. The second graphic showing flow at t=80 hours includes the flow vectors [33].

Table 1: Desalination capacity in m^3/day in KSA [12].

	MED	MSF	RO	Total
Gulf coast	833,844	3,140,459	923,020	4,897,323
Red Sea coast	324,780	2,446,478	1,707,012	4,478,270
Inland locations/inland	19,173	12,491	359,425	391,089
Total	1,177,797	5,599,428	2,989,457	9,766,682

Table 2: Energy demand of desalination processes and other water supply options [1, 15-17].

Water supply	Main energy form	Electrical energy [kWh/m^3]	Thermal energy [MJ/m^3]
BWRO	Electrical	0.5-3.0 [15]; 0.5-2.5 [1]	
SWRO	Electrical	2.5-7.0 [15]; 3-4 [1]	
MSF	Steam/thermal	3.0-5.0 [15]; 2.5-4 [1]	250-330 [15]
MED with TVC	Steam/thermal	1.5-2.5 [15]; 1.5-2 [1]	145-390 [15]
Surface water treatment	Electrical	0.2-0.4 [16, 17]	
Waste water reclamation	Electrical	0.5-1.0 [16, 17]	
Long-distance water transport [*]	Electrical	1.6-2.8[**] / 12.0[***]	

BWRO: Brackish water reverse osmosis

TVC: Thermal vapor compression

[*] Depends on the transport distance and the elevation gap between source and destination, e.g., normal distribution costs are around 0.5-0.6 kWh/m^3

[**] Power required to convey surface water to San Diego, Los Angeles and Orange County [16]

[***] Power required if water was conveyed to Perth via the Kimberley pipeline [18]

Table 3: A schedule of processes in a batch-operated ADC. The optimal intervals are dependent on the temperatures of heat source, cooling and chilled water.

Heat exchanger (-)	Cycle 1 (Time interval = 250-900s)	Switching 1 (Time interval = 20-45s)	Cycle 2 (Time interval = 250-900s)	Switching 2 (Time interval = 20-45s)
Bed-1	Adsorption	Pre-heating	Desorption	Pre-Cooling
Bed-2	Desorption	Pre-cooling	Adsorption	Pre-heating