Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications of integrated systems

Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications of integrated systems

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Abstract

Despite the tremendous improvements in conventional desalination technologies, its wide use is still limited due primarily to high energy requirements which are currently met with expensive fossil fuels. The use of alternative energy sources is essential to meet the growing demand for water desalination. In the last few decades a lot of effort has being directed in the use of different renewable energy (RE) sources to run desalination processes. However, the expansion of these efforts towards larger scale plants is hampered by several techno-economic challenges. Several medium-scale RE-driven desalination plants have been installed worldwide. Nevertheless, most of these plants are connected to the electrical grid to assure a continuous energy supply for stable operation. Furthermore, RE is mostly used to produce electric power which can be used to run desalination systems. This review paper focusses on an integrated approach in using RE-driven with an emphasis on solar and geothermal desalination technologies. Innovative and sustainable desalination processes which are suitable for integrated RE systems are presented. An assessment of the benefits of these technologies and their limitations are also discussed.

Keywords: Renewable energy; Desalination; Solar and geothermal energy-driven integrated systems; Emerging processes; Sustainable technologies.

1. Introduction

Water desalination has become a technologically and economically viable solution to tackle the challenges associated with increasing water shortages existing in many regions of the world [1,2]. Yet, desalination is an energy intensive process normally requiring high tonnage plants that

utilize expensive and non-renewable fossil fuels, which in turn contribute to global warming and air pollution [3-7]. While some countries are rich in conventional energy sources, such as oil and gas, others depend on fossil fuel imports. Furthermore, environmental restrictions, and continuously increasing fossil fuel prices, are two of the main constraints for technologies that utilize fossil fuels [8]. Likewise, oil producing countries such as those found in the Gulf Cooperation Council (GCC) have realized that they are vulnerable to any future global energy crisis. As a result they have developed plans to diversify their energy sources. This diversification includes renewable energy (RE), sources primarily solar [9]. Saudi Arabia, for example, has targeted 23% and 39% of energy produced by concentrated solar power (CSP) and photovoltaic (PV) by 2030 and 2050, respectively [9].

The current installed desalination capability using RE is negligible compared to the world's total capacity [10,11]. For example, as stated by the Prodes Group-Experts [12], the target for the use of solar energy (SE) is a 3-5% share of new installations in the global desalination market by 2016. Worldwide, several small-scale RE-driven desalination plants have been installed and most of them have been successfully operated and proved that they need very simple maintenance [13-20]. However, a major goal is to identify and assess RE sources as a precondition to satisfy the ever growing demand for freshwater in an economically and environmentally sustainable way especially in water-scarce regions. Solar, and possibly geothermal energy (GE) could be a good alternative source because it is permanent, abundantly available and is environmentally friendly [8,13]. However, most of the installed plants are connected to a grid from where the desalination plants are fed (i.e. compensation). In fact, the electricity produced by RE could be used for any other application such as air-conditioning systems.

Although renewable desalination systems cannot currently compete with conventional technologies in terms of the cost of water produced, they remain applicable for remote and arid areas and are likely to represent a feasible solution at the large scale in the near future.

There has been much progress over the past decade in advancing the development of new emerging seawater desalination technologies which could significantly lower specific energy consumption compared to the present conventional processes such as seawater reverse osmosis (SWRO). As a baseline, SWRO is an energy-intensive process that has a specific energy consumption of 3 - 4 kWh/m^3 (electrical energy only) with energy recovery. As a comparison,

multi-stage flash (MSF) and multi-effect distillation (MED) have a specific energy consumption of 10-16 kWh/m^3 and 5.5-9 kWh/m^3, respectively, (about 7.5-12 kWh/m^3 thermal and 2.5-4 kWh/m^3 electrical energy, and 4-7 kWh/m^3 thermal and 1.5-2 kWh/m^3 electrical energy, respectively) [3].

Innovative low-energy desalination processes which provide an opportunity to lower energy consumption to, potentially, below a threshold of 2 kWh/m^3 have been developed such as adsorption desalination (AD) and membrane distillation (MD). These processes can be driven by waste heat, SE or GE. In some cases, these technologies may substitute for SWRO while, in other cases, they represent potential niche applications (e.g., water extraction from desalination brine or produced water treatment).

A combination of several RE sources is also possible. Missimer et al. [21] 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.

The aims of this review paper are to evaluate different RE technologies and the potential matches between the individual desalination and RE technologies, to assess water desalination using various integrated RE-driven desalination technologies, to discuss their limitations and promotion in regions where RE, such as SE or GE, are abundantly available and to assess innovative desalination technologies which are more suitable for integrated RE-driven systems and have great potential for hybridization and scale up. The market potential, environmental concerns, socio-economic factors are also evaluated as well as the needs for accelerated development of RE-driven desalination technologies.

2. Global desalination capacity and trends

Many water-stressed and/or arid regions are augmenting their water supplies with desalination to meet the increased demands caused by increased population, industrial expansion, tourism, and agriculture development. In some areas, desalination is no longer a marginal or supplemental water resource. Some countries such as Qatar and Kuwait rely 100% on desalinated water for domestic and industrial supplies [22].

At present (i.e. first quarter of 2014), the total global desalination capacity stands at 81 million m^3/day. This is expected to reach over 100 million m^3/d by 2015 [10]. On a global scale, 68% of the desalinated water is produced by membrane processes and 30% by thermal processes. The remaining 2% is produced by other technologies. Desalination water is split with 59% from seawater and 22% from brackish groundwater sources, and the remaining from surface water and saline wastewater [10]. Furthermore, these figures are constantly changing because the desalination market is growing very rapidly.

The growth of desalination capacity worldwide is shown in Figure 1. Thermal desalination was widely used before the 1990's – that is right before membrane technology started to gain in popularity. The membrane technology based desalination market is mostly dominated by reverse osmosis (RO), while the thermal market is in competition between MSF and multi-effect distillation (MED).
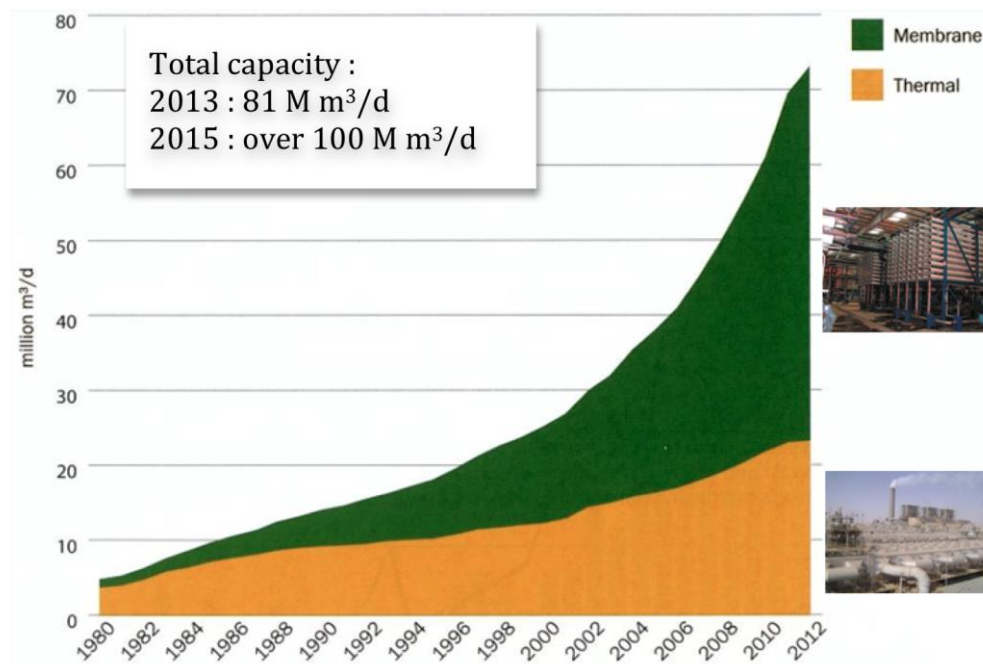

Figure 1. Installed membrane and thermal water desalination capacity [10].

The increase in desalination capacity was caused primarily by increased water demand and by the significant reduction in desalination cost as a result of substantial technological advances which made desalinated water cost-competitive [23]. More details on the technical descriptions

and types of energy required for conventional desalination processes may be found in a paper by Ghaffour et al. [3]. In some specific areas, desalination is now able to successfully compete with conventional water resources and water transfers for potable water supply (e.g., construction of dams and reservoirs or canal transfers) [24].

3. Finding the right match between desalination and renewable energy technologies

Selecting the most suitable RE-driven desalination technology depends on several factors such as size of the plant, salinity of the feed water and required product, remoteness, existence of access to an electricity grid, technical infrastructure and the RE source and its availability, potential and exploitation cost. There are several combinations of desalination and RE technologies (Figure 2), which are particularly promising with regards to their economic and technological feasibility. Some combinations are more suited for large-scale desalination plants, whereas others are more appropriate for small-scale applications.
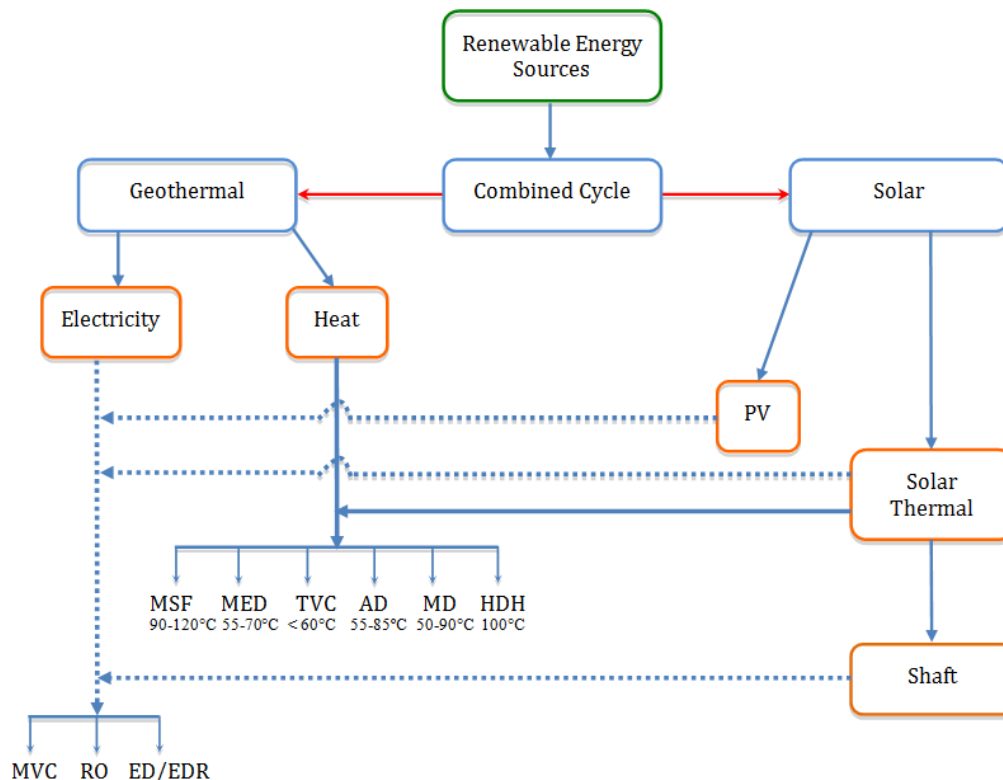

Figure 2. Possible combinations of integrated systems: renewable energy sources with conventional and innovative desalination processes.

The selection of the best technology or process requires chemical characterization of the raw water resources that shall be desalinated or decontaminated. Desalination/treatment of polluted surface water or brackish water is more economical compared to seawater since its salinity is lower and therefore the energy required is less. Brackish water is frequently available in inland areas whereas seawater is often the only available water source in coastal areas.

Thermal energy can be used directly to drive distillation processes. Compared to MSF plants, MED plants have the advantage that they are more flexible to operate at partial loads. In addition they are less sensitive to scaling, cheaper and more adequate for limited capacity [4-6,14,25]. Nevertheless, they remain energy intensive processes accounting for up to 50% of the operating cost [4-6, 25,26] and their gain output ratios (GOR) are limited (i.e. huge amounts of feed water needs to be heated), which may limit their integration with RE. Furthermore, the MSF electrical consumption is almost equivalent to the total energy required for SWRO [3] which is favoring MED over MSF since the electricity demand for MED is much lower (only 1.5-2 kWh/m^3). If electricity is produced from solar RE (not widely covered in this paper) it can be used to power membrane desalination (RO, electrodialysis (ED)) or mechanical vapor compression (MVC) technologies.

As experience has shown, there are no significant technical obstacles in combining RE and desalination technologies. The most frequently used combination is PV with RO. Since heat losses are more significant in small thermal distillation units, large sizes are more attractive. More recently, a combination consisting of RE-powered MD and AD processes have shown promising results. Several MD pilot plants powered with SE and GE have been installed [27-31]. They showed better performance with less operational challenges compared to conventional processes. In addition, a 8 m^3/day solar AD pilot unit installed at KAUST (King Abdullah University of Science and Technology) in Saudi Arabia produced not only high quality water with less energy consumption but also provided cooling which is suitable for air-conditioning at a nominal capacity of 10 Rtons (refrigeration tons) [13,32]. Details of these innovative processes are presented in Section 5.1.

4. Renewable energy systems challenges and trends

4.1. Concentrated solar power

CSP is an electricity generation technology that uses heat provided by solar irradiation

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concentrated on a small area. Using mirrors, sunlight is reflected to a receiver where heat is collected by a thermal energy carrier (e.g. molten salt). This thermal energy can be used directly in thermal desalination plants or it can subsequently be used directly in a secondary circuit to power a turbine and generate electricity. In order to provide continuous and year round operation, the CSP process can be enhanced by the incorporation of two technologies, i.e., thermal energy storage and backup systems.

At present, there are four available CSP technologies (see Figure 3): parabolic trough collector (PTC), solar power tower (SPT), linear Fresnel reflector (LFR) and parabolic dish systems (PDS). A recent technology called concentrated solar thermoelectrics was also described by Zhang et al. [33]. These medium to large-scale operation CSP technologies are currently located in Spain and in the USA. Zhang et al. [33] argues that while PTC technology is the most established CSP scheme, solar tower technology occupies the second place and is of increasing importance as a result of its advantages, as will be deliberated further.

Widespread deployment of CSP plants has been hindered by cost and intermittency issues [13]. However, these difficulties may be somewhat eased with, for instance, the addition of thermal energy storage using for example molten salt or compressed air underground heat storage (CAES). The latter can be used in place of a natural gas boiler to provide backup energy for a concentrated solar thermal power plant during cloudy periods and nighttime. Wagner and Rubin [34] reported on the economic implications of thermal energy storage for concentrated solar thermal power. The additional equipment associated with a thermal energy storage system can add substantially to the already high capital cost of a plant. An investor, for instance, will only accept the additional cost of these components if the potential exists for an economic benefit that exceeds the extra cost. Wagner and Rubin [34] went on to argue that a price of $US 153 per ton CO_2eq or higher could make concentrated solar thermal power competitive with coal electricity generation.

Zhang et al. [33] in an excellent review noted that concentrated solar power (CSP) plants are gaining increasing interest, mostly by using the parabolic trough collector system (PTC), although solar power towers (SPT) progressively occupy a significant market position due to their advantages in terms of higher efficiency, lower operating costs and good scale-up potential (Table 1). Large-scale CSP technology was successfully demonstrated by Torresol in the Spanish Gemasolar project [35]. The 19.9 MWe GEMASOLAR Plant became the first CSP commercial

system ever to generate uninterrupted electricity for 24 hours.

Table 1. Comparison between leading CSP technologies (Adapted from [33]).

	Relative cost	Land occupancy	Cooling water (L/MW h)	Thermo-dynamic efficiency	Operating T range (°C)	Solar concentration ratio	Outlook for improvements
PTC	Low	Large	3,000 or dry	Low	20–400	15-45	Limited
LFR	Very low	Medium	3,000 or dry	Low	50–300	10–40	Significant
SPT	High	Medium	1,500 or dry	High	300–565	150–1500	Very significant
PDC	Very high	Small	None	High	120–1500	100–1000	High potential through mass production

4.1.1. Solar power towers and parabolic trough collectors

The very high temperatures achieved with solar towers increases the efficiency at which heat can be produced for thermal desalination or be converted into electricity and also reduces the cost of thermal storage in case of use for electricity generation. SPT, also known as central receiver systems (CRS), use a heliostat field collector (HFC), i.e., a field of sun tracking reflectors, called heliostats that reflect and concentrate the sun's emissions onto a central receiver located at the top of a fixed tower (Figures 3 and 4). Heat is absorbed by a heat transfer fluid (HTF), which then transfers heat to heat exchangers to provide thermal energy for direct applications or to power a steam Rankine or Kalin cycle. The Rankine or Kalin cycle, in the form of steam engines, generates electric power. Some commercial tower plants now in operation use direct steam generation, others use different fluids, including molten salts as the heat transfer fluid and storage medium [33].
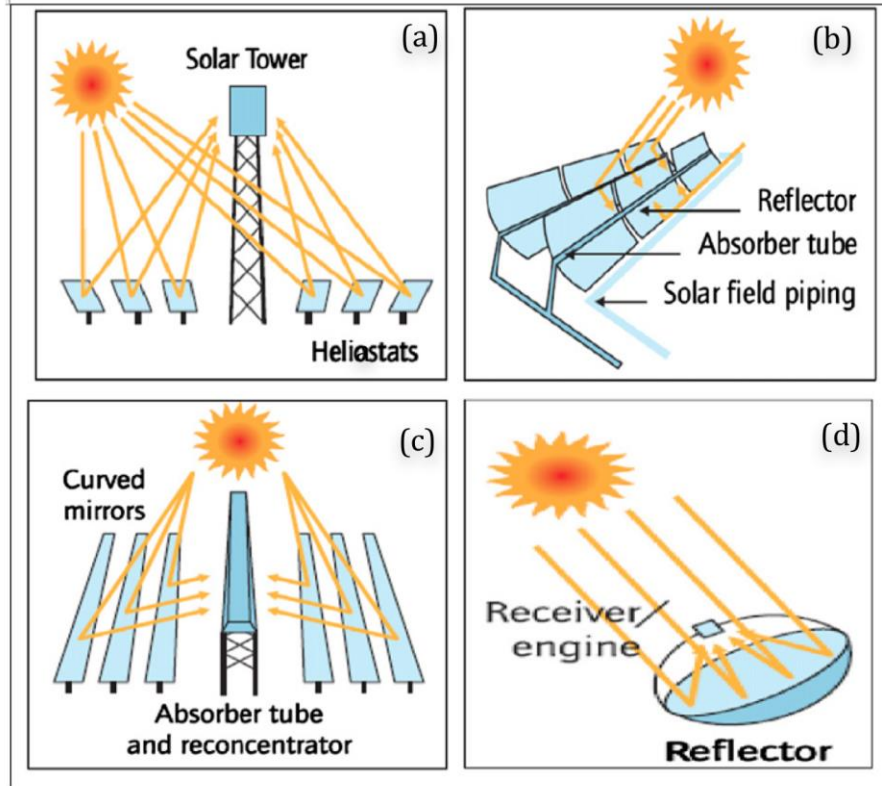
Figure 3. Currently available CSP Technologies: (a) SPT; (b)PTC; (c) LFR; (d) PDC [33].

A PTC focuses sunlight onto an absorber tube that is mounted in the focal line of the parabola. The reflectors and the absorber tubes move in tandem with the sun. Typically, thermal fluids are used as primary HTF, thereafter powering a secondary steam circuit and Rankine power cycle. Molten salts can be used as HTF as well as a direct steam generation system. The absorber tube (Figure 3) is coated with a selective material that has high solar irradiation absorbance and low thermal remittance. Zhang et al. [33] noted that the glass-metal seal is crucial in reducing heat losses.

4.1.2. Parabolic dish systems, Linear Fresnel reflectors and *concentrated solar thermo-electrics*

With parabolic dish collectors (PDC), the entire system tracks the sun, with the dish and receiver moving together. Barlev et al. [36] reported that PDCs are expensive and have a low compatibility with respect of thermal storage and hybridization. Supporters on the other hand argue that mass production will allow dishes to compete with larger solar thermal systems.

According to Zhang et al. [33] the Maricopa Solar Project in Arizona, USA, is the only operational PDC plant, with a net capacity of 1.5 MW.

Linear Fresnel reflectors (LFR) are similar to the parabolic shape of the trough systems by using long rows of flat or slightly curved mirrors to reflect the sunlight to a downward facing linear receiver. Barlev et al. [36] argued that the main advantage of LFR systems is that their simple design of flexibly bent mirrors and fixed receivers requires lower investment costs and facilitates direct steam generation, thereby eliminating the need of heat transfer fluids and heat exchangers. Zhang et al. [33] reported that the first LFR plants, Puerto Errado 1 plant was constructed in Germany in March 2009, with a capacity of 1.4 MW. This was followed by a 30 MW plant in Spain. A 5 MW plant has also been constructed in California, USA.

As well as with photovoltaic (PV) systems, direct conversion of SE into electricity can also be achieved with concentrated solar thermo-electric (CST) technology [33,36]. Thermo-electric energy conversion uses temperature difference across solids to convert heat into electricity. Concentrating solar thermoelectric generators have the potential to achieve greater solar-to-electrical energy conversion efficiency and provide electricity day and night. Zhang et al. [33] contends that the current cost of thermo-electric materials hampers the widespread use of CSTs.

4.1.3. Comparison of CSP technologies

Among the viable CSP technologies, PTC plants are the most established of all commercially operating plants [33]. Table 1 compares the technologies on the basis of different parameters. In terms of cost related to plant development, SPT and PDC systems are currently more expensive. Furthermore, Zhang et al. [33] notes that parabolic dish collectors (PDC) have the smallest land requirement among CSP technologies.

As in other thermal power generation plants, CSP requires water for cooling and condensing processes. For example 3000 L/MWh are required for PTC and LFR plants which is similar to a nuclear reactor and which is higher than that required for a coal-fired power plant [37]. It can therefore be argued that water requirements are of high importance for those locations with water scarcity. However, if the plant is located at the coast, this problem does not exist as seawater can be used for cooling. As water cooling is more effective, operators of hybrid systems tend to use only dry cooling in the winter when cooling needs are lower, then switch to combined wet and dry cooling during the summer [33]. This is a factor that needs to be kept in mind when

designing CSP plants for different locations.

Finally, CSP can be enhanced by the incorporation of two technologies in order to improve the competitiveness with respect to conventional systems: thermal energy storage and backup systems. Both schemes offer the possibility of year round operation, providing a stable energy supply in response to thermal energy or electricity grid demands [38].

4.1.4. Thermal energy storage, backup systems and economics

As mentioned previously, extensive utilization of solar power plants has been hindered by cost and intermittency issues [13]. Nonetheless, these challenges may be to some extent eased with the application of thermal energy storage using for instance molten salt. With thermal energy storage systems excess heat collected in the solar field is sent to a heat exchanger and warms the heat transfer fluid going from the cold tank to the hot tank [33]. When needed, the heat from the hot tank can be used for direct heat applications or be sent to the steam for electricity generation. Storage circumvents losing the daytime excess energy while prolonging the production after nightfall.

Thermal storage can be achieved directly or indirectly. Liquids such as mineral oil, synthetic oil, and molten salts, can be used for sensible heat in direct thermal storage systems. For molten salts, the desired characteristics for sensible heat usage are high density, low vapor pressure, moderate specific heat, low chemical reactivity and low cost [39]. Molten single salts, however, tend to be expensive [36]. Indirect storage is where a heat transfer fluid circulates heat, collected in the absorbers, and then pumped to the thermal energy storage system which is normally a solid material. Fernandes et al. [39] in a good review provided a comparison of various materials for high temperature thermal energy storage. The authors also introduced a potentially useful new energy storage material; a mixture of phase change material embedded in a metal foam. The thermal properties of the material were optimized for latent heat energy storage.

CSP plants, with or without storage, are commonly equipped with a fuel backup system that helps to regulate production and to guarantee a nearly constant generation capacity, especially in peak periods [33]. CSP plants equipped with backup systems are called hybrid plants. Burners can provide energy to the heat transfer fluid, to the storage medium, or directly to the power block. One of the main advantages of the integration of the back-up system with CSP plant is the reduction in the required investments in the solar field and storage capacity. CSP can also be

used in a hybrid mode by adding a small solar field to a fossil fuel fired power plant. These systems are called integrated solar combined cycle plants. Integrated systems will be discussed in more detail in the next section

Using an engineering-economic model Wagner and Rubin [34] argued that if the goal is to encourage the widespread use of CSP plants, incentives such as investment tax credits are necessary to reduce the levelized cost of electricity (LCOE) and result in a positive annual profit. LCOE is often cited as a convenient summary measure of the overall competiveness of different generating technologies. It represents the per-kilowatt-hour cost (in real dollars) of building and operating a generating plant over an assumed financial life and duty cycle. Key inputs to calculating LCOE include capital costs, fuel costs, fixed and variable operations and maintenance (O&M) costs, financing costs, and an assumed utilization rate for each plant type. Table 2 [13], for example, gives a range of estimates of the levelized cost of electricity from a variety of studies. The highest average value is from solar PV at 491 US$/MWh with solar thermal next at 225 US$/MWh (see bottom of Table 2). The challenge here is to significantly reduce the levelized cost of solar thermal technologies to make it more competitive. DeCanio and Fremstad [40] noted that there is every expectation that solar costs will decrease over time with research and experience, and a number of efforts to estimate the rate of decline have appeared in the literature.

Table 2. Estimates of levelized cost (US$/MWh) of electricity by source (adapted from [13, 40]).

Study Reference	Measure	Coal	Nuclear	Wind	Geo-thermal	Solar PV	Solar Thermal
U.S. Energy Information Administration, 2010a, 2010b	$2008 per MWh, 2016	100.4	119	149.3	115.7	396.1	265.6
RETI Stakeholder Steering Committee, 2010	Levelized cost ranges in $/MWh			90-130	100-160	250-350	240-290
Lazard ltd., 2009	Levelized cost ranges in $/MWh	78-144	107-138	84-140	85-120	212-296	199-325
Borenstein, 2008	$/MWh, annual real interest rate from 1-7%					337-565	
Renewables 2010 Global Status Report	Typical energy cost, $/MWh			50-90 (Onshore) 100-140 (Offshore)			
Benson and Orr, 2008	$/MWh (2007$)	43		75		280	200
Greenpeace Int., SolarPACES, and ESTELA,2010	$/MWh at sites with very good solar radiation						150
IEA/NEA 2005	$/MWH, see IEA/NEA 2010 for details	28-75 (pulverized)	33-74	50-156 (Onshore) 71-134 (Offshore)		226-2031	292
European Commission 2008	$/MWh, see IEA/NEA 2010 for details	52-65 (pulverized)	65-110	97-142 (Onshore) 110-181 (Offshore)		674-1140	220-324
EPRI 2008	$/MWh, see IEA/NEA 2010 for details	64 (pulverized)	73	91			175
IEA/NEA 2010	$/MWh	54-120 (r = 5%) 67-142 (r = 10%)	29-82 (r = 5%) 42-137 (r = 10%)	48-163 (onsh. r = 5%) 101-188 (offsh. r=10%)		215-333 (high load) 600 (low load)	136-243
Average	$/MWh	79	84	112	99	491	225

4.2. Solar thermal desalination

Thermal desalination such as MSF, MED and VC are energy intensive processes especially in areas with higher water salinity levels such as in the Middle East and GCC countries (35-45 g/L) [41]. Those regions are characterized by abundant solar energy; typical solar radiation ranges from 2200–2400 kWh/m^2 year [42]. The scarcity of water and the availability of solar radiation make solar energy the most suitable option to mitigate the water deficit [31].

Solar thermal desalination consists of two separate devices; the commercial solar thermal collector and the conventional distiller (desalination plant). The solar collector can be a flat plate, evacuated tube or solar concentrator and it can be coupled with any of the thermal desalination processes types which use the evaporation and condensation principle, such as MSF, VC, MED

and MD [31].

The most relevant solar thermal plants implemented in the world are summarized in Table 3 [43-56].

Table 3. Summary of solar thermal desalination plants in the world [43-56].

Project	Capacity (m³/day)	Process
Margarita de Savoya, Italy [43]	50–60	MSF
Islands of Cape Verde [44]	300	Atlantis 'Autoflash
Tunisia [45]	0.2	MSF
El Paso, Texas, USA [46]	19	MSF
University of Ancona, Italy [47]	30	MEB
Dead Sea, Jordan [48]	3000	MEB
Safat, Kuwait [48]	10	MSF
Takami Island, Japan [43]	16	ME-16 effects
Abu Dhabi, UAE [49]	120	ME-18 effects
Al-Ain, UAE [50]	500	ME-55 stages, MSF-75 stages
Arabian Gulf [4]	6000	MEB
Al Azhar University, Palestine [51]	0.2	MSF 4 stages
Almeria, Spain [52]	72	MED-TVC 14 effects
Berken, Germany [53]	10	MSF
Hzag, Tunisia [48]	0.1–0.35	Distillation
Gran Canaria, Spain [54]	10	MSF
La Desired Island, France [55]	40	ME-14 effects
Lampedusa Island, Italy [56]	0.3	MSF
Kuwait [43]	100	MSF
La Paz, Mexico [57]	10	MSF 10-stages

4.3. Photovoltaic desalination

Much research has been presented to address the potential use of SE for water desalination [57-59]. PV technology can be connected directly to a RO system. Many prototypes have been implemented and tested in different regions suffering from freshwater shortage. Ahmad et al. [60] studied the feasibility of brackish water desalination in the Egyptian desert using PV systems. In the same context, Gocht et al. [61] reported the Jordanian experience on a brackish water PV-RO system, while Richards et al. [62] outlined a solar powered desalination system for remote communities in Australia. Feasibility studies for PV-powered RO systems have been performed for Agrigento in Sicily [63] and Ginostra in Sicily [64]. Calice et al. [65] investigated a novel solar tri-generation system integrating PV thermal collectors and seawater desalination.

Kalogirou [66], Tzen et al. [67] and Bouguecha et al. [68] evaluated PV–RO desalination systems. Al Suleimani and Nair [69] reported the Omani experience and presented a detailed cost

analysis of a pilot plant installed at Heelat ar Rakah camp of the Ministry of Water Resources. Thomson and Infield [70, 71] and Thomson et al. [72] reported an interesting study based on the simulation and implementation of a PV-driven RO designed for Eritrea. The system was operated at variable flow and without need for batteries storage. Hasnain and Alajlan [73] performed a cost analysis on a PV-RO brackish water desalination plant in Riyadh, Saudi Arabia. Joyce et al. [74] proposed an interesting small PV-RO system designed for small rural sites or which could be used during catastrophes when potable water is not accessible. Herold et al. [75] reported the Spanish experience with its small RO plant supplied by a PV power supply fitted at the Gran Canaria Island. Finally, Khaydarov and Khaydarov proposed a new solar-powered direct osmosis process driven by natural osmosis, installed in a village in the Aral Sea region (Uzbekistan) [76]. The process does not require external pumping energy as in the RO process.

The use of PV cells with ED is more attractive than RO for remote areas in which SEand brackish water are available throughout the year. Several pilot plants of ED systems connected to PV cells have been implemented.

Lundstorm [77] was a pioneer who presented the first small-scale process for water desalination using PV- ED. Experimental research on PV- ED was also performed at Laboratory for Water Research, University of Miami, USA [78] and at the University of Bahrain [79]. Ishimaru [80] assessed the feasibility of a brackish water ED system operated by photovoltaic cells in a remote area of Japan. Gomkale [81] concluded that PV-ED seems to be more advantageous for desalting brackish water than conventional solar still for remote Indian villages. The Bureau of Reclamation (USA) [82, 83] planted a PV driven ED plant in the Spencer Valley, in New Mexico. AlMadani [84] performed an experimental device of ED associated with photovoltaic cells. The influences of process parameters (flow rates, temperature) were assessed. Ortiz et al. [85] presented a mathematical model that can both predict the functioning of an ED system powered by photovoltaic energy and allows the design of the system.

Many other PV-ED systems were installed in many parts of the world, the most important are: Thar desert, India [86], Spencer Valley, New Mexico [82], Ohsima Island, Nagasaki, Japan [87] and Fukue city, Nagasaki, Japan [88].

The main limitation in using PV technology for water desalination is the high cost of PV cells. According to a new report published by GTM Research, production costs for PV cells

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industry will fall from 50 cents per watt in the fourth quarter of 2012 to 36 cents per watt by the end of 2017. The report predicts that the majority of these cost declines will derive from technology innovations such as diamond wire sawing for PV wafers, advanced metallization solutions, and increased automation in place of manual labor [89]. Consequently, in the near future PV technology can be expected to compete with conventional resources.

4.4. Concentrating photovoltaic technology

A concentrating photovoltaic (CPV) system converts light energy into electrical energy in the same way that conventional PV technology does except that they use optics to concentrate the sun onto solar cells that do not cover the entire module area. Traditional PV systems utilize large amounts of silicon solar cells. In contrast, CPV systems utilize a small amount of high-efficiency solar cell material. The cells used in high concentration CPV systems are referred to as multi-junction or III-V cells. However, CPV modules must accurately face the sun. Therefore, CPV modules are used in conjunction with high-performance trackers that intelligently and automatically follow the sun throughout the day with the aim to keep the focal point on the cell as the sun moves across the sky. CPV, with its higher efficiency delivers higher energy production per megawatt installed and provides the lowest cost of SE in high solar regions of the world [90,91].

Recently, the International Business Machines Corp (IBM) and the King Abdulaziz City for Science and Technology (KACST), Saudi Arabia's national research and development organization, have initiated a joint research collaboration aimed at building a new, energy-efficient desalination plant in the city of Al Khafji with an expected production capacity of 30,000 m^3/day. The plant will be powered with the ultra-high concentrator photovoltaic (UHCPV) technology that is being jointly developed by IBM and KACST which could significantly reduce water and energy costs [11].

4.5. Geothermal direct heat for desalination
4.5.1. Geothermal energy as heat source for direct desalination

Electricity generation from high-enthalpy geothermal resources (>150°C), which in the case of the exploitation and power generation from on-shore geothermal resources is a mature technology that has been developed and applied during the last four decades. It is obvious that

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this energy source is a very suitable option for electricity-driven desalination technologies. However, direct geothermal heat applications, often from low-enthalpy resources (50-150°C) did not receive much attention in the past due to poor economic feasibility if temperatures are less than 120°C. However binary technologies are continuously improving and electricity generation gets ever more economical at ever lower temperatures. These resources are applied mostly on small-scale in industry, agriculture, households and for bathing. Globally installed geothermal heat consisted of 48,493 MWt (Megawatt thermal) by 2009, thermal energy: 423,830 TJ/year (117,740 GWh/year) [92]). However, they are used in a large number of countries (78 reported in the year 2010 [19]).

Compared with other RE sources, the huge benefit of the geothermal option is that it provides a constant stable energy. In contrast, solar and wind energy are intermittent so that they require technically more complex capturing devices and costly energy storage devices which further are limited in size so that scale-up large units is hindered. All these negative impacts do not exist in the geothermal option. However, high exploration costs, the high investment risk and high installation costs are disadvantages if new geothermal reservoirs are targeted. Nonetheless, these high costs will be off-set by freely available geothermal heat production during operation of the desalination unit (in contrast to heat produced from fossil fuel, which permanently requires purchasing fuels if no waste heat can be used). In addition, there are several cases, where the high exploration cost and the investment risk can be eliminated; these options will be discussed in the next section. Geothermal heat provision from geothermal resources is generally below the cost of solar, and can be therefore highly beneficial in areas where suitable geothermal resources are available; however, economic modes must prove – on a case-by-case basis, which option is the most beneficial; also the combination of solar and geothermal in hybrid systems can provide a possible option to be evaluated.

4.5.2. Low-cost, low-enthalpy geothermal heat (0-150°C)

Low-enthalpy geothermal aquifers can be accessed at depths close to the surface down to several hundred meters whereas high-enthalpy hydrothermal resources are mostly exploited at depths between 1000 and 3000 m. Therefore, the exploration and exploitation of low-enthalpy geothermal heat is much less costly due to less drilling, which corresponds to the largest part of the exploration and exploitation costs. Lower temperatures also mean lower cost regarding

infrastructure and materials for the capture of geothermal heat (e.g. non-corrosive plastic pipes), and in most cases, less occurrence of scaling, lower grade of mineralization and less aggressivity of the fluids to pipes and infrastructure.

It is of key importance to consider the following options, that can provide low-cost geothermal heat and which can be found in many places around the world:

(i) Hot water, which is co-produced in large volumes, during hydrocarbon exploitation, which is a waste product and requires expensive management (nominal value of 0.50 US$ per barrel oil produced [93]); using its heat content, e.g. for thermal desalination, could set-off part of these costs. That the heat potential of the coproduced water can be high can be demonstrated using the study in the seven Gulf Coast states (USA). The potential for electricity generation should consider only fluids with temperatures above 100°C which results in a value of 985-5300 MWe [94,95]. Considering a minimum temperature of 50°C, for direct heat applications, such as geothermal desalination, potentials are obviously larger. These resources need assessment on a global scale.

(ii) Heat from other existing deep wells and underground mines can provide heat at temperatures >50°C in areas where the natural geothermal gradient and/or depth of the well/mine are large enough to reach these temperatures. Especially attractive are wells that have been drilled during the last four decades for geothermal exploration but then have been abandoned as temperatures were too low for electricity generation.

(iii) In many cases, the heat of residual fluids from geothermal power plants (80-150°C depending on resource type and power generation technology used), is not used and fluids are just injected underground. This heat can be used for thermal desalination.

(iv) Heat from shallow coastal off-shore/on-shore heat resources can be another attractive option as the access to these resources is at moderate to low cost (depending on the individual site) and the brine produced during the desalination process can be simply discharged into the sea [96]. Coastal-offshore geothermal resources are addressed in more detail in the next section.

(v) In many places around the world, there exist geothermal springs, the heat of this water can be used for thermal desalination at smaller scale if temperatures exceed 50°C. Alternatively, shallow wells can be drilled to increase temperature and the amount of extractable heat.

4.5.3. Submarine geothermal resources

Submarine geothermal resources have only been marginally considered for energy purposes and only recently a large research project on their exploitation has been started in Italy [96]. The heat of submarine geothermal resources can be excellent energy sources for thermal desalination, which can take place either offshore or onshore at the coast. Seawater desalination powered by heat from offshore geothermal resources has several disadvantages but also some significant benefits when compared to onshore geothermal resources. It allows the easy discharge of brines/wastes from the desalination into the sea. No land space is needed, a fact that is especially important when considering small islands. The reservoir needs no cap rock, and recharge of the reservoir is guaranteed through seawater [97]. The visual environmental impact is less; however discharging geothermal fluids may negatively influence the marine environment and need proper management [98].

At present, submarine geothermal resources are not used. This is despite the fact that these energy resources are much larger than offshore geothermal resources. However, these resources have been recently considered for exploitation using mature technologies from onshore geothermal and offshore hydrocarbon exploitation [99,100], which makes this an economical affordable option to provide energy for various industrial, agricultural and domestic direct heat or electricity purposes [97-99]. The use of submarine geothermal resources for desalination benefits from the fact that seawater is on-site and that the residuals (brines or salts) can be disposed easily back into the ocean without constituting any environmental damage.

In respect to occurrence and accessibility – and therefore scale of projects - , there are two principal types of offshore geothermal resources: (i) deep resources, located along marine spreading zones which have a global extent of 65,000 km^2 [101], at depths between 1,000 and 4,000 m below sea level where geothermal fluids discharge at vents into the seawater (e.g. at 350° average velocity of 0.15 m/s at 21°N on the East Pacific Rise [102], at 400°C [103-105]; at 464°C at the Mid-Atlantic Ridge [106]), and (ii) coastal resources found at depths between 1 and 50 m. Both types of resources have been described in the scientific literature from all over the world; however this research did not target their use as energy resources (e.g., [107-122]). Heat capacities of individual vents are 60 to 5,000 MWt [123].

So far, offshore geothermal resources have only been evaluated for electricity generation. Hiriart et al. [101] considered submarine geothermal binary cycle plants at the top of vents to power seawater desalination plants at the Gulf of California where they estimated the electrical

capacity of an average vent (24" diameter; 1 m/s discharge velocity; 365°C discharge temperature) to be 20 MW. However the heat could be much more efficiently used if the 450 MW_t are applied as direct heat for thermal desalination.

That the exploitation of large-scale offshore geothermal resources can be an economically affordable option for large scale electricity supply has been demonstrated by the preliminary results of the Marsili project, which targets the exploitation of the geothermal reservoir of the Marsili seamount area in South Tyrrhenian Sea (geothermal potential of Marsili area: 1 GWe; [98, 99, 124]. A 200 MWe pilot project would require an investment of 700 million euro and could produce 1.46 TWh/year of electricity [97,124]. Some rough estimates indicate that the full exploitation of the thermal potential of the entire volcanic district of the South Tyrrhenian Sea, could satisfy 7-10% of the actual Italian electricity demand [97, 124]. Using these resources for thermal water desalination should be considered for water scarce Italy with its ever increasing demand.

Middle-scale off-shore geothermal heat use to power thermal desalination can be considered for areas where shallow coastal geothermal resources are available including islands, e.g. those of the Caribbean, the Mediterranean and the Pacific where extensive submarine hydrothermal systems have been described e.g. in the areas of Tonga [125,126], However these geothermal systems have yet been exploited despite the fact that temperatures range from 245-265°C and their easy accessibility at depths of only 385-540 m [127,128] and a distance of only 50 km from Tongatapu [125]. The same is true for the region of the Northern Marianas Islands where high heat flux of submarine systems has been reported along the Mariana arc [125,129]. The shallow geothermal potential of the Gulf of California (Mexico) has a minimum geothermal potential at around 350 MWt/km^3 (rock) corresponding to 8,100 MWe, (average temperature 350°C and the caldera area of Santorin island (Aegean, Greece) gas a geothermal potential of 869 MWe [98]. These potentials could easily produce freshwater to entirely supply both regions which are water scarce.

4.5.4. Geothermal heat powered desalination technologies

Geothermal heat can be used to power conventional mature and economically proven technologies such as MSF, and MED or technologies still in the development such as MD. Ponds fed or heated by geothermal water, can be employed for desalination (operation temperature: 30-

95°C). Geothermal heat can power MSF plants (operation temperature: at 90-110° [130]) applying a liquid-liquid heat exchanger [131]. Furthermore, the use geothermal heat with MED technology has the advantage that the operating temperature is <70° and therefore lower than that of MSF. In contrast to solar heat used for MED and MSF the units of which are limited to < 100 m^3/day, since the size of solar ponds is economically limited [3], or heat storage is expensive and technically limited in size [14]. The use of geothermal heat does not imply such restrictions to size of the desalination plant so that geothermal can be potential options – of course depending on the site-specific geothermal potential - for small scale (<10 m^3/day), middle scale (10-1,000 m^3/day) and large-scale (>1,000 m^3/day, the present-day largest ones have productivities of about a million m^3/day) [3,132], e.g. Al-Jubail Phase II MSF plant has a production capacity of about 90,0000 m^3/d. The provision of low-cost geothermal heat to power MSF and MED plants makes them especially competitive to RO and ED technologies which require less energy. Geothermal fluids with temperature between 55 and 85°C can be used for AD, which is a very promising innovative technology for desalination (see section 5.1.1). MD units [133-135], which are still in the development phase to improve throughput and reduce costs, and of which at present (semi)commercial units with freshwater production rates between 0.5 to 100 m^3/day are available from different R&D providers (e.g. Scarab, Fraunhofer, Memsys, Memstill) are well suited to be used with geothermal fluids as their operational temperatures are normally in the range of 50-90°C (for details on MD technologies see Section 5.1.2). For all mentioned technologies, depending on the site-specific conditions, saltwater can be desalinated or – if the grade of mineralization is not too high, the geothermal water itself can be desalinated. The last is especially important, if the geothermal water is the only available water source.

4.5.5. Geothermal desalination: Where we stand and the road ahead

Due to the political, regulatory and policy reasons that will be discussed separately in section 7, there exists so far no industrial-scale geothermal desalination plant. Despite that there occur a significant number of geothermal heat powered thermal desalination units with sizes ranging from small to the lower limit of middle size units (e.g., [136]), there are only few feasibility studies and/or prototype designs [e.g. 98, 99, 137] or pilot/demonstration units [138,139]. In a feasibility study, Rodriguez et al. [140] used a combination of MED/boiling (MED or MEB) and MSF ("multi-flash with heaters"; MFWH) and showed that, for the conditions of Baja California

state (Mexico) where coastal geothermal water of 80°C is found, 14 m^3 geothermal water are required to desalinate 1 m^3 of seawater, which shows economic potential. In another feasibility study in the same geographic area, Gutiérrez et al. [141] assessed the coastal geothermal potential at La Joya and evaluated options for geothermal seawater desalination by MSF and MED .The authors designed and tested in the laboratory a prototype geothermal desalination unit in which all chambers were heated. The application of 118 m^3 of geothermal groundwater at 80°C was able to desalinate 20 m^3/day.

Sephton Water Technology has developed a pilot project for simulating process conditions for a demonstration project for showcasing its viability under commercial conditions [138,139]. They used heat (non-commercial low pressure steam; temperature: 100°C) from a geothermal power plant to reduce salinity of Salton Sea using MED in which a vertical tube evaporator (VTE) distillation process was applied for geothermal desalination [138,139]. The freshwater production of the pilot unit (MED/VTE 2 effects) and the demonstration unit (MED/VTW 15 effects) were 18.9 and 79.5 m^3/day, respectively, and the respective consumptions were 454 and 3402 kg/h [137,138].

The Aegean region (Greece, Turkey), is very rich in geothermal resources. There are plenty of small islands that depend on expensive water imports in particular during the tourist season. Despite a bounty of geothermal resources, the option of industrial-scale geothermal desalination has not been seriously considered so far. There exists only one geothermal desalination unit at pilot scale (MED, 2 stages) that has been installed in the year 2000 at Kimolos Island [142,143]. The unit is producing 80 m³/day of freshwater using 1440 m³/day of geothermal water at 60-61°C that is tapped at a shallow depth of 188 m [142,143]. A feasibility study from the 1990s in Milos Island found very promising results but so far has not yet resulted in the installation of a geothermal desalination plant [142,144]. The study located the availability at 12,840 m^3/day (using 7 production wells) of geothermal water at temperatures of 55-98°C at shallow depths (85-184 m) and proposed the construction of a geothermal seawater desalination plant with a capacity of 75-80 m^3/day of freshwater [144]; however the identified geothermal potential would be able to provide heat to much larger capacities. Other feasibility studies have been performed at Sousaki Korinthos where the installation of a MED/MSF unit and using low-enthalpy geothermal resources could produce about 225 m^3/day at Nysyros Island [145].

The costs of the produced freshwater, including plant costs, are ranging from 0.65 US$ at Salton Sea [138,139] to 1.5-2 US$ for the Aegean islands [143,144]. These numbers prove the economic viability of geothermal desalination in cases where geothermal energy is practical for free (non-commercial geothermal waste steam at the Salton Sea unit) or where geothermal water can be tapped at shallow depth as in the cases from Kimolos and Milos islands.

In closing, considering the road ahead, there is a need to accelerate the development of geothermal desalination, future work must include (i) a more detailed assessment of potentials of low to moderate but still economic low-enthalpy geothermal fluids from on-shore and from off-shore sources on global scale; (ii) the elaboration of detailed geothermal desalination units of commercial scale combining proven well-established thermal desalination technologies such as MSF and MED but also technologies which still need further development and upscaling such as MD and proven geothermal technologies considering all components needed for a complete the desalination plant; (iii) performing detailed economic modeling for analysis of all the configurations possible for geothermal desalination plants; (iv) the provision of energy, water and environmental policies which actively favor the development of geothermal desalination technologies at small to large scales, facilitating market entry and wide market penetration; and (v) installation of a first commercial-scale desalination plant which could showcase the economic viability and so pave and accelerate the development of geothermal desalination as a competitive and sustainable option at global level contributing to freshwater and energy security and independency and at the same time to food security environmental sustainability.

5. Integrated renewable energy-driven low energy and innovative desalination processes

5.1. Innovative desalination technologies

Several integrated RE-driven desalination processes are under development. In this review paper, two promising processes which have great potential for scale-up are presented, mainly AD and MD. It can be argued that the main advantages of these more sustainable technologies when compared with traditional technologies such as MSF, MED, RO, ED, are that they are simple, compact, scalable, operate at low temperatures, do not require continuous operation and at atmospheric pressure, and they can function with intermittent energy supply (variable loads) without additional operating modifications and energy storage, which makes them suitable for a

intermittent energy sources such as solar without requiring energy storage or connection to electrical grid as opposed to SWRO. Detailed descriptions of AD and MD have been widely reviewed in [133-135] and [32, 42,146-147], respectively. A short description of these processes is presented in this paper with a focus on their integration with RE sources, mainly SE, as it is abundantly available in regions where water shortage is a big issue, and to some extent GE (see section 4.5.4 and 4.5.5), as well as a combination of both in a 24-hour cycle as proposed by Missimer et al. [21] (Figure 4).
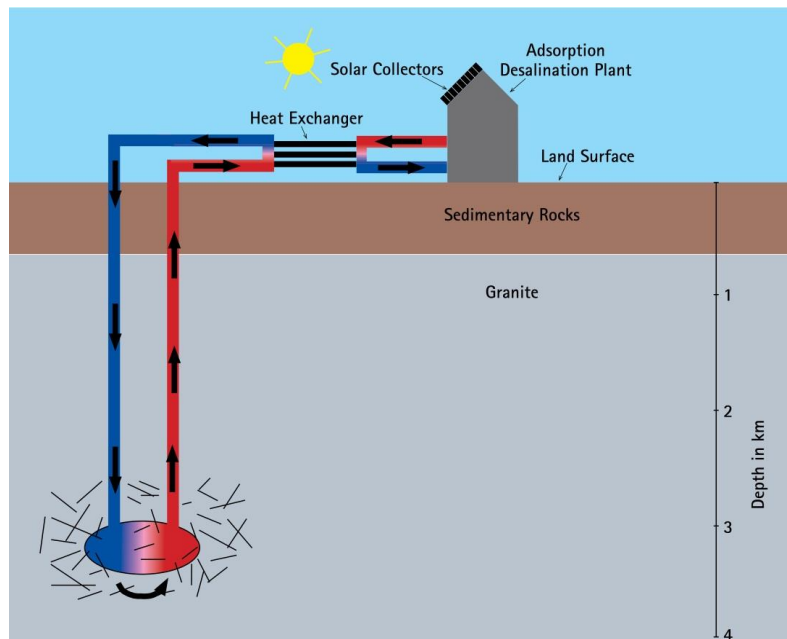

Figure 4. Coupled solar and geothermal energy source to power thermally driven desalination processes [21].

5.1.1. Adsorption desalination (AD)

In recent years, Ng et al. [32,148], Thu et al. [146], Chakraborty et al., [148,149] , and Wang and Ng [150] have reported an emerging and yet efficient heat-driven adsorption cycle for desalination that has an unprecedented kWh/m^3 of twice that of the thermodynamic limit. This novel process employs a low-temperature heat source to power the sorption cycle. It can produce two useful effects with only one heat input, namely cooling and high-grade potable water. An adsorbent (e.g. silica gel, which is packed around tube-fin heat exchangers used for desorption by circulating hot water; one ton of silica gel produces a specific cooling and water production capacities of 25 Rton/day and 12 m^3/day, respectively) is used to suck the vapor produced in the

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evaporator at very low pressure and temperature. 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. Raw water, e.g. seawater, is fed to the evaporator at its ambient temperature, which means there is no need to heat feed water as it is the case for other thermally-driven processes. When saturated, the adsorbent is heated to release the vapor (desorption) and is then condensed (Figure 5).

Hot water (55 to 85°C, which could be extracted from the renewable solar, geothermal or a combination of both to minimize heat storage problems [21]) is recirculated through the adsorbents' beds in a closed loop and connected to a heat exchanger to recover the heat. Such low-temperature heat sources match well with the discarded or free heat from either low-grade waste heat or RE (solar or low-cost, low-enthalpy geothermal; see Section 4.5.2). Based on a demonstration solar-AD pilot plant constructed at KAUST and a life cycle assessment, Ng et al. (21,32,42,146] showed that a specific energy consumption yields a value of <1.5 kWh_e/m^3, which is unmatched by any other desalination process. Owing to the low evaporative temperatures of evaporator, no significant scaling is observed on the surfaces of evaporator tubes even with concentrations up to 250 ppt (parts per thousand) [21,32,146-150]. In addition, the AD process produces distilled water from brines to the level of crystallization and chilled water simultaneously (can reach 7°C, which could be used for air conditioning, for example). Besides energy efficient, the AD cycle is inherently low in maintenance by design because it has almost no major moving components. An estimation of CO_2 emission of the AD cycle yielded 0.64 kg/m^3 [21,32,146-150] which is the least polluting when compared to the emissions from conventional cycles are in excess of 5 to 12 folds higher than the AD cycle. Schematics of the major components of an AD cycle and the solar-powered AD cycle are presented in Figures 5 and 6 [32,151].
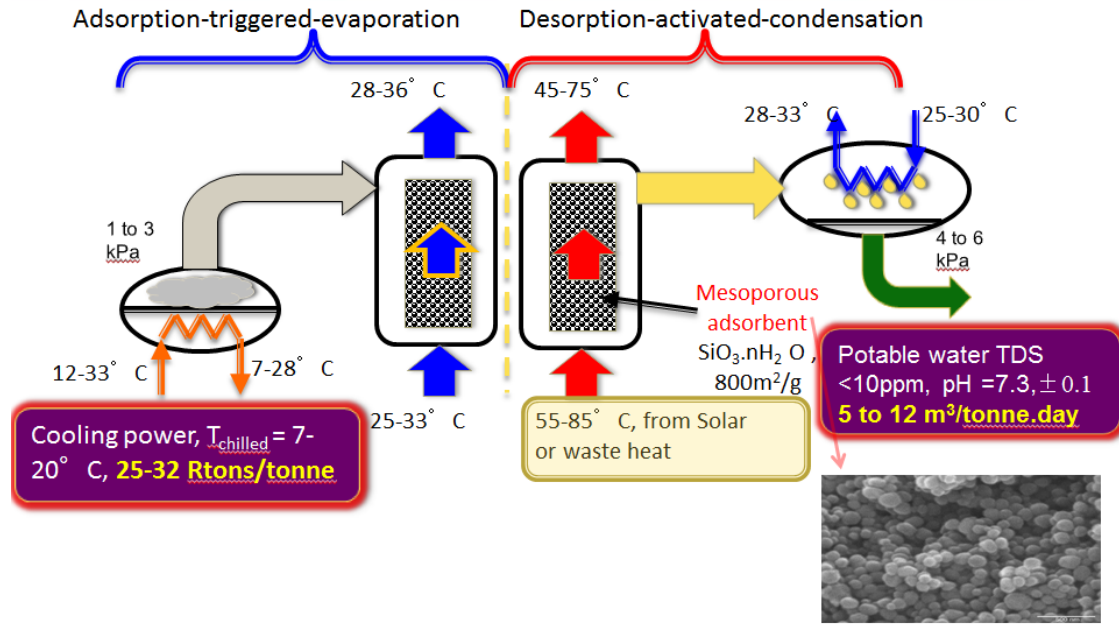
Figure 5. A schematic of the major components of an AD cycle showing the production of chilled water at the evaporator (7 – 20 °C), potable water at the condenser (salinity <10 ppm), and hot water circulation coming from renewable energy source for desorption [32].
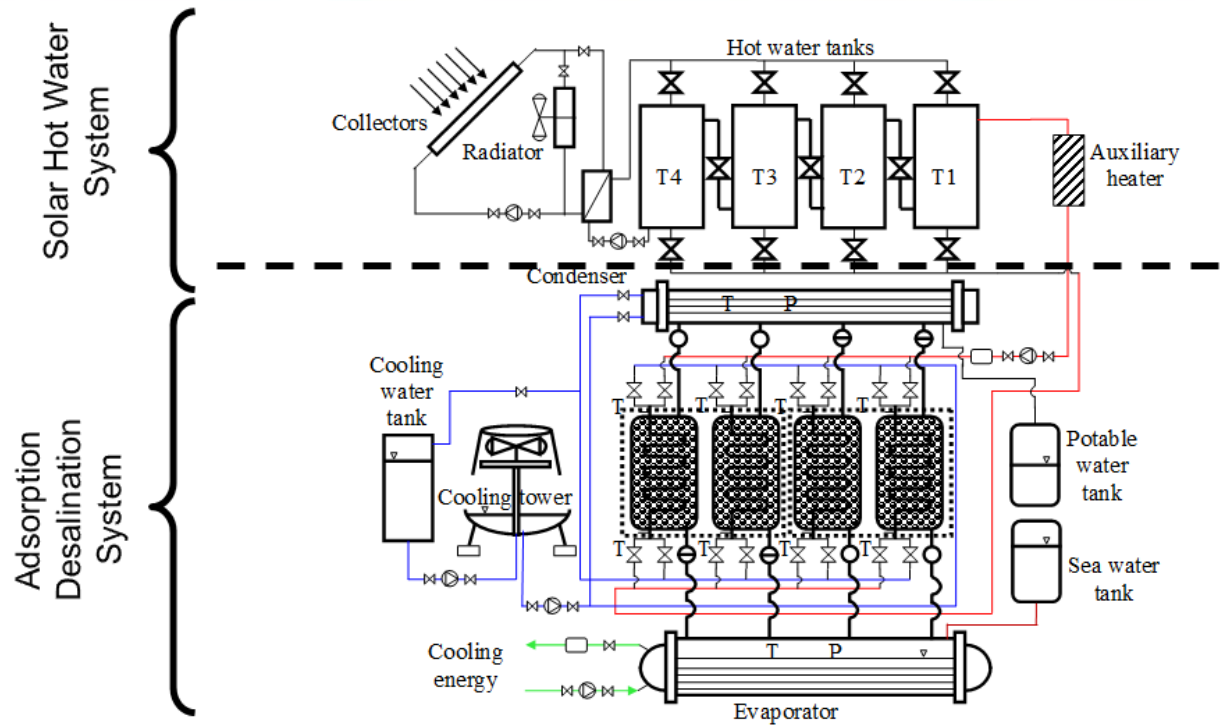

Figure 6. Schematic of the solar-powered AD system [151].

5.1.2. Membrane Distillation (MD)

MD is a thermally driven process that utilizes a hydrophobic, micro-porous membrane as a contactor to achieve separation by liquid-vapor equilibrium. Rather than a pressure, concentration or an electrical potential gradient, the driving force for the MD process is the partial vapor pressure difference maintained at the two sides of a hydrophobic micro-porous membrane (Figure 7). The feed solution, after being heated, is brought into contact with the membrane which allows only the vapor to go through the dry pores so that it condenses on the permeate side (coolant), as shown in Figure 7. A temperature difference of 7-10°C between the warm and cold streams is potentially enough to produce freshwater [133-135, 152-154]. Separation occurs when pure water vapor with its higher volatility, compared with sodium chloride, passes through the membrane pores by a convective or diffusive mechanism. This process works at relatively low temperatures (range of 50–90°C), which is very suitable for treating thermal brines which are already preheated. Under these operating conditions (low temperatures and ambient pressure), corrosion is not an issue as no metallic materials are used in MD units.
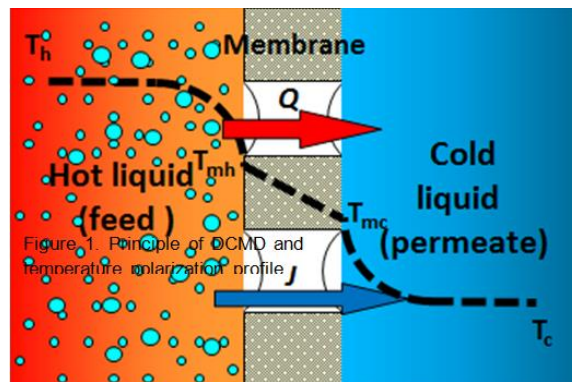

Figure 7. Principle of MD process and temperature profile.

MD holds the potential of being efficient and cost effective separation process that can utilize low-grade waste heat or RE such as geothermal or solar energies [13, 31, 42, 124-157]. In order to be cost-effective, with waste heat being considered as non-payable, specific energy consumption needed for pumping can potentially be lowered to 1 kWh/m^3. As it is the case for AD one of the main advantages of MD is that the process performance is not highly affected by high feed salinity, as it has been proven in bench and pilot scale studies [13,31,42,153,155,158].

The major technology constraint is the need for better MD membranes with high flux and low wettability. In addition, beyond better membranes, other challenges are facing MD process scale-up which have delayed its commercialization; these include, enhancing the water vapor flux, reducing conductive losses in order to maintain flux stability over time, enhancing thermal efficiency, minimizing temperature polarization, and avoiding pore wetting. Performance evaluation of these issues is very complex as it significantly varies from bench-scale to larger-scale module investigations because their operating conditions are completely different, contrary to other processes, due mainly to the significant variation of temperatures through the MD module itself.

A solar-assisted multistage MD desalination system with heat recovery and temperature modulating units is being designed [30] using the optimized experimental data and will be tested at KAUST for long term operation using Red Sea water as feed (Figure 8). Detailed description and components of the MD and solar unit, including energy required to run the process, is presented in [30]. Details of other SE-driven MD units developed by different groups can be found in [e.g., 20,159-161]. Also, case studies of some GE-driven MD systems are presented in Section 4.5.
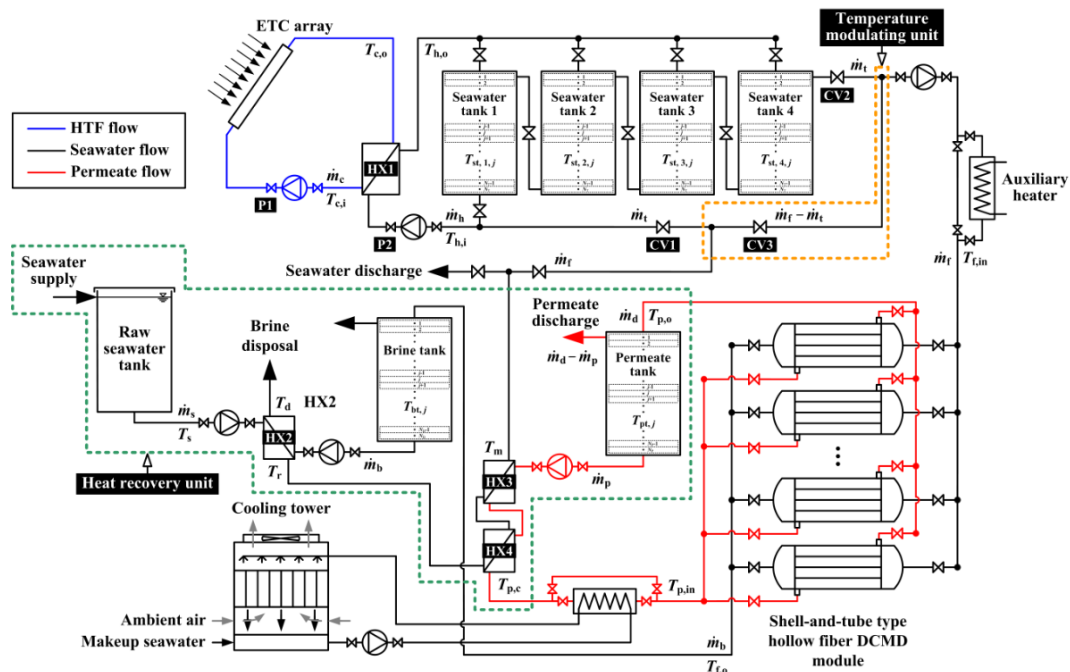

Figure 8. Schematic of solar-assisted multistage MD desalination system with the heat recovery and temperature modulating scheme [30].

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5.2. Greenhouse desalination

Water is a key factor to providing food security. Crops and livestock need water to grow. Agriculture requires large quantities of water for irrigation and confirmed its position as the biggest user of water on the globe with approximately 70% of all freshwater appropriated for human use [162].

Nowadays, the world is experiencing a water crisis [163,164]. The consequences of water scarcity will be especially felt in arid and semiarid areas of the planet [165,166], where scarcity of water has resulted in a significant use of desalinated seawater for agricultural purposes [167].

The sea/brackish water greenhouse desalination process is a new development that offers sustainable solution to the problem of providing water for agriculture in hot and arid regions where brackish and/or seawater are available. This enables the year round cultivation of high value crops that would otherwise be difficult or impossible in such environment.

The greenhouse is a versatile system that can be adapted for water desalination [168-170]. The seawater greenhouse uses sunlight, sea/brackish water, and the atmosphere to produce freshwater and cool air, creating more comfortable conditions for the cultivation of crops (Figure 9). The process recreates the natural hydrological cycle within a controlled environment. The two humidifiers that consist of a cardboard honeycomb lattice produce humidified air at saturation point. This helps to keep the greenhouse cool while allowing the crops to grow in high light conditions. Saturated air leaving the evaporator passes over the condenser. The freshwater condensing from the humid air is of overall zero salinity. This water is piped to the storage tank for irrigation [169]. The system has several advantages such as flexibility in capacity, moderate installation and operating costs, simplicity and possibility of using low temperature and the use of RE (e.g. solar [169], wind energy [21] and geothermal [171]).
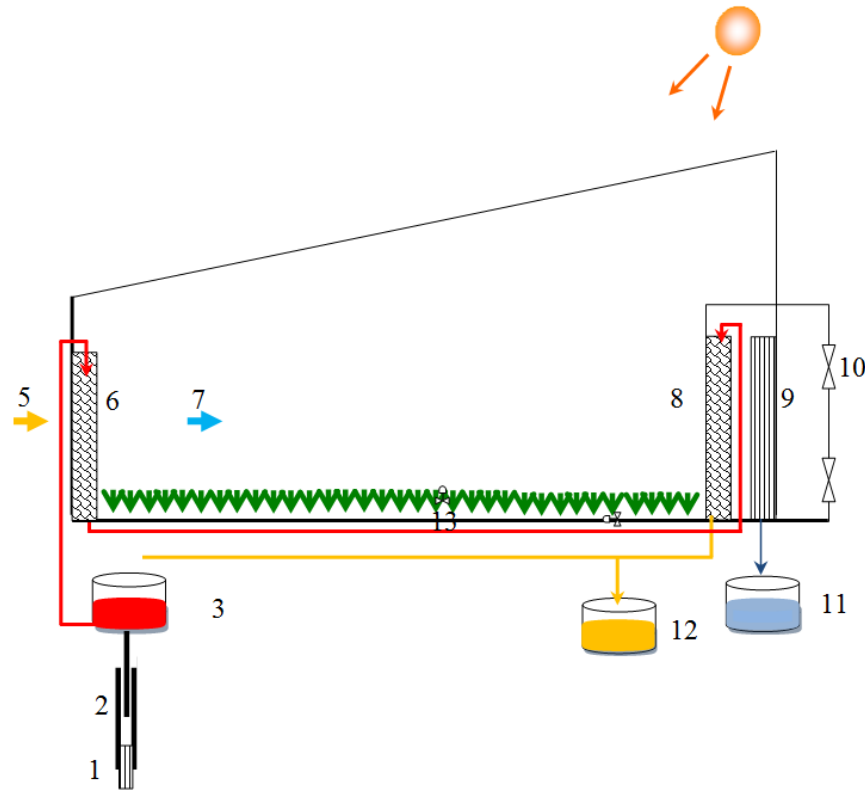
Figure 9. Process schematic of HDH; 1) Pump, 2) Brackish well, 3) Brackish water tank, 4) Dry air, 5) Evaporator 1, 7) Humidified air, 8) Evaporator 2, 9) Immersed condenser, 10) Fans, 11) Fresh water reservoir, 12) Brine reservoir, 13) Valve [169].

The first pilot was built and tested by Paton and Davies in the Canary Island of Tenerife in 1992 [172]. The first results were promising and demonstrated the possibility to develop the technology in other arid regions. In 2000, a new seawater greenhouse was constructed on Al-Aryam Island of Abu Dhabi in the United Arab Emirates [157]. For the two pilots, the production of crops was excellent, and fresh water was successfully produced for the greenhouse irrigation proposes. In 2004 a new improved version of the seawater greenhouse was built near Muscat in Oman (Figure 10) [169]. The aim of the project was to demonstrate the technology to local farmers and organizations in the Arabian Gulf. Recently two new pilots, one in Las Palmas of Gran Canaria and the second in Australia were built with new materials to enhance the condensation rate in aim to produce more fresh water [173].

Figure 10. The Seawater Greenhouse at Al-Hail, Muscat in the Sultanate of Oman, 2004 [169].

Geothermal energy has also great potential in greenhouse desalination technology. Mahmoudi et al. [171] verified that geothermal energy could be used for electricity production (including the power of the greenhouse), for commercial, industrial, and residential direct heating purposes, and for efficient home heating through geothermal heat pumps in the surrounding areas of the seawater greenhouses.

The condenser in the greenhouse desalination system constitutes the most critical component. For the greenhouse to be cost effective the condenser has to be efficient, uncomplicated, inexpensive, and low in maintenance. In a recent study, Mahmoudi et al. [174] proposed a new passive condenser in order to enhance the performance of the ancient one. The simulated condensate values for the proposed passive cooling condenser suggest that the passive condenser has a much greater water production capacity than the existing pump driven system [174].

5.3. Humidification–dehumidification (HDH)

Water shortages occurs most at places of high solar radiation, which usually peaks during the hot summer months of maximum solar radiation. Therefore, solar desalination techniques could be an excellent application of SE in sunny countries having limited resources of freshwater [175]. One of the most promising recent developments in solar desalination is the use of the humidification-dehumidification (HDH) process. The earlier shows great potential when applied for desalination of decentralized and small capacity plants.

The principle of functioning of the HDH process is based on the utilization of air as a carrier gas to evaporate water from the saline feed and to form fresh water by subsequent condensation.

A number of advantages of this technique can be presented which include flexibility in

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capacity, moderate installation and operating costs, simplicity, and possibility of using new RE sources such as SE and GE as well as recovered energy or cogeneration [175]. The HDH process functions at atmospheric pressure and low temperature, so the components are not submitted to mechanical solicitations and the most important characteristic required for materials is the resistance to corrosion.

Water desalination by HDH has been the subject of many investigations [175-178]. Different experimental data are available for using HDH at the pilot or industrial scale. An inspection of these data allows establishing many perspectives for this process. An example of an HDH system is a pilot plant built at Kuwait University [170]. The system consists of a salt gradient solar pond, which was used to load the air with humidity. Freshwater was collected by cooling the air in a dehumidifying column, also described an air-dehumidification method suitable for coastal regions. In a similar study, a closed-air cycle HDH process was used by Al-Hallaj et al. [179] for water desalination. Paton and Davis [180], Goosen et al. [181], Sablani et al. [182] and Mahmoudi et al. [183], used the HDH method in a greenhouse type structure for desalination and for crop growth.

6. Market potential, environmental concerns and socio-economic factors

6.1. Market potential, process selection and risk management

In a recent critical review, Goosen et al. [13] argued that in order to aid commercialization, different types of governmental policy instruments (e.g. tax breaks; low interest loans) can be effective for different renewable energy sources. However, broad-based policies, such as tradable energy certificates, are more likely to induce innovation on technologies that are close to competitive with fossil fuels. There is also a need to eliminate subsidies for fossil-fuel energy systems and to start taxing fossil-fuel production and use to reflect the costs of environmental damage. The authors went on to point out that one worrisome observation is that RE sources have consistently accounted for only 13% of the total energy use over the past 40 years (Table 4).

Hetal et al. [184] performed a review of seawater desalination processes that included an evaluation of various systems that use RE sources for desalination (Tables 4-6). They concluded that the most suitable desalination combinations were 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 (Table 6). It

can be argued that solar direct and indirect energy is the most suitable for installed desalination capacity.

At 62% market share, RO was the main user of RE in desalination (Table 5). Furthermore, in 2005, 32% of RE provided was PV for RO and 19% was wind for RO as reported by Hetal et al. [184] (Table 6).

Table 4. Global primary energy use in exajoules (EJ), 1970-2006 (adapted from Goosen et al. [13] and Moriarty and Honnery [185].   In describing national or global energy budgets, it is common practice to use large-scale units based upon the joule; 1 EJ = 10^{18} J.

Energy source	1970	1980	1990	2000	2006
Fossil fuels (i.e. coal, oil, natural gas)	196.7	255.1	305.0	339.0	400.1
Nuclear	0.7	6.7	19.0	24.5	26.6
Renewable	29.4	37.6	48.5	55.6	66.2
All energy	216.8	299.5	372.4	419.0	492.9
Renewable (%)	13.6	12.6	13.0	13.3	13.4

Table 5. Global renewable energy (RE) installed desalination capacity by technology (adapted from Hetal et al. [184]).

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

Table 6. Distribution of renewable energy powered desalination technology (adapted from Hetal et al. [184]).

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

Ghermandi and Messalem [186] addressing market anxieties determined that CSP and RO desalination are the most promising fields of development for large-scale solar desalination. They argued that CSP–RO systems may compete in the medium-term with conventional RO desalination and as a result, gain large market shares. They noted that there is a need for testing in demonstration and full-scale plants. According to the authors, the rapid advancement of both CSP and PV solar technologies offers the best outlook for the wider implementation of these potentially sustainable water supply technologies.

Li et al. [187] in a recent review noted that solar assisted desalination has been proved technically feasible; however the combined solar and fossil fuel desalination, and desalination using low grade waste heat could be more cost effective at this time. Though solar assisted desalination processes have not been commercialized yet, with the current ongoing research, they remain a valid option for future desalination plants.

Three international desalination markets have been studied for export opportunities to European Union (EU) technology developers [186,188]. The project called Promotion of RE for Water production through Desalination (ProDes) brought together 14 leading European organizations in order to support the market development of RE desalination in Southern Europe [188]. This excellent in depth analysis will help companies to expand their international activities and to support their case to investors for backing their expansion efforts. The markets analyzed were the Middle East and North Africa (MENA) region, with a profile on Morocco; the Oceania region, with a profile on Australia; and South Africa, with an in-depth report. Each report provided details on the economic and governmental structures, the power sector, RE legislation, the water sector, recent investment and a summary of the renewable desalination market potential.

Goosen et al. [13] claimed that at present application of solar technologies in desalination cannot be implemented for large scale commercial uses due to technological and economic limitations. There is a need to encourage the wider use of solar technologies since this will eventually increase the demand for these systems, making it possible to go for mass production of photovoltaic cells, collectors and solar thermal power plants. This should ultimately lead to a reduction in the costs of these technologies. In addition, economic and political factors are often critical to large-scale deployment of renewable energy.

Reif [189] performed a profitability analysis and risk management of geothermal projects being implemented in Bavaria Germany. It was recommended that the initiators of a plan must run profitability simulations in order to analyze varying scenarios before implementing the project. Reif's study also concluded that the sensitive response of the project's rate of return to changes in the parameters of their computer simulations made it clear that geothermal projects are financially risky.

Grubert et al. [190] in an effort to aid policy makers developed a customizable tool for identifying favorable locations for desalination facilities based on selected criteria. GIS-multi-criteria decision analysis (MCDA) was applied to desalination site selection. This work demonstrated how an integrated GIS-MCDA framework can enable decision-makers to simultaneously incorporate economic, environmental, and other societally defined criteria when making decision regarding the best location for a desalination plant.

6.2. Environmental, government policy, limitations and costs considerations

Goosen et al. [13] in a recent review argued that the successful application of renewable technology requires an understanding of sustainable development. In particular there is a need to find a balance between three sets of goals; social, economic and environmental. The problem is that these goals are not always compatible and trade-offs are required. For example, what comes first, economic growth, or environmental protection and human health? As noted by Grubert et al. [190], the relationship between these areas is a complicated process, affecting both the quality and sustainability of the society in which we live. Goosen et al. [13] concluded that one way to help achieve a balance is to educate people (e.g. decision makers, students, industrial workers) as this represents the primary vehicle available for catalyzing cultural changes.

Government sponsorship of RE projects in Germany is often mentioned as a model to be

imitated, being based on environmental laws (e.g. RE Sources Act) that go back nearly twenty years [191]. The authors maintained that the government's support mechanisms have essentially failed as a result of massive expenditures that showed little long-term promise for stimulating the economy, protecting the environment, or increasing energy security. Frondel et al. [191] explained that it is most likely that whatever jobs are created by RE promotion would vanish as soon as government support is terminated.

Let us take a closer look at the environmental impacts that must be considered during utilization of geothermal resources as outlined by Goosen et al. [13]. The environmental advantages of RE can be seen when comparing, for instance, a coal-fired power plant to a geothermal power plant; the former produces in average about 25 times as much carbon dioxide (CO_2) and sulfur dioxide (SO_2) emissions per MWh (i.e. 994 kg vs. up to 40 kg for CO_2, 4.71 kg vs. up to 0.16 kg for SO_2, respectively) [192,193].

We can reason that the ready availability of inexpensive oil and natural gas reserves in such areas of the world as the Arabian Gulf may reduce the need for using RE for desalination. Nevertheless, looking at this more carefully we see that this is non-sustainable since fossil fuels are non-renewable, and with a constantly rising population there is an ever increasing demand on the use of fossil fuels for desalination. Take Saudi Arabia as an explicit example; in 2008 total petroleum (i.e. oil and gas) production was 10.8 million bbl/d with internal oil consumption at 2.4 million bbl/d (i.e. about 25% of the total production) [194-195]. Most of the internal consumption was used for electricity generation and water desalination. The population is anticipated to increase from 30 million in 2010 to about 100 million by 2050 [196]. It has been projected that by then 50% of the fossil fuel production will be used internally in the country for seawater desalination in order to provide freshwater for the people. This will reduce the state's income, increase pollution and is clearly non-sustainable.

Hegedus and Luque [197] assessed the achievements and challenges of solar electricity from PV. They claimed that there is sufficient land, raw materials, safety protocols, capital, technological knowledge and social support to allow PV to provide over 12% of the world's electrical needs by 2030. However, new ways of economically sound energy storage would need to be found. They noted that the present PV development has been made possible by public support, driven by public opinion, which has led to administrations spending considerable cash to fund PV.

A key problem of RE, mainly solar, desalination is the efficiency of the system. During evaporation and the process of condensation, high heat and mass transfer govern the system's efficiency and consequently the surfaces must be adequately designed within the contradictory aims of heat transfer efficiency, economics, and reliability [14]. For high efficiency a solar still, for instance, should maintain a high feed water temperature, large temperature difference between feed and condensing surface and low vapor leakage. In addition, solar desalination is currently not a viable option for large-scale applications, either technically (due to fluctuation in energy supply leading to operation at different loads) or economically [13]. In addition, solar energy is only available during day time and its intensity changes from morning to evening, with peak intensity in the afternoon [30], while the energy requirement of conventional desalination processes is constant and continuous. System efficiency is low if operated at variable load and variable operating conditions. This affects a plant's life [3-6,13,25]. An energy storage system or an alternative back-up source of energy is therefore required to run the desalination plant continuously at constant load. Available conventional desalination processes may also not be suitable, technically and economically.

Solar desalination requires huge collector areas, which makes it more expensive than the conventional technologies using fossil fuels. Correspondingly, a successful implementation of solar desalination technologies at commercial level is depending on economic improvements in converting SE into electrical and/or thermal energy.

Currently, the cost of solar desalination exceeds those of conventional desalination by at least factor four. More efforts need to be directed worldwide to reduce the cost of RE for desalination applications. These activities should be undertaken by both RE and water experts working in collaboration. It seems to be obvious the cost of solar desalination cannot be reduced to a comparable range of conventional technologies in the near future. Also, electrical power is subsidized in most of the countries where there is lack of freshwater [1,3,22,198]. This makes water desalination technology unsustainable.

Water generation cost and energy demand of some possible combinations of SE with desalination technologies are presented in Table 7 [20,25,30,32,160,161]. A techno-economic investigation of a large number of indirect solar desalination pilot plants was also widely reviewed [199]. As shown in Table 7, the reported energy demand and cost vary significantly and they are considered very high compared to conventional systems. For example and for

comparison purpose (direct with indirect), PV-RO energy demand was reported at 5 kWh/m^3 and 19 kWh/m^3 and water cost of US\$ 15.6/m^3 and US\$ 27/m^3 by Paparetrou et al. [159] and Ali et al. [20], respectively. Thermal energy required for MD varied between 100 kWh/m^3 [20] and 2,200 kWh/m^3 [20,30,159,161] and water unit costs varied between US\$10.4 to US\$19.5. In fact, in some cases SE or low-grade waste heat were considered as free of charge (non-payable energy) while in other cases the calculated values took into account all the parameters without including subsidies. Finally, we can argue that while SE itself is available free of charge, capturing it is certainly not.

Table 7: Water production cost of some possible combinations of solar energy with desalination technologies [20,30,32,159-161].

	Typical capacity (m³/d)	Energy demand (kWh/m³)	Water cost (US\$/m³)
Solar still	<0.1	Solar passive	1.3-6.5
Solar (MEH)	1-100	Ther: 100 Elec: 1.5	2.6-6.5
Solar MSF	1	Ther: 81-144 [20]	1-5 [20]
Solar tower MSF	1	T: 53.7 [160]	-
Solar/CSP MED	>5,000	Ther: 60-70; Elec: 1.5-2 [159] T: 50-94 [20]	2.3-2.8 [159] (prospective cost) 2-9 [20]
Solar tower MED	1	T: 42.4 [160]	-
Solar tower VC	1	Elec: 55.5	-
PV-RO	<100	Elec: BW: 0.5-1.5; SW: 4-5 [159]; BW-SW: 1.2-19 [20] Elec: 41-45 [160]	BW: 6.5-9.1; SW: 11.7-15.6 [159]; 3-27 [20]
Solar tower RO	1		-
PV-EDR	<100	Elec: BW: 3-4 [159] BW: 0.6-1 [20]	10.4-11.7 [159] 3-16 [20]
Solar MD	0.15-10	Ther: 150-200 [159]; 100-600 [20]; 436 [30]; 180-2,200 [161]	10.4-19.5 [159] 13-18 [20]
Solar AD	8	Elec: 1.38 T: 39.8 [32]	0.7 (electrical cost only) [32]

Ther: Thermal; Elec: Electrical; T: Total; BW: Brackish water; SW: Seawater.

7. Towards sustainable energy technologies based desalination for freshwater production

Desalination is an energy intensive activity. To manage the escalating global freshwater demand for food production and drinking water supplies, desalination is increasingly becoming more important. Thermal desalination of seawater or saline or brackish groundwater, which in many areas will be the only available option for regional or national food production, is even more energy demanding. These facts and resulting demands for sustainable provision of energy solutions is clearly reflected in the statement: "*Modern society continues to rely largely on fossil*

fuels to preserve economic growth and today's standard of living. However, for the first time, physical limits of the Earth are met in our encounter with finite resources of oil and natural gas and its impact of greenhouse gas emissions onto the global climate. Never before has accurate accounting of our energy dependency been more pertinent to developing public policies for a sustainable development of our society, both in the industrial world and the emerging economies." (Minutes, Debate of Senate (Eerste Kamer), 2009 (in Dutch)* [200]).

The FAO (Food and Agriculture Organization of the United Nations), has estimated that global food production must be increased by 70% to cover the global food demand for a population being forecasted to reach 9 billion by 2050 [201]. This, together with demands from other sectors translates to a forecast of the global primary energy demand to increase by one third during the 2010-2035 period [202].The annual global freshwater demand increase, the largest part of which is needed for agriculture, is expected to grow by ~10–12% per decade (a 38% increase from 1995-2025; UNESCO [203]), making the securing of energy and water supplies a key challenge facing modern society.

Conventional fossil fuels have become increasingly limited. This can be clearly shown for the example by oil, the peak production of which has been already exceeded and the exploitation of which is forecasted to reduce by 2030 to half of its 2010 value [204]. It can be argued that the development and use of non-conventional fossil fuel resources such as shale gas, coal bed methane and tar sands, may cover the electricity demand for some decades more. However, it must be recognized that these options are being increasingly questioned by the public due to the potential adverse effects of their exploitation on freshwater resources, the environment, and human health, which favors the development of environmentally-friendly renewable energy resources for applications with high electricity demand such as desalination. The increasing scarcity of conventional fossil fuels and the fact that fossil fuel combustion is the principal contributor to global warming, shows that the negative consequences such as pollution and global warming are occurring much faster and more dramatically than formerly thought [205-207].

These developments strongly suggest that the future food supply is intrinsically linked with energy, water and climate issues. Guaranteeing food and drinking water security requires energy and water security. For more than a century, fossil fuels have been the primary global energy source. However, the increasing scarcity of fossil fuels and related continuous high fuel price and

supply uncertainties, and the demand for significant reductions in greenhouse gas emissions has placed a renewed emphasis on the search for new alternative and renewable energy sources. Implementation of RE technologies, including those for powering thermal desalination technologies, are essential and governments and industries around the world are obliged to look into cutting-edge applications for RE-based water desalination together with other applications of renewables.

Despite of these needs, only limited progress has been made to achieve the sustainable RE goals. Many decision makers around the globe have the impression that RE technologies and options are not economically viable. This belief is wrong and the opposite is true. It has been demonstrated that the use of new technologies will contribute to job creation and economic growth if RE technologies will be developed and produced in large numbers. The experience of Germany has clearly proved this: since 1998, employment in the RE sector has increased by more than 10-times, from about 66,600 (1998) to 377,800 (2012) with the aim to reach 500,000 in the year 2020; in this country. After the automotive industry, the renewables technology sector in Germany has the second-highest share of employment [208]. These positive developments in Germany, which produced in the year 2013 about 25% (50% forecasted for the year 2030 – middle scenario) of its electricity from renewables, is in contrast to the concerns expressed by Frondel et al. [191].

There are a number of experts, who demonstrated that RE technologies in the different industrial sectors, including that of desalination, can grow much faster than generally assumed. So, Fell [205] reported that RE technologies can expand similar as other technologies such as plasma TVs and mobile phones, which only required a few years. There already exist well-proven conventional thermal desalination technologies which are powered by fossil fuels. There also exist a number of sustainable renewable energy technologies, suitable for applications in desalination technologies, in large numbers and on a commercial scale, which are continuously improved and the cost of which is decreasing primarily due to increasing numbers produced. Hence, there is no need to introduce completely new technologies. In contrast, the existing thermal desalination just needs to be adapted to be powered by heat from RE sources such as thermal and solar. Nevertheless, it is obvious that an acceleration in implementation can only occur if the political, policy and financial framework conditions are favorable. Hence, there should be a provision for profitable investments in the production and use of RE powered

desalination units as those described and discussed in detail in the book by Fell [205] on the introduction of RE technologies.

In many countries unsustainable fossil fuels are subsidized by governments. Such benefits must be removed and economic incentives for investing in sustainable RE desalination technologies leading to market penetration must be provided. This is the only way to push the private sector, i.e. desalination industry, to invest in these technologies. This will result in establishing mass production facilities, which in turn will lead to cost reduction and wider market penetration. If this process is successful then state regulations will no longer be required as RE desalination will be cost competitive with fossil fuel based ones.

7.1. Promoting renewable energy desalination

RE-driven desalination is an environmentally friendly technology. Waste production is minimal and there is a beneficial contribution to creation of local industries and business. Furthermore RE desalination may help to reduce the need for fossil fuel imports and it can also provide solutions to the agriculture sector (e.g. provision of irrigation water) [209]. Promotion of RE desalination, mainly solar energy, is dependent on the following parameters:

- *Plant location:* Solar energy is abundant in many coastal areas of arid and semiarid regions where most of the population lives.

- *Seasonal changes:* Tourism often leads to a seasonal sharp increase of the freshwater demand which often coincides with summer times when availability of SE is high.

- *Energy availability:* In remote areas, the supply of conventional energy is often difficult. The supply of fuels through long distances can be costly or not possible during the whole year due to adverse climate conditions. The construction of grids to off-grid areas may be technically or economically unsustainable. In these cases, locally available solar energy can provide an important energy source contributing to the sustainable socioeconomic development.

- *Self-sufficiency:* Energy diversification can be increased through the inclusion of SE in the energy source mix; increased use of solar energy further reduces dependence on energy imports in case that no national fossil-fuel resources are available.

- *Technology:* The development and commercialization of SE-driven desalination units allow the export of these technologies and so opens new markets.

- *Economics:* Solar desalination is an ideal solution for remote areas and inland cities, which otherwise often depend on freshwater transport over long distances that transcribes to high costs and potential microbial contamination due to improper hygienic conditions.

- *O&M:* Solar energy systems can generally easier being operated and maintained than conventional energy systems; therefore they are the more suitable option for remote areas [210].

- *Promising commercial perspectives:* During the last decades, the mass production of SE systems has led to significant cost reduction; this trend is expected to continue. On the other side, the cost of fossil fuels is ever increasing. These both trends continuously increase the competitiveness of solar seawater desalination. Realistically, solar desalination will increase the demand on these technologies, facilitating commercialization, market launch and finally market penetration with mass production, which translates to significant cost reduction.

In summary, solar desalination can be promoted by applying the following four steps:

- Encouraging paths to improve the understanding of how SE could be used to supply the two commodities electricity and freshwater and its particular benefits to rural and remote areas and at the same time contributing to the preservation of the environment and contributing to the reduction of unemployment.

- Urging the establishment of partnerships of non-governmental organizations to share knowledge and experience, and create innovative programs to promote of the use of solar energy for desalination.

- Promoting and harmonizing the cooperation in training, research, and in the transfer of research to industry at national and international level.

- Demonstrating how a massive use of solar desalination can be cost-effective through reducing the dependence on fossil fuel imports, improving the trade balance of countries that presently depend on fossil fuel imports and at the same time improving their energy independency and energy security.

Governments should be encouraged to subsidize RE desalination. Even today, for the high costs of extending the electrical grid, or to transport fossil fuels over long distances to remote areas, may be cost-effective and justify the use of solar desalination or solar electricity generation. The recent projects and R&D efforts, such as those presented in this paper, for the development of RE are very encouraging.

8. Conclusions

An overview of the status of RE-driven desalination technologies, with a focus on integrated systems, their promotion and potential applications, as well as their current technological and economic limitations has been presented in this review paper. Existing RE technologies can be combined with prevailing desalination technologies. Presently, technological and economic constraints hinder large-scale applications. Current research on RE technologies and mass production of these systems can reduce the cost of solar energy. Geothermal energy can provide an attractive option for desalination, in particular where low-cost, low-enthalpy sources are available (e.g., from shallow depth, produced water from hydrocarbon wells, from existing deep wells, residual heat from geothermal power plants). Offshore geothermal resources can be tapped using mature technologies from onshore. Furthermore, since the price of fossil fuels is increasing, RE-driven desalination will eventually become feasible for large-scale applications.

RE-driven desalination is a sound technology for freshwater production at small- or medium-scale to supply remote off-grid areas. However, there is a necessity to improve the thermal performance and technical efficiency of these systems. Also there is a need to make modifications to conventional desalination processes to make them more suitable for integrated systems.

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.

A combined-cycle solar and geothermal powered desalination process can provide the most effective use of RE without the need for energy storage.

Nomenclature

AD   Adsorption desalination
CAES   Compressed air underground heat storage
CPV   Concentrating photovoltaic
CRS   Central receiver systems

CSP	Concentrated solar power
CST	Concentrated solar thermo-electric
ED	Electrodialysis
FAO	Food and Agriculture Organization of the United Nations
GCC	Gulf Cooperation Council
GE	Geothermal energy
GOR	Gain output ratio
HDH	Humidification–dehumidification
HFC	Heliostat field collector
HTF	Heat transfer fluid
IBM	International Business Machines Corp
KACST	King Abdulaziz City for Science and Technology
KAUST	King Abdullah University of Science and Technology
LCOE	Levelized cost of electricity
LFR	Linear Fresnel reflector
MCDA	GIS-multi-criteria decision analysis
MD	Membrane distillation
MED	Multi-effect distillation
MENA	Middle East and North Africa
MSF	Multi-stage flash
MVC	Mechanical vapor compression
MWt	Megawatt thermal
O&M	Operation and maintenance
PDC	Parabolic dish collectors
PDS	Parabolic dish systems
ProDes	Promotion of RE for Water production through desalination
PTC	Parabolic trough collector
PV	Photovoltaic
RE	Renewable energy
RO	Reverse osmosis
SE	Solar energy

SPT   Solar power tower
SWRO   Seawater reverse osmosis
UHCPV   Ultra-high concentrator photovoltaic

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