University of Wollongong

Research Online

Faculty of Engineering and Information
Sciences - Papers: Part B

Faculty of Engineering and Information
Sciences

2018

Application of solar energy in water treatment processes: A review

Ying Zhang

University of Wollongong, yz393@uowmail.edu.au

Muttucumaru Sivakumar

University of Wollongong, siva@uow.edu.au

Shu-qing Yang

University of Wollongong, shuqing@uow.edu.au

Keith Enever

University of Wollongong, kenever@uow.edu.au

Mohammad Ramezaniapour

Ara Institute of Canterbury, mr417@uowmail.edu.au

Follow this and additional works at: <https://ro.uow.edu.au/eispapers1>

Part of the [Engineering Commons](#), and the [Science and Technology Studies Commons](#)

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

Application of solar energy in water treatment processes: A review

Abstract

The utilization of solar energy to drive water treatment processes is a potential sustainable solution to the world's water scarcity issue. In recent years, significant efforts have been devoted to developing and testing innovative solar based water treatment technologies, which are comprehensively reviewed in this paper. Recent developments and applications of seven major solar desalination technologies, solar photocatalysis process and solar disinfection are investigated. Potential integration of solar technologies and desalination processes are summarized. By collecting and analysing performance data from recent studies, the status of productivity, energy consumption and water production costs of different technologies is critically reviewed. The real world applicability as well as technical and economic feasibility is also evaluated. Presently, most of the solar water treatment processes are still under development with limited real applications. Economic competitiveness is among the major reasons that affect the scaling up and commercialization. It is revealed that the reported water costs of small to medium scale solar desalination plants are in the range of US\$0.2-22/m³, much higher than conventional fossil fuel based plants. However, the estimated low water costs (US\$0.9-2.2/m³) for large scale solar based plants indicate that solar based alternatives will become potentially viable in the near future.

Disciplines

Engineering | Science and Technology Studies

Publication Details

Zhang, Y., Sivakumar, M., Yang, S., Enever, K. & Ramezaniapour, M. (2018). Application of solar energy in water treatment processes: A review. *Desalination*, 428 116-145.

Application of solar energy in water treatment processes: a review

Ying Zhang¹, Muttucumaru Sivakumar^{1,*}, Shuqing Yang¹, Keith Enever¹, Mohammad Ramezaniapour²

¹ School of Civil, Mining and Environmental Engineering, Faculty of Engineering and Information Sciences, University of Wollongong, NSW, Australia

² Department of Engineering and Architectural Studies, Ara Institute of Canterbury, Christchurch, New Zealand

Contents

Abstract.....	2
Key words	2
1. Introduction.....	2
2. Solar desalination technologies.....	3
2.1 Direct solar desalination--solar still	4
2.2 Indirect solar desalination	10
2.2.1 Solar humidification-dehumidification	10
2.2.2 Solar-powered MSF	16
2.2.3 Solar-powered MED	21
2.2.4 Solar-powered MD.....	30
2.2.5 Solar-powered RO.....	37
2.2.6 Solar-powered ED.....	42
2.3 Summary of solar desalination technologies.....	45
3. Solar photocatalysis and disinfection.....	47
3.1 Solar water photocatalytic application	47
3.2 Solar Disinfection of water (SODIS)	52
4. Conclusions.....	53
Acknowledgement	54
References.....	54

*Corresponding author. Tel.: +61 2 4221 3055.

E-mail addresses: siva@uow.edu.au (M. Sivakumar), yz393@uowmail.edu.au (Y. Zhang)

Abstract

The utilization of solar energy to drive water treatment processes is a potential sustainable solution to the world's water scarcity issue. In recent years, significant efforts have been devoted to developing and testing innovative solar based water treatment technologies, which are comprehensively reviewed in this paper. Recent developments and applications of seven major solar desalination technologies, solar photocatalysis process and solar disinfection are investigated. Potential integration of solar technologies and desalination processes are summarized. By collecting and analysing performance data from recent studies, the status of productivity, energy consumption and water production costs of different technologies is critically reviewed. The real world applicability as well as technical and economic feasibility is also evaluated. Presently, most of the solar water treatment processes are still under development with limited real applications. Economic competitiveness is among the major reasons that affect the scaling up and commercialization. It is revealed that the reported water costs of small to medium scale solar desalination plants are in the range of US\$0.2~22/m³, much higher than conventional fossil fuel based plants. However, the estimated low water costs (US\$0.9~2.2/m³) for large scale solar based plants indicate that solar based alternatives will become potentially viable in the near future.

Key words

Solar energy; water treatment; desalination technologies; photocatalysis; SODIS

1. Introduction

Water and energy security are two of the major issues mankind must tackle to achieve the sustainable development of human society. Water scarcity which is already a major challenge faced by many regions is becoming even worse due to the increasing water demand brought by rapid population and economic growth in developing countries. Meanwhile, the discharge of municipal and industrial wastewater effluent without proper treatment that caused serious pollution on fresh water sources has aggravated the problem. According to the United Nations Environmental Programme (UNEP), 1/3 of world population live in water-stressed countries, while by 2025, 2/3 of world population will face water scarcity [1]. The scarcity of water strongly limits the socio-economic development of these countries.

In 2012, 13,371 million tons oil equivalent (MTOE) of total primary energy supply were consumed in the world, with 81.7% from fossil fuels (oil 31.4%, natural gas 21.3%, and coal 29.0%) and only a small amount from biofuel and waste (10%), nuclear (4.8%), hydro (2.4%) and other source (1.1%) [2]. Energy demand will continue to increase over the coming decades to meet the growing population while associated economic development and a 31% increase in global energy consumption is foreseen by 2035 [2]. However, global reserve of crude oil, natural gas and coal are depleting. Many scientists believe that an oil production peak has either occurred already or will be likely to occur in the coming few years [3]. Global oil consumption rate is expected to decline by 75% by 2050 due to the depletion of many oil reserves. It is also forecasted that natural gas and coal production will peak within decades of oil peak [3]. Meanwhile, the emission of large amount of greenhouse gases and other air pollutants such as hydrocarbons, nitrogen

oxide, sulphur dioxide, etc. by combustion of fossil fuels has caused serious environmental concerns. Clean, renewable primary energy must be utilized to solve the energy crisis in the near future.

Solar energy is by far the most abundant renewable energy source. It shows the highest technical feasible potential (about 60TW) among all renewable energy sources [4], which surpassed the total world energy consumption (13,371MTOE is equal to 17.75TW) in 2012. Although presently solar energy only accounts for a very small fraction of world energy supply (about 0.5% electricity generation globally) [5], the continuous development of modern solar energy conversion technologies in the past decades is making solar energy systems less expensive and more efficient. According to International Energy Agency, solar energy could become the largest electricity source by 2050 [6].

To address water shortage, a variety of non-traditional water sources have been considered for water production for drinking, industrial, agriculture or other usages, such as seawater/brackish water, treated municipal/industrial wastewater, contaminated surface or groundwater, etc. However, sustainable water supply cannot be achieved without considering the energy required in the treatment process. Coincidentally, many of the world's arid and semi-arid regions which face severe water shortage are generally blessed with abundant solar radiation. This allows the address of water scarcity with sustainable solar energy. Suitable technologies need to be developed to integrate solar energy into water treatment processes. Solar desalination technologies, solar photocatalysis technologies and solar disinfection are the most widely investigated solar based water treatment technologies, which will be discussed in detail in this paper. Among them, solar desalination technologies have received considerable attention all over the world due to its applicability to arid or remote regions. Various solar desalination technologies have been examined and reviewed [1, 7-14]. The global applicability and opportunities of solar desalination have been further demonstrated by researchers [1, 8, 11]. Specially, Adrian *et al.* [8] identified 30 nations with high applicability and 28 countries with 'moderate applicability' by a newly proposed method. Detailed reviews of the principles and features of different solar desalination technologies have been provided [9, 10, 13]. Sharon *et al.* [10] also discussed briefly the advantage and disadvantages of each technology as well as the problems existing in desalination processes. Special focus of thermodynamic and thermo-economic analysis of solar desalination systems were presented by Iman *et al.* [9]. However, only limited application cases were shown in these reviews so that the present status and development of specific technologies were not clearly shown. A very comprehensive review in solar assisted seawater desalination was given by Li *et al* [13]. Nevertheless, latest research and applications were not included in this review since it was written before 2012. Therefore, in this paper, the current status and progress of different solar water treatment technologies have been extensively reviewed by summarizing research and applications in recent years. The economics and applicability are also discussed.

2. Solar desalination technologies

Desalination of seawater and brackish water is well known to be an alternative solution to provide fresh water for many water-stressed regions. For decades, large commercial desalination plants powered by fossil fuels have been installed in countries that suffer from water shortage, especially oil-rich countries in Middle East. Solar energy can be used directly or indirectly to drive desalination plants. In direct solar desalination systems, solar energy is used directly for the production of distilled water in solar collector, with solar still as the most representative technology;

whereas in indirect solar desalination systems, solar energy is harvested either by solar thermal collectors to provide heat or photovoltaic panels to generate electricity for thermal or membrane desalination technologies such as multi-effect desalination (MED), multi-stage flash desalination (MSF), membrane distillation (MD) or reverse osmosis (RO).

In the sections below, brief descriptions of fundamentals of different desalination processes are provided in order to discuss the performance evaluation and operation parameters, as well as recent trends of technologies. Detailed explanations of those processes can be found in books and review papers [9, 10, 13, 15].

2.1 Direct solar desalination--solar still

Solar still is the most common direct solar desalination technology which is mainly suitable for low capacity water supply systems in remote areas where construction of pipelines or water delivery by truck is uneconomical and unreliable [16]. The simplest design of a single basin solar still consists of an airtight, sloping transparent cover which encloses a black painted basin with saline water (see **Fig.1**). Water evaporates after being heated up with the absorbed solar energy by the basin. Condensation occurred in the inner surface of the sloping cover and then distilled water is collected at the lower end of the cover. Despite its technical simplicity and relatively less maintenance requirement, solar still is not widely used due to the low productivity per unit installation area, normally $1\sim5\text{ L/m}^2/\text{d}$ for a single basin still. Consequently large areas of land are required for the installation of solar still.

Fig.1 Schematic diagram of a single slope single basin solar still

Parameters affecting the productivity of a basin type solar still include absorption area, water depth, inlet water temperature, water-glass cover temperature difference, etc. A comprehensive review has been given by Prakash *et al.* [17]. Extensive modifications have been carried out to improve the productivity of solar stills. The objectives of modifications are basically to enhance water evaporation in the basin, condensation on the cover or to recover latent heat of evaporation. **Fig. 2** shows major approaches in literature to improving still productivity [18-23]. **Table 1** is a list of selected solar still studies and applications. Generally solar still can be classified into two categories: passive and active solar stills. In active solar stills, additional devices are adopted, including vacuum fan, pump, sun tracking system and solar collectors. Although the efficiency can be enhanced, however, it also results in increasing costs and

complexity of the system. A balance needs to be made between improving the productivity and keeping its simplicity and economic feasibility in the modification of solar still.

The diversity of modifications again indicates its simplicity and little reliance on high technology. Many locally available materials can be used for its construction and amelioration. For example, Ahsan *et al.* investigated a low cost solar still – triangular solar still (TrSS) with cheap, lightweight locally available materials [24]. The TrSS solar still consisted of a polythene triangular cover, a frame and a rectangular trough, which was made of polythene film, PVC pipes and perspex, respectively. The whole experimental set-up cost only \$35. It is a good example for low cost solar still for rural and remote area. Meanwhile, an all-plastic solar still system could result in easier maintenance as the traditional glass cover which is heavy and vulnerable to damage was replaced by the PE film. Besides the approaches listed in **Fig. 2**, some researchers have proposed other novel methods or designs. The addition of nano-particles to the feed water to enhance solar still performance has been studied recently [25, 26]. Nanofluid was expected to possess superior heat transfer features compared with normal saline water. Kabeel *et al.* investigated the effect of nanofluid on the performance of a single basin solar still [26]. The daily productivity increased by 76% and 116% with or without additional vacuum fan operation. Instead of modifying the conventional basin type still, Ahsan *et al.* proposed and fabricated the novel Tubular Solar Still (TSS) using cheap, lightweight materials [27]. The new TSS was made from polythene film, carton paper and galvanized iron (GI) pipes/wire. The daily water productivity is 5 L/m².d with water production cost estimated as \$ 9.56/m³, which is much cheaper than the water costs of most of the other lab scale solar stills (**Table 1**).

Despite of the various modifications, the productivity is still quite limited, varying from 1~10 L/m².d in most cases as shown in **Table 1**. The thermal efficiency of the system can be evaluated with GOR_{so} (Gain Output Ratio solar) and SSEC (specific solar energy consumption) which are defined in Table 1. The reported GOR_{so} are in the range of 0.28~0.94 while mostly less than 0.8 with the corresponding SSEC in the range of 697~2340 kWh/m³. Most reported studies about solar stills are on a laboratory scale with less than 10 L/d water production. Very little information can be found in literature about pilot or real plant in recent years, while only a few plants were reported in the 1980s and 1990s. The water costs estimated in different studies varies from \$6~143/m³ with most up to \$30/m³. Ayoub *et al.* estimated the water production cost of a modified solar still with rotating cylinder at \$6~60/m³ with variation of capital cost, interest rate, service lifespan and productivity [28]. Ayoub *et al.* stressed that environmental damage costs should be considered to evaluate the economic feasibility of desalination technologies [28]. By combining the CO₂ trading cost, external environmental degradation costs due to air pollution with the water costs from literature, water costs of conventional fuel-based desalination technologies was estimated at \$4.7-5.7/m³, which lies in the lower range of renewable energy based desalination techniques.

Considering the low productivity, solar still is only recommended for small scale commercial application with the capacity of less than 10 m³/d to supply freshwater for fisherman, small islands and small villages in remote areas. Except for the efforts in performance improvement, to keep the simplicity, low maintenance and low cost feature of solar still is also of vital importance. Thus, active solar still with extra solar thermal collectors should not be a future focus. As pilot or real plants has not been reported in recent years, real application studies should be conducted to further demonstrate and evaluate the applicability and economic feasibility of this technology in the present world.

Fig. 2 Approaches to achieving higher productivity in solar stills

Table 1 Summary of selected solar still studies

Authors	year	location	Plant Type	System description	Totally passive or not	Feed water	Solar radiation W/m ²	Capacity 10 ⁻³ m ³ /d	Productivity L/m ² .d	Productivity increase rate (%)	GOR _{so}	SSEC kWh/m ³	Water Cost US \$/m ³
Hansen <i>et al.</i> [29]	2015	Tamil Nadu, India 9°11'N	Lab scale	Stepped solar still with water coral fleece and wire mesh on the absorber plate. The absorber plate area was 0.75m ² .	Passive	-	488 ^e (6am ~6pm)	4.3	5.71	71.2	0.64 ^k	1024	-
El-Samadon y <i>et al.</i> [30]	2015	Kafrelsheikh, Egypt 31°07'N	Lab scale	Stepped solar still with external condenser and air-suction fan. Basin area was 0.5m ² .	Vacuum fan used	Saline Water	578 ^e (9am ~7pm)	2.7	5.5	66.6	0.54	1212	-
				Stepped solar still with both internal, external reflectors and additional external condenser and air-suction fan. Basin area was 0.5m ² .	Vacuum fan used		-	4.5	9.0	165	0.66	993	36
El-Naggar <i>et al.</i> [31]	2015	Tanta, Egypt 30°47'N	Lab scale	Finned-basin liner still (FBLs)-single basin solar still integrated with metallic fins. Basin area was 1m ² .	Passive	Brackish Water	590 ^e (7am ~7pm)	4.8	4.80	11.8	0.55	1191	-
Kabeel <i>et al.</i> [26]	2014	Kafrelsheikh, Egypt 31°07'N	Lab scale	Single basin still with vacuum fan and external condenser. Basin area was 0.5m ² .	Vacuum fan used (powered by PV panel)	Saline Water	680 ^e (7am ~5pm)	3.0	6.0	46.6	0.71 ^k	923	41
				Single basin still with vacuum fan. Basin area was 0.5m ² . Suspended aluminum-oxide nanosized particles were mixed with feed water.			695 ^e (7am ~5pm)	4.2	8.4	116	0.94 ^k	697	50
				Same as above but without operating vacuum fan	Passive		-	7.9	15.8	76	-	-	
El-Agouz <i>et al.</i> [32]	2014	Tanta, Egypt 30°47'N	Lab scale	Stepped solar still with storage tank and continuous water circulation; basin made of 10 steps with an effective absorber area 1m ² covered with black paint.	Pump needed	Seawater	644 ^e (10am ~7pm)	5.3	5.30	43	0.60 ^k	1092	35
				Same as above while basin is covered with a layer of cotton cloth.			608 ^e (10am ~7pm)	5.3	5.30	53	0.63 ^k	1039	
Ayoub <i>et al.</i> [28]	2014	Lebanon	Lab scale	Double-slope solar still with rotating cylinder. Basin area was 1 m ² . The rotating cylinder was powered by a photovoltaic (PV) panel	Rotating motor powered by PV panel	seawater	-	4.2	4.2	190	-	-	6~60

Authors	year	location	Plant Type	System description	Totally passive or not	Feed water	Solar radiation W/m ²	Capacity 10 ⁻³ m ³ /d	Productivity L/m ² .d	Productivity increase rate (%)	GOR _{so}	SSEC kWh/m ³	Water Cost US \$/m ³
Ahsan <i>et al.</i> [24]	2014	Selangor, Malaysia	Lab scale	Triangular solar still (TrSS) made from lightweight local materials with a footprint of 0.8 m ² .	Passive	Saline water	-	1.3	1.60	-	-	-	-
Rajaseeni vasan <i>et al.</i> [33]	2014	Tamil Nadu, India 9°11'N	Lab scale	Double slope double basin solar still with black cotton cloth. Basin area was 0.63m ²	Passive	Saline water	497 (6 am ~6 pm)	3.5	5.57	-	0.60	1091	-
Omara <i>et al.</i> [34]	2013	Kafrelsheikh, Egypt 31°07'N	Lab Scale	Stepped solar still with internal reflectors installed on the vertical sides of the steps. Absorber area was 1.16 m ²	Passive	Saline water	660 (9 am ~7pm)	7.4	6.35	75	0.56	1170	-
Ahsan <i>et al.</i> [27]	2012	Japan / UAE	Lab scale	A tubular solar still (TSS) with a tubular cover and rectangular trough. Footprint was 0.07 m ² .	Passive	Saline water	-	0.35	5.0	-	-	-	9.56
Tabrizi <i>et al.</i> [35]	2010	Zahedan, Iran 29°29'N	Lab scale	Weir type cascade flow stepped solar still with PCM (paraffin wax under the absorber plate). Absorber area was 0.45 m ²	Passive	-	610 ^j	2.2	4.85	-	0.53 ^{j,k}	1235	-
El-Sebaei <i>et al.</i> [36]	2009	Jeddah, Saudi Arabia 21°42'N	Mathematical model	Single slope, single basin solar still integrated with 3.3cm of PCM (stearic acid) beneath the basin liner; basin area 1m ²	Passive	-	542 ^e (7 am ~7pm)	9.0	9.0	44.5	0.85	771	-
Kumar <i>et al.</i> [37]	2009	New Delhi, India, 28°36'N	Lab scale	Single slope solar still coupled with PV/T system; basin area was 1m ² . The PV/T system included two 2 m ² flat plate collectors and a 0.66 m ² PV module integrated at the bottom of one collector.	Integrated with flat plate solar collectors and PV panel	ground water	-	4.6 ^g	4.63 ^g	250	-	-	49~143
Kabeel <i>et al.</i> [38]	2009	Tanta, Egypt 30°47'N	Lab scale	Solar still with four side pyramid shape cover and concave wick basin. Basin aperture area was 1.44 m ² .	Passive	Saline water	731 ^e (10 am ~7pm)	4.0	2.78	-	0.28 ^k	2340	65
Abdallah <i>et al.</i> [39]	2008	Amman, Jordan, 31°56'N	Lab scale	Single slope still integrated sun tracking system, basin area 1m ² .	With sun tracking system	Saline water	600 ^e (7am ~6pm)	-	-	22	-	-	-
Abdel-Rehim <i>et al.</i> [40]	2007	Cairo, Egypt 30°03'N	Lab scale	Single solar still coupled with parabolic trough collector, copper pipe serpentine loop heat exchanger installed in the bottom of the still to transfer heat.	Coupled with parabolic trough collector	Saline water	635 ^e (9am ~7pm)	2.6	-	18	-	-	12

Authors	year	location	Plant Type	System description	Totally passive or not	Feed water	Solar radiation W/m ²	Capacity 10 ⁻³ m ³ /d	Productivity L/m ² .d	Productivity increase rate (%)	GOR _{so}	SSEC kWh/m ³	Water Cost US \$/m ³
Fath <i>et al.</i> [41]	2003	Aswan, Egypt, 24°05'N	Mathematical model	Pyramid shaped single basin still, basin area 1.53 m ²	Passive	-	694 ^f	6.5	4.25	-	0.4 ^k	1638	30
Delyannis <i>et al.</i> [42]	1995	Kimolos island, Greek, 36°48'N	Real plant	Absorber area 2008 m ²	Passive	Seawater	-	12500 ^h	5.97	-	-	-	-
Tiwari <i>et al.</i> [43]	1984	New Delhi, India, 28°36'N	Real plant	The plant consisted of 28 multi-wick solar stills (1 m ² basin area each), 1000L large storage tank and some small storage tanks and pipes.	Passive	-	-	70 ⁱ	2.5	-	-	-	-

Note:

a. GOR_{so} (gain-output ratio-solar) in this table is defined as the energy ratio of total latent heat of distillate to the total input solar energy to solar still. The subscript 'so' was used to make a difference between the GOR definitions in other thermal desalination technologies. Normally this parameter is referred to as thermal efficiency (η) in solar still studies. It can be determined by the equation below.

$$GOR_{so}(\eta) = \frac{m_d \cdot \Delta H_v}{3.6 A_a \cdot G} \quad (1)$$

m_d , average distilled water mass flow rate, kg/h;

ΔH_v , latent heat for evaporation, kJ/kg;

A_a , total area of absorber; m²

G , solar radiation intensity over absorber area, W/m².

b. SSEC (specific solar energy consumption) refers to the amount of input solar energy consumed per m³ fresh water production. The relationship between SSEC and GOR_{so} is:

$$SSEC, \frac{\text{kWh}}{\text{m}^3} = \frac{\Delta H_v}{3.6 GOR_{so}} \quad (2)$$

ΔH_v at 60°C (2358 kJ/kg) was used in the calculation of GOR_{so} and SSEC when the values are not available in literature. All SSEC values in this table were calculated with equation (2) by the authors.

c. Productivity in this table refers to the amount of water produced per m² basin area per day. Productivity increase rate refers to the productivity increase in comparison with the single basin still before the specific modification in literature.

d. As the performance of solar still will be largely influenced by meteorological conditions, the solar radiation, productivity, capacity, GOR_{so} and SSEC in this table mostly refer to the parameters for selected testing days. The exceptions will be specified below.

e. These are the average solar radiation data in the testing days between certain periods of time during which data was available in the solar radiation curves.

f. This is converted from the typical daily solar radiation in July of Aswan, Egypt by assuming 10 hours sunshine per day.

g. These values are average yield and productivity of 260 clear days in a year.

h. This is the summer time capacity of the plant.

i. This is the designed capacity of the plant.

j. The average solar radiation of testing day was obtained from local meteorological station. 10 hours sunshine was assumed in the calculation of GOR_{so}.

k. These GOR_{so} values were calculated with equation (1) by the authors.

m. Some of the water cost values were converted from local currency to US dollars with the exchange rate at the paper received date available in internet by the authors.

2.2 Indirect solar desalination

2.2.1 Solar humidification-dehumidification

Humidification-Dehumidification (HDH) technology utilized the moisture carrying capacity of hot air to realize the separation of saline water and pure water (moisture). Unlike solar still, which is mostly passive, HDH is normally coupled with external heaters such as solar collectors. Also, humidification and dehumidification take place in separate components, which allows each individual element to be designed and optimized independently [44]. Consequently, much higher thermal efficiency could be achieved in HDH than solar still. The major components of HDH process are humidifier, dehumidifier and external heater [45]. Solar HDH desalination is recognized as a suitable choice for decentralized water production with relatively low capacity.

Fig. 3 Schematic diagram of solar HDH configurations: (a) water or air heated closed air, open water cycle (CAOW); (b) water or air heated closed water, open air cycle (CWOA); (c) water or air heated open water, open air cycle (OWOA).

HDH process can be classified into three categories based on the cycle configuration: closed air, open water cycle (CAOW), closed water, open air cycle (CWOA), and open water, open air cycle (OWOA). The configurations are shown in Fig.3 while descriptions can be found in Sharon *et al.* [10] and Wael *et al* [46]. Either air or the feed water will be directly heated with external energy source in the HDH cycle (AH and WH are used as abbreviations for air heated system and water heated system in the text below). Solar thermal collectors for both water and air heating can be applied in solar HDH process.

Most of the investigations on solar HDH are concerned about the improvement on productivity and efficiency of the system, which can be made by design and optimization of the HDH cycle and individual element, as well as the optimization of operating conditions, such as the air/water mass flow rate and temperature of feed water and inlet air [47].

Table 2 shows a list of selected solar HDH studies reported in recent years. Al-Sulaimain *et al.* [44] studied the performance of an OWOA HDH system integrated with the parabolic solar air collector based on thermodynamic model while comparing two different configurations in which the solar collector was placed at different position in the HDH cycle, i.e. before the humidifier (first configuration) or between humidifier and dehumidifier (second configuration). The second configuration showed significantly higher average GOR_{so} (defined in **Table 2**) value (4.7) than the first configuration (1.5). As a result, much higher productivity was achieved in the second configuration with annual average value of 954kg/d rather than 293kg/d for the first one. HDH process can also be designed into multi-stage systems (sometimes referred to as multi-effect in literature). A 500 L/d two-stage CAOW-WH solar HDH pilot system was designed and constructed in Qom, Iran by Zamen *et al.* [48]. A mathematical model was developed for multi-stage solar HDH process as well. The multi-stage solar CAOW-WH HDH described in this study was featured by several smaller closed-air loops between humidifier and dehumidifier with each small loop stand for one stage. Modelling results showed that the specific water production was significantly improved by more than 40% in a two-stage HDH process, while only 4% and 1% increment can be achieved than lower-stage process for 3- and 4-stage HDH processes, respectively. Considering the increased desalination unit cost with increased stages, two-stage HDH process was regarded as the most suitable choice. The pilot system was tested during summer and winter days. Specific water production could reach 7.25 L/ m² •d in summer days, which was about 40% higher than single-stage unit tested in previous study.

Different types of humidifiers and dehumidifiers utilized in HDH process have been extensively reviewed by Narayan *et al* [49]. As shown in Table 2, packed bed humidifiers and finned-tube heat exchanger (dehumidifiers) are mostly adopted in recent solar HDH applications.

Solar thermal collectors such as flat plate solar collector, evacuated tube solar collector, parabolic trough solar collector have been adopted in solar HDH studies. However, compared with widely commercialized solar water heating devices, there is less experience in terms of solar collectors for air heating and the technology is relatively immature. Standard thermal efficiency of a few commercial solar air heater were reported as only 10.2%-32.3% [49]. Developing high efficient solar air collector specially for solar HDH applications have received considerable attention [50-53]. Summers *et al.* [51] designed a novel flat-plate solar collector for air heating with built-in phase change material (PCM) paraffin wax for HDH desalination. It was found that the solar collector with 8cm PCM layer below the absorber plate could produce constant output temperature with an average collector thermal efficiency of 35%. In the solar HDH pilot system developed by Li *et al.* [50], a new evacuated tube solar air collector was designed and adopted. It contained 20 dual-wall glass tubes connected in parallel and mounted on a insulated metal frame equipped with a header for air supply and return. The thermal efficiency of the solar air collector could reach 47% with optimized air flow rate ($140\text{m}^3/\text{h}$).

Reported GOR_{so} of HDH varies between 0.92~4.7, significantly higher than that of solar still. The corresponding specific solar energy consumption (SSEC) was calculated as $139\sim 712\text{ kWh}/\text{m}^3$. The specific water production was reported in the range of $0.36\sim 19.08\text{ L}/\text{m}^2\cdot\text{d}$. The two lowest values reported by Soufari *et al.* [54] and Zhani *et al.* [55] were all lab scale studies with very small capacity (10L and 20L) in which the solar collector may have been oversized compared to the actual requirement of the HDH system. Water cost was estimated in a range of $\$2.90\sim \$500/\text{m}^3$ with the higher cost range $\$115\sim 500/\text{m}^3$ estimated by Dayem [56, 57] and Zhani *et al.* [55] based on lab scale systems with $10\sim 20\text{L}/\text{d}$ daily production while the lower cost range was $\$2.90\sim 22.1/\text{m}^3$ for the data from pilot scale studies. According to Narayan *et al.* [49], for small capacity desalination plants, the water cost can go up to $\$3.00/\text{m}^3$ for the currently most economical RO desalination system. It seems that solar HDH could be economically comparable with conventional desalination plants in small scale applications. It has also been suggested by Li *et al.* [13] that HDH system should be targeting at small scale desalination plants with $5\sim 100\text{ m}^3/\text{d}$ capacity.

Presently, solar HDH process is still under research and development. Very limited work has been done in identifying the advantages and disadvantages of different configurations, the influence of which is considered considerable on HDH performance [47]. In order to commercialize this technology, further optimization of HDH cycle and the three major components will remains to be the most important focus of HDH research. Besides, better understanding of the thermodynamics of solar HDH process and development of mathematical model are also crucial for the scaling up of the process.

Table 2 Summary of selected solar HDH Plants

Authors	year	location	Plant type	Energy Source	System description	Feed Water	Solar radiation W/m ²	Capacity (m ³ /d)	SWP L/ m ² •d	GOR _{so}	SSEC Specific solar energy consumption kWh/m ³	Water cost ,m US \$/m ³
Al-Sulaiman <i>et al.</i> [44] ^e	2015	Dhahran, Saudi Arabia 26°16'N	Theoretical modeling	Parabolic trough solar air collector (PTC)	OWOA-AH system, PTC air heater located before the humidifier. The length of parabolic trough was 10m, the width was 5m.	-	150~750	0.293	5.86	1.5	437	-
					Same as above except that PTC was located between humidifier and dehumidifier.			0.954	19.08	4.7	139	-
Zamen <i>et al.</i> [48]	2014	Qom, Iran 34°38'N	Pilot plant	Flat-plate solar collector (FPC)	Two stage CAOW-WH system, polypropylene packed bed humidifier; finned tube condenser used in dehumidifier; 80m ² FPC heated water indirectly via heat exchanger.	Saline water	-	0.58 ^f	7.25 ^f	-	-	-
Kabeel <i>et al.</i> [58]	2014	Tanta, Egypt 30°47'N	Lab scale	Flat plate solar water heater and solar air heater	Hybrid solar desalination system consisted of a CWOA HDH unit, a single stage flash evaporation unit and solar water/air heating system; packed bed humidifier; counter-flow shell and multi-pass tube heat exchanger used as dehumidifier. Nano-fluid was used as heat transfer fluid for the solar water heater loop.	Seawater	670 ^g (9am-6pm)	0.042 ^h	-	-	-	-
Chang <i>et al.</i> [59]	2014	China	Pilot plant	Thermo-syphon water heater	Two stage CAOW-WH HDH system, two successive humidifiers and dehumidifiers, operating at higher and lower temperature, respectively; packed bed humidifier filled with porous plastic balls and dehumidifier with heat exchanger made of corrugated aluminum finned copper tubes were adopted.	Seawater	-	0.5 ⁱ	-	-	-	4.4

Authors	year	location	Plant type	Energy Source	System description	Feed Water	Solar radiation W/m ²	Capacity (m ³ /d)	SWP L/ m ² •d	GOR _{so}	SSEC Specific solar energy consumption kWh/m ³	Water cost US \$/m ³
Dayem [56]	2014	Makka, Saudi Arabia 21°25'N	Lab scale	Flat plate solar collector	CAOW-WH HDH unit with one single dual wall storage and desalination tank. The inner space functioned as humidifier while outer layer acted as the condenser. 1.15 m ² flat plate solar collector was used.	Saline water	-	0.010 ^h	9 ^h	-	-	500
Yuan <i>et al.</i> [60]	2011	Beijing, China 39°55'N	Pilot plant	Evacuated tube solar air heater and solar water heater	CWOA air/water heated HDH system; honeycomb-structured pad humidifier and dehumidifier with fin-tube condenser; 100m ² solar air heater, 14m ² solar water collector	Seawater	500 ^k	1.0 ^j	8.77	2.0	328	2.9
Dayem [57]	2011	Cairo, Egypt 30°03'N	Lab scale	Flat plate solar collector	CWOA-WH HDH system with a 100L insulated galvanized tank as desalination unit. An built-in air atomizer to eject the hot water used for humidification and 2 containers condenser used for dehumidification. 2.35 m ² flat plate solar collector was used as heat source.	Saline water	-	0.010 ^h	4.25 ^h	-	-	200
Zhani <i>et al.</i> [55]	2010	Sfax, Tunisia 34°44'N	Lab scale	Flat plate air/water solar collector	CAOW air/water heated HDH system with a pad humidifier, an evaporator, and a dehumidifier; 16m ² air solar collector and 12m ² water solar collector	Seawater	689 ^g	0.021 ^h	0.71 ^h	-	-	115.2
Mathioulakis <i>et al.</i> [61]	2010	Geroskipou, Cyprus 34°46'N	Pilot plant	Flat plate solar collector	CAOW-WH HDH system, 1000L/d commercial HDH unit, flat plate solar collector with surface area 96m ² and a 5 m ³ thermal storage tank.	Saline water	-	1.0 ^j	10.41 ^j	-	-	22.1
Soufari <i>et al.</i> [54]	2009	Karaj, Iran 35°50'N	Lab scale	Flat plate solar collector	CAOW-WH HDH system, packed bed humidifier, fin-tube heat exchanger used as dehumidifier; 28 m ² flat plate solar collector.	Saline water	-	0.010 ^j	0.36 ^j	-	-	-
Yamali <i>et al.</i> [62]	2008	Ankara, Turkey 39°56'N	Lab scale	Double pass flat plate solar air collector	CWOA-AH HDH; pad humidifier with four plastic pads mounted vertically; heat exchangers made with copper tubes and corrugated aluminum fins used as dehumidifier; 0.5 m ² double-pass flat-plate solar collector.	Saline water	814 ^g (10am ~4pm)	0.004 ^h	8.0 ^h	0.92 ^l	712	-

Authors	year	location	Plant type	Energy Source	System description	Feed Water	Solar radiation W/m ²	Capacity (m ³ /d)	SWP L/ m ² •d	GOR _{so}	SSEC Specific solar energy consumption kWh/m ³	Water cost US \$/m ³
Houcine <i>et al.</i> [63]	2006	Kairouan, Tunisia 35°40'N	Pilot plant	Four-fold-web-plate solar air collector	CAOW-AH HDH with successive 4 stage air heating and humidification process prior to the dehumidifier. Pad humidifier, finned-tube heat exchanger dehumidifier was adopted. Total surface area of solar air collector was 205m ² .	Seawater	-	0.564 ^h	2.75 ^h	-	-	-

Note:

a. GOR_{so} (gain-output ratio-solar) in this table is defined as the energy ratio of total latent heat of distillate to the total input solar energy to the HDH system. It can be determined by the equation (1). Aa in the equation refers to total aperture area of solar collectors instead of absorber area.

b. SSEC (specific solar energy consumption) refers to the amount of solar energy (that reached the aperture area of solar thermal collectors) consumed per m³ fresh water production. The relationship between SSEC and GOR_{so} is shown by equation (2). ΔH_v at 60°C (2358 kJ/kg) was used in the calculation of GOR_{so} and SSEC when the values are not available in literature.

c. SWP (specific water production) refers to the water production per m² of solar collector area per day [46].

d. The solar radiation, GOR_{so}, SSEC values in this table mostly refer to the parameters for specific testing days or average value of testing days; capacity and specific water production (SWP) in the table refers to the fresh water production in specific days or the designed capacity for the pilot or real plant. The descriptions of these values will also be specified below.

e. The solar radiation in this reference refers to the range of monthly average values throughout a year while GOR_{so}, capacity and SWP refers to the annual average values.

f. The capacity and SWP was derived from daily production rate on typical summer days in this reference.

g. These are the average solar radiation data in the testing days between certain periods of time during which data was available in the solar radiation curves.

h. These values are based on experimental production rate in specific testing days.

i. This is estimated daily production rate based on the steady state performance of the unit.

j These values are based on designed capacity of the pilot plants or experimental setups.

k. This is the daily average solar radiation when the daily production met the designed capacity.

l. These GOR_{so} values were calculated with equation (1) by the authors.

m. Some of the water cost values were converted from local currency to US dollars with the exchange rate at the paper received date available in internet by the authors.

2.2.2 Solar-powered MSF

Multi-stage flash (MSF) is currently the most dominant thermal desalination technology, which has around 21% share of worldwide desalination installation capacity, being second only to reverse osmosis [64]. MSF evaporator consists of several consecutive stages with decreasing pressures. As shown in **Fig. 4**, the feed seawater/brackish water is first preheated by the condensation of vapour while flowing through these stages in tubes. Then the preheated brine receives external heat from a brine heater normally with heating steam, after which it successively passes through stage by stage, where sudden boiling (flash) of the feedwater takes places as a result of the reduced pressure.

Fig. 4 Schematic diagram of a solar MSF desalination system with thermal storage

In solar powered MSF, solar thermal collectors are used in connection with a conventional MSF desalination system. The selection of solar thermal collector, proper design of solar heating cycle, design and optimization of MSF unit are all of vital importance to the successful application of solar powered MSF process. The performance and GOR (gain output ratio) of MSF plants could be improved by increasing TBT (top brine temperature, temperature of the brine entering the first flashing stage), reducing intake saline water temperature, increasing numbers of stages and specific heat transfer area. Since relatively high and stable TBT (normally 90~120°C in a conventional MSF plant) is required, an effective thermal storage system used for thermal buffering is favorable in solar MSF systems.

Some selected solar MSF studies are listed in **Table 3**. Several solar MSF pilot plants have been reported since 1980s with the capacity of 10~20 m³/d [65]. A 10 m³/d self regulating solar MSF pilot system was designed and tested in Safat, Kuwait in 1983 [66]. A 7 m³ thermal storage tank was installed in the system which served as a thermal damper between the solar collector and the MSF subsystem. The reported specific thermal energy consumption (STEC) of the MSF subsystem was in the range of 83–105 kWh/m³ with the corresponding GOR being 6.5–8.

Fig.5 Schematic diagrams of different solar MSF-BR desalination plants proposed by Mohamed *et al.* [67]

Very limited publications on solar MSF plants are available in the past 20 years. Meanwhile, reported solar MSF studies are mostly focused on low capacity plants. Only recently, Eldean *et al.* [67] analyzed and evaluated a 5000 m³/d solar MSF-BR (multi-stage flash brine recycle) system with

REDS-SDS software package in Matlab/Simulink environment. Three different configurations (shown in **Table 3** & **Figure 5**) of the solar thermal cycles were proposed to be integrated with the MSF unit: 1) direct vapor generation (DVG) , 2) indirect vapor generation (IDVG) , 3) The combination of MSF unit with solar organic Rankine cycle (SORC) for electricity-water cogeneration (Description see **Table 3**). Design parameters such as solar field dimensions, heat exchanger details, flow rates, operating conditions, etc. were derived from the software with basic input data including capacity, weather conditions, top brine, seawater and blow down temperatures, mechanical efficiencies of turbo machinery units, etc. A GOR of 12 were achieved with 40 stages MSF. The water cost of the proposed plant were estimated at \$1.36~1.58/m³, which could be comparable with conventional MSF plants powered by fossil fuels. This study indicates that solar MSF can be an economically and technically viable option for large scale desalination plants.

Compared to its alternative technology solar MED (multi effect distillation, see section 2.2.3), reported research and applications are far less in solar MSF. This indicates that solar MSF may be either technologically or economically less competitive than solar MED probably due to three major reasons: 1) the high TBT requirement makes it relatively less favorable to be combined with solar energy; 2) with higher TBT, it will exhibit higher fouling and scaling trend; 3) MSF is thermodynamically less efficient than MED. However, as the present mostly installed thermal desalination technology, the transformation of conventional fossil fuel based plants into solar-fuel integrated plants may be a future need with the depleting of fossil fuel resources. Thus further research should be conducted in solar MSF to realize high efficiency integrated systems. Besides, dual purpose plants that combines concentrating solar power plant with solar thermal desalination is also a potential option for future MSF development. Further information of CSP+D plants has been presented in section 2.2.3.

Table 3 Summary of selected solar powered MSF studies

Authors	year	location	Plant type	Energy Source	System description	Feed Water	Solar radiation W/m ²	Capacity (m ³ /d)	TBT °C	GOR	STEC kWh/m ³	GORso	Water cost US \$/m ³
Sharaf Eldean <i>et al.</i> [67]	2013	Egypt	Model d	Parabolic trough collector (PTC)	DVG Solar MSF- BR system consisted of PTC solar field, brine heater, 40 stages MSF-BR unit. Brine was heated by the steam which is directly generated from solar collector. Water was used as working fluid for the solar thermal cycle. Collector outlet steam temperature 135°C. Solar collector area 61680m ²	Seawater	594 ^e	5000	90~130	12	53 ^g	-	1.36
					IDVG solar MSF-BR system, similar as above but HTO (heat transfer oil, Therminol-VP1) was used as working fluid in solar field, HTO transferred energy to steam via a boiler heat exchanger (BHX) unit. Seawater was heated up by steam via brine heater. Collector outlet temperature 350 °C , brine heater steam temperature 135°C. Solar collector area 61680m ² .								
					MSF combined with solar organic Rankine cycle (SORC), the system was consisted of 40 stages MSF-BR unit, pumps, PTC solar field, BHX unit, turbine expander unit and condenser unit. The condenser in ORC loop was used as brine heater for the MSF unit. HTO and toluene was used through the solar field and the ORC, respectively. Collector outlet temperature 350°C, brine heater steam temperature 135°C. Solar collector area 93050m ² .								1.58
Nafey <i>et al.</i> [68]	2007	Suez, Egypt 29°58'N	Lab scale	Flat plate collector (FPC)	The system consisted of a flash chamber, a condenser unit with copper tube heat exchanger, and a flat plate solar collector with surface area of 2.39m ² .		556 ^f (9am~4pm)	0.011 ^f	49~56	-	-	0.7~0.9	-

Authors	year	location	Plant type	Energy Source	System description	Feed Water	Solar radiation W/m ²	Capacity (m ³ /d)	TBT °C	GOR	STEC kWh/m ³	GOR _{so}	Water cost US \$/m ³
Lu <i>et al.</i> [69]	2001	El Paso, US 31°47'N	pilot	Solar pond	A small 3-effect, 4-stage flash distillation unit powered by solar pond. LCZ (lower convective zone) brine from a 3000m ² pilot solar pond with temperature of 77~87°C was used to heat up the feed water.	Saline water	-	2.3~7.2	63~80	1.7~3.7	h 175~380	-	-
Moustafa <i>et al.</i> [66]	1985	Safat, Kuwait 29°22'N	Pilot	PTC	A self-regulating 12 stages MSF system, energy derived from 220 m ² PTC solar field. A 7m ³ thermal storage tank was installed between them. Heat exchanger was used as interface between MSF subsystem and the thermal storage tank.	Seawater	-	10	40~90	6.5~8	83~105	-	-

Note:

- a. GOR (gain-output ratio) in this table is defined as the energy ratio of total latent heat of distillate to the directly input thermal energy to drive MSF process (sometimes referred to as performance ratio in literature). Normally it is the latent heat of heating steam that enters brine heater. At this case, GOR is equal to the ratio of distillate mass flow rate to the heating steam mass flow rate.
- b. GOR_{so} (gain-output ratio-solar) in this table is defined as the energy ratio of total latent heat of distillate to the total input solar energy to the MSF system. It can be determined by the equation (1). A_a in the equation refers to total aperture area of solar collectors.
- c. STEC (specific thermal energy consumption) refers to the amount of input thermal energy consumed per m³ fresh water production. STEC can be calculated with GOR value when these two factors refer to the same thermal desalination process. In that case, the relationship between STEC and GOR is:

$$\text{STEC}, \frac{\text{kWh}}{\text{m}^3} = \frac{\Delta H_{v,T}}{\text{GOR}} \quad (3)$$

Where $\Delta H_{v,T}$ refers to the latent heat of evaporation at a reference temperature (assumed as the evaporation temperature of produced steam).

- d. The simulation was based on a visual modular program (REDS-SDS software package) developed by [70] using Matlab/Simulink environment.
- e. This is the daily average value of the input designed solar radiation. 10h daylight hour was assumed in the calculation.
- f. This is the average solar radiation between 9am~4pm of the testing day. The capacity is the daily production of the same day.
- g. The STEC value was calculated with the available GOR value, $\Delta H_{v,T}$ at 90°C (2383 kJ/kg) was used in the calculation.
- h. The STEC value was calculated with the available GOR value, $\Delta H_{v,T}$ at 70°C (2336 kJ/kg) was used in the calculation.

2.2.3 Solar-powered MED

Fig. 6 Schematic diagram of solar MED desalination system with feed preheating

In multi effect distillation (MED) (see **Fig. 6**), seawater/brackish water is delivered to several cells (i.e. ‘effects’) maintained at low pressure successively. External energy is supplied to the first effect. Latent heat of vapourization is recovered as the succeeding effect serves as the condenser for the vapour produced in the previous effect. While MSF is currently the predominant thermal desalination technology adopted in large scale plants, MED is regraded as thermodynamically more efficient and could be operated at much lower top brine temperature (TBT) (55~120°C) to avoid scaling and corrosion problem [71, 72]. MED process has received considerable attention regarding solar powered systems due to the low TBT requirement.

Fig.7 Schematic diagram of four heat pumps used in MED (a) Thermal vapour compression (TVC), (b) Mechanical vapour compression (MVC), (c) Absorption heat pumps (AHP), (d) Adsorption heat pumps (ADHP)

The performance of MED plants can be significantly affected by design and operating parameters such as number of stages, top steam temperature (heating steam temperature of the first effect), heating steam flow rate, temperature difference in the final condenser, etc. Except for optimizing these parameters, four types of heat pump have also been adopted for coupling with MED (**Fig. 7**) to achieve higher efficiency in MED system, including mechanical vapour compression (MVC), thermal vapour compression (TVC), absorption heat pumps (AHP) and adsorption heat pumps (ADHP) [13]. To some extent, these heat pumps all aims to recover the last effect steam or the low grade energy of it. Among them, TVC have been widely used in commercial desalination plants since 1990s [72]. TVC features the steam-jet ejector based on Venturi principle through which the pressure and temperature of the steam generated in the last effect of the MED process is elevated by introducing high pressure motive steam. As the last effect steam is partly reused, the required motive steam, the size of thermal energy supply system and the final condenser are drastically reduced. In MED-MVC, the low temperature/pressure steam from the last effect of MED is compressed to high temperature/pressure steam by mechanical compressor which is mostly driven by electric power or diesel engine. Final condenser is eliminated in this configuration which make it even more compact. However, presently MVC application is limited to small to medium desalination plants with maximum 5000 m³/d capacity [73]. Hygroscopic absorbent/adsorbent is utilized in AHP and ADHP, respectively. Four basic heat exchange units are included in a typical single-effect AHP loop: evaporator, absorber, generator and condenser. When combined with MED [74], evaporation of refrigerant (water) is induced by recovering latent heat from the MED last effect steam. External thermal energy is provided to the generator so that the high temperature steam is produced which serves as the heating

steam of the first MED effect. In a MED-ADHP hybrid system, vapour produced in the last effect of MED is adsorbed in the adsorber/desorber bed. Silica gel and zeolite are the most commonly used adsorbents. This combination enables the last effect to be operated below ambient temperature, and thus more effects can be inserted at the same TBT. Since adsorption and desorption cannot take place simultaneously, the AD cycles are batch type. Two or multi adsorber bed configuration is essential for continuous production. MED-ADHP is regarded as presently infeasible for commercial desalination applications due to poor performance and the operating challenge brought by its batch feature [75].

Table 4 lists selected solar powered MED systems reported in recent years. Solar desalination based on MED have been investigated and tested in the Spanish solar research centre Plataforma Solar de Almeria (PSA) since 1988 with the implementation of STD project (1987-1994) followed by AQUASOL project (2002-2006). Several types of solar MED systems have been tested and evaluated [74, 76-78], including the MED powered by parabolic trough solar collectors (PTC), MED-TVC system driven by high pressure steam derived from a small solar thermal power plant, and MED-DEAHP system driven by PTC or hybrid solar-gas energy source. A 14-effect forward-feed commercial MED unit with nominal distillate production rate of 3 m³/h was adopted in these systems. Two prototypes of DEAHP (double effect absorption heat pump) system have been designed and tested with the first one drove the MED first effect by directly supplying low-pressure steam whereas the second one drove the first effect by providing hot water via auxiliary hot water tanks. Several advantages of connecting AHP with MED were pointed out by Alarcon-Padilla *et al* [74], including reduction of thermal energy consumption, which result in significant reduction of solar field size in the case of solar desalination; decrease of electrical energy consumption and seawater intake capital cost because of the reduced cooling seawater flow requirement; possibility of reducing last effect operating temperature below ambient allowing extra effects at same TBT.

Solar powered MED-AHP was also adopted in a recent study by Stuber *et al* [75]. The pilot plant was implemented and operated in California, USA which aims to reuse subsurface agriculture drainage water after desalination. The open-loop AHP system mainly consisted of an absorber and a steam generator (desorber) while the MED unit worked as evaporator and condenser of a traditional AHP circuit. Low temperature steam from last effect of MED was fed to the absorber. High temperature steam was produced in the generator via heat exchange with the heat transfer fluid from 656 m² parabolic trough collector solar field, after which it condensed in the first effect of the MED system. By comparing two different operation mode (MED only and AHP-MED operation), it was found that specific thermal energy consumption (STEC) was largely reduced (by 49%) with the heat pump, a minimum STEC of 133.2kWh/m³ compared to 261.87 kWh/m³ without heat pump. This result also indicated a 49% reduction in solar collector area requirement at the same freshwater production rate. Based on the pilot system, an optimized commercial system using a 10-effect MED and an open-

cycle double-effect AHP was simulated. The STEC of the system was estimated at 34.9 kWh/m³ with the GOR of MED as 18.4.

The integration of concentrating solar power plants (CSP) and desalination technologies (CSP+D) has also attracted some research interests in recent years. With the merit of cogeneration of electricity and fresh water, CSP+D could become a sustainable solution to solve both power and water problems while reducing the solar power and desalination water cost when compared with independent plants [79]. The CSP+D concept is especially suitable for middle or large scale solar desalination applications. Low temperature MED (LT-MED) and Reverse Osmosis (RO) are regarded as the most promising desalination technologies to be coupled with CSP [79]. Although no real plant has been built yet, CSP+MED have been investigated by researchers based on simulation and different configurations have been discussed [79-82]. The size of CSP could be designed either to fit the MED desalination plant when all the exhaust steam from the turbine are used to drive MED or with larger size just to meet the electricity capacity required. A techno-economic analysis of CSP+MED plant configurations for two sites in Israel and Jordan was conducted by Olwig *et al* [81]. Desalination plants with 24,000 m³/d capacity were designed and simulated. The CSP plant capacity (42 MW electricity generation capacity) was selected to meet the exhaust steam requirement of MED plant. Thus MED unit replaced the cooling subsystem of the power generation cycle. Simulation result showed that the water cost in these two plants were \$0.943/m³ and \$1.215/m³, respectively. This lies in the water cost range of fossil fuel powered large scale commercial MED plants reported in literature [83], indicating that CSP+MED is an economically realistic option for fresh water supply in the MENA region (middle east and north africa). It should be noted that ‘power credit method’ was applied in the calculation of unit water price, in which the steam cost for MED plant was estimated by assuming that the power loss due to the use of backpressure turbine instead of condensing turbine adopted in independent power plants has to be compensated by purchasing power from the grid. Casimiro *et al* [80] simulated a CSP+MED system with a CSP+MED-TVC integrated plant model developed based on the CSP simulation model-SAM physical trough model developed by NREL (U.S. National Renewable Energy Laboratory). Considering the high intermittence of CSP plant, the MED plant was downsized compared with the CSP installed capacity so that it can be operated more frequently under designed conditions. Seawater cooling circuit was essential in this case as the heat load output from the CSP plant is only partly utilized by the MED plant. A 36,112 m³/d MED desalination plant was simulated at 40% heat load output from the 110 MWe gross capacity CSP plant. When simulated with the weather condition in Sicily, Italy, 34.2% yearly installed capacity of the CSP plant and 41.4% yearly capacity of the MED plant could be achieved.

As shown in **Table 4**, reported GOR values of the desalination unit in solar MED plants are in the range of 2.7~15, with the lowest value correspond to a 3-effect forward feed MED system and the highest value correspond to a 16-effect MED-MVC system. Water cost were estimated at \$4.1~22/m³

for small to medium solar MED plants with the capacity between 2.3~160 m³/d; while in contrast estimated water cost for large scale solar MED plants or CSP+MED plants are much lower, being in the range of \$0.94~1.32/m³. This is comparable with the conventional large scale thermal desalination plants. Till now, significant progress has been made in the research and development of solar MED systems. Solar MED could be a sustainable alternative for middle to large scale conventional desalination plants though no large scale plants have been built yet. Dual purpose plants that combines CSP has no real case as well. Further research based on demonstration and thermodynamic modelling need to be done to realize the scaling-up of solar MED as well as to demonstrate the technical and economical feasibility of this technology. Meanwhile, reducing the environment impact of solar MED plants by effectively managing the brine should also be a future focus.

Table 4 Summary of selected solar powered MED studies

Authors	Year	Location	Plant Type	Energy source	System Description	Feed Water	Capacity (m ³ /d)	GOR	STEC (kWh/m ³)	SEEC (kWh _e /m ³)	Water cost US \$/m ³
Stuber <i>et al.</i> [75]	2015	Firebaugh, US 36°51'N	Pilot Plant	Parabolic trough collector (PTC)	Solar-AHP-MED pilot system, 3-effect MED with plate and frame evaporator; an open-loop absorption heat pump integrated with MED; PTC solar thermal system with 656m ² aperture area, heat transfer fluid was circulated through solar array and delivered heat to the steam generator of AHP, a set temperature of 180°C for heat transfer fluid was used in operation.	Brackish agricultural drainage water	6.74 ^d	5.27	133	-	-
Casimiro <i>et al.</i> [80]	2014	Sicily, Italy 37°30'N	Model ^g	Parabolic trough CSP (concentrating solar power) plant	CSP+MED-TVC plant: CSP plant with design gross output of 110 MW _e (design net output) at designed solar radiation 950W; 12-effect MED-TVC plant operates at 40% CSP heat load output (an extra condenser absorb the rejected heat load from CSP); MED feed saturated steam temperature 64.5°C. Yearly capacity factor of CSP and MED plant are 34.2% and 41.4%, respectively.	Seawater	36,112	10.2	64 ^e	2.81	-
Liu <i>et al.</i> [84]	2013	Dalian, China 38°55'N	Mathematical Model	Evacuated tube collector (ETC) and auxiliary electrical heater	Major component of the system included ETC subsystem, thermal storage tank, a flash evaporator (produced driving steam for MED), MED subsystem and auxiliary electrical heating/cooling devices. Solar collector area 4000m ² ; 10 effect MED with the first effect steam temperature 66°C.	Seawater	160	-	-	-	4.1 ^g
Kim <i>et al.</i> [85]	2013	Jeddah, Saudi Arabia 21°32'N	Numerical Model	ETC and auxiliary heater	Major component of the system included a 6-effect backward feed MED, 849 m ² ETC solar collector, 280m ³ hot water storage tank and auxiliary heater. When heating water temperature was set at 80°C, annual solar fraction was 49.4%.	Seawater	15.6	4.11	159 ^e	-	-

Authors	Year	Location	Plant Type	Energy source	System Description	Feed Water	Capacity (m ³ /d)	GOR	STEC (kWh/m ³)	SEEC (kWhe /m ³)	Water cost US \$/m ³
Olwig <i>et al.</i> [81]	2012	Aqaba, Jordan 29°31'N	Model ^h	Parabolic trough CSP plant, natural gas as backup	Two 10-effect MED units with horizontal tube falling film evaporators, coupled with an Andasol-type CSP plant (mainly consists of parabolic trough collectors, molten salt thermal storage tanks and Rankine steam power cycle). 42MW _e power generation capacity was selected to meet the steam consumption of MED plant. Designed top brine temperature (TBT) 65°C.	Seawater	24,000	8.35	77.8	2.4	0.943
		Ashdod, Israel 31°48'N						8.52	76.3	2.3	1.215
Sharaf <i>et al.</i> [73]	2011	Egypt	Model ^j	PTC	Solar MED-TVC system mainly consisted of PTC solar collector field, 5-effect parallel feed MED-TVC unit and the boiler heat exchanger (BHX) which generated motive steam that directly drive the TVC section. Total solar field area was 94760 m ² . TBT in the first effect was 58.5°C	Seawater	4545	8.04	81.5 ^e	1.58~2.0	1.32
					Solar MED-MVC system mainly consisted of PTC solar collector field, organic Rankine cycle (ORC) for electricity production, the boiler heat exchanger (BHX) which generated steam in the ORC, and 16-effect parallel feed MED-MVC unit. MED-MVC was directly powered by electricity. Total solar field area was 14370 m ² . TBT in the first effect was 59.9°C			15	-	4.18	0.94

Authors	Year	Location	Plant Type	Energy source	System Description	Feed Water	Capacity (m ³ /d)	GOR	STEC (kWh/m ³)	SEEC (kWh/m ³)	Water cost US \$/m ³
Sharaf <i>et al.</i> [82]	2011	Egypt-Suez Gulf region 30°N	Model ^j	PTC	The system mainly consisted of 16-effect MED unit, solar collector field and the boiler heat exchanger (BHX) where top steam was generated with the thermal power from the heat transfer oil from solar cycle. Four different flow arrangements of MED were studied: forward (FF), backward (BF), parallel (PF), and forward feed with feed heaters (FFH).	Seawater	100	f, BF 9.88 FF 4.48 FFH13.9 PF 15.2	BF 65.2 FF 143.8 FFH 46.3 PF 42.4	-	BF 7.14 FF 12.9 FFH 5.75 PF 5.47
					The system mainly consisted of 16-effect MED unit, solar collector field, BHX and organic Rankine cycle (ORC). The exhaust steam from ORC was used as top steam of the MED unit. Water and electricity was produced at the same time. Four different flow arrangements of MED were studied.			BF 9.21 FF 4.56 FFH15.0 PF 19.4	BF 71.1 FF 143.5 FFH 43.7 PF 33.7	-	BF 8.03 FF 13.8 FFH 5.13 PF 5.06
Leblanc <i>et al.</i> [86]	2010	Melbourne, Australia 37°48'N	Pilot plant	Solar Pond	3-effect forward feed MED system with submerged tube evaporator, thermal energy supplied by 720m ² solar pond. The seawater in the first effect was heated up by the hot brine from the low conductive zone (LCZ). LCZ brine temperature 60~85°C.	Seawater	2.3	2.7 ^f	244	-	18~22
Alarcon-Padilla <i>et al.</i> [87]	2010	Almeria, Spain 36°50'N	Plant Design	PTC and gas boiler	The system mainly consisted of a forward feed 14 effect MED unit, a LiBr-H ₂ O double-effect absorption heat pump (DEAHP), the gas boiler, the PTC solar collector field with thermal storage and steam generator. Thermal energy is supplied to the MED-DEAHP system at a generator (separation of water steam from LiBr solution) of DEAHP. Gas boiler was used as the backup for the solar thermal system to guarantee 24h operation. The MED unit was connected to DEAHP indirectly via two auxiliary tanks. MED top brine temperature was designed at 70°C.	Seawater	72	>9	<72 ^e	-	-

Authors	Year	Location	Plant Type	Energy source	System Description	Feed Water	Capacity (m ³ /d)	GOR	STEC (kWh/m ³)	SEEC (kWh/m ³)	Water cost US \$/m ³
Alarcon-Padilla <i>et al.</i> [76]	2008	Almeria, Spain 36°50'N	Pilot Plant	Compound parabolic concentrator (CPC) and gas boiler	The system mainly consisted of a forward feed 14 effect MED unit, a LiBr-H ₂ O double-effect absorption heat pump (DEAHP), the gas boiler, 500m ² stationary CPC solar collector field with 24 m ³ thermal storage. Gas boiler was used as the backup for the solar thermal system to guarantee 24h operation.	Seawater	67	10	64	-	-

- a. GOR (gain-output ratio) in this table is defined as the energy ratio of total latent heat of distillate to the directly input thermal energy to drive MED process (sometimes referred to as performance ratio in literature). Normally it is the latent heat of heating steam that enters the first effect that drives the MED process. At this case, GOR is equal to the ratio of distillate mass flow rate to the heating steam mass flow rate.
- b. STEC (specific thermal energy consumption) refers to the amount of input thermal energy consumed per m³ fresh water production. STEC can be calculated with GOR value when these two factors refer to the same thermal desalination process. In that case, the relationship between STEC and GOR has been shown in equation (3).
- c. SEEC (specific electrical energy consumption) refers to the amount of electrical energy consumed per m³ fresh water production.
- d. This is calculated by assuming 8h operation per day based on the product water flow rate derived from literature [75].
- e. The STEC values are calculated with the available GOR values, $\Delta H_{v,T}$ at 60°C (2358 kJ/kg) was used in the calculation.
- f. The GOR values are calculated with the available STEC values, $\Delta H_{v,T}$ at 60°C (2358 kJ/kg) was used in the calculation.
- g. The water cost values was converted from Chinese Yuan (26 Yuan/m³) to US dollar with an exchange rate of 6.365 (the exchange rate found in the Internet at the article received date).
- h. A steady-state CSP-MED model was used, which is established based on the SAM physical trough model from NREL (U.S. National Renewable Energy Laboratory) .
- i. The MED plants were Designed and simulated using the software IPSEpro developed by SimTech Simulation Technology, Austria.
- j. Design and simulation of the solar desalination plants was based on an established SDS (Solar Desalination System) software package.

2.2.4 Solar-powered MD

Membrane distillation (MD) is a thermally driven membrane separation process, in which only water vapour or other volatile species are allowed to pass through the hydrophobic membrane. The driving force of MD is the transmembrane vapour pressure difference. There are four basic configurations of MD according to the different means to recover vapour in the permeate side[88]: direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), vacuum membrane distillation (VMD) and sweeping gas membrane distillation (SGMD). Besides, some new configurations have also been developed by researchers in recent years, including V-MEMD [89-91] and PGMD (a variation of AGMD) [92]. The performance of MD is largely affected by the configuration adopted, the design of membrane module, the properties of used membrane (such as membrane pore size distribution, porosity, thickness, etc.) and operating conditions (such as temperature of feed water and cooling water, feed and cooling flow rate, permeate side pressure for VMD, air gap thickness for AGMD, etc.) [88]. Modest operating temperature is required in MD process, normally between 60~80°C [93], which enables it to be easily coupled with low-grade and renewable energies. Solar powered membrane distillation has received considerable attention from researchers. A schematic diagram of solar powered membrane distillation is shown in **Fig.8** with AGMD module as an example. Several demonstration plants have been built over the past decades. **Table 5** is a summary of selected solar MD studies in recent years.

Fig.8 Schematic diagram of a solar powered AGMD system

Several solar driven MD pilot plants using AGMD spiral-wound membrane modules have been installed in Spain, Jordan and Egypt within a European Commission funded project ‘SMADES’ [94-98]. One of the plant built in Jordan successfully desalinated real seawater from the Red sea with actual output of 0.14~0.8 m³/d and specific energy consumption of 200~300 kWh/m³ [97]. Achmad *et al.* [99] developed and studied the performance of a standalone 100 L/d solar driven pilot membrane distillation system in Saudi Arabia. A novel memsys Vacuum Multi-effect Membrane Distillation (V-MEMD) module was adopted in the system. Meanwhile a heat pump was integrated into the system to improve the performance by simultaneously preheating the feed and cool the cooling water for condenser. A daily production rate range of 32.4 L/d to 99.6 L/d was achieved at different weather conditions. It was found that the presence of heat pump significantly affected the condenser input temperature and feed temperature and considerably increased distillate flux. Raluy *et al.* [100] reported the 5-year operational experience and data analysis of a 100 L/d solar MD demonstration plant located in Gran Canary Island, Spain. During the five years operation, daily water production in the range of 5~120 L/d with the lowest production in winter months was obtained, while high quality distillate with conductivity at 20~200µS/cm was produced. Specific thermal energy consumption of 140~350 kWh/m³ was achieved. This plant further demonstrated the technical feasibility of autonomous solar powered membrane distillation system. The increase of unit productivity and reduction of specific energy consumption should be the aim of further development as pointed out by the author. There are very limited reports on the economic evaluation of solar MD desalination. Banat *et al.* [101] conducted economic analyses of small scale stand-alone solar powered MD plants based on 0.1m³/d and 0.5m³/d plants installed in Jordan. The annual cost was calculated as a sum of amortized capital cost, operating and maintenance cost and membrane replacement cost. Detailed capital investment was given for each of the plant components. The potable water production cost was estimated at \$15/m³ and \$18/m³ for the 0.1m³/d and 0.5m³/d plants, respectively with the distilled water blended with 1000mg/L raw brackish water by ratio 1:1. Saffarini *et al.* [102] also carried out an economic evaluation on solar powered membrane distillation systems. Water production costs from seawater were calculated at fixed membrane module parameters and a fixed recovery ratio of 4.4% (indicating a capacity of 158kg/h) for 3 different configurations. The cost of \$12.7, \$18.26 and \$16.2 were estimated for solar powered DCMD, AGMD and VMD systems, respectively. It was suggested that the cost of solar thermal collectors can account for 70~80% of the total water production cost.

As shown in Table 5, the reported GOR values of the membrane module in literature are in a wide range of 0.7~6 with the corresponding STEC at 100~896 kWh/m³. The reported highest GOR value corresponds to a spiral-wound AGMD membrane module developed by Fraunhofer ISE [95], Germany, while the lowest value corresponds to a lab scale DCMD membrane module [103]. Energy efficiency of 5 pre-commercial membrane modules have been analysed and compared in a recent research conducted by Zaragoza *et al.* [104]. The specific energy consumption varies between

different configurations and at different operating conditions. The spiral-wound PGMD membrane module developed by solar spring shows the lowest STEC of 210 kWh/m³, while the others vary from 200 to up to 1000 kWh/m³. This also indicates that membrane distillation process is still relatively less energy efficient compared to mature thermal desalination technologies MED and MSF. Besides, relatively low permeate flux of MD membrane, as well as the fouling and wetting phenomenon during long term operation, are obstacles that interfere with the commercialization of MD. Nevertheless, MD technology is still under development, tremendous efforts are being made to overcome these drawbacks by using novel membrane materials, or by optimizing MD configurations and modules. Meanwhile, further application and research also needs to be done to examine the technical and economic feasibility of solar MD.

Table 5 Summary of selected solar MD studies

Authors	year	location	Plant Type	Energy source	System Description	Feed water	Solar Radiation (W/m ²)	Capacity (m ³ /d)	Permeate flux L/m ² h	STEC (kWh/m ³)	GOR	GOR _{so}	SSEC kWh/m ³
Shim <i>et al.</i> [103]	2015	Suncheon, Korea 34°57'N	Lab scale	Solar water heater and electricity	DCMD membrane module with 0.06m ² PTFE flat sheet membrane; solar heater area 4.7m ² ; feed water heated via a titanium heat exchanger. Inlet temperature was controlled at constant value 65 °C , cooling temperature controlled at 25°C. Feed flow rate 2.5 L/min.	Seawater	-	0.014 ^g	28.5 ⁱ	896 ^j	0.7 ^j	-	-
Wang <i>et al.</i> [105]	2014	Xiamen, China 24°28'N	Lab scale	Evacuated tube collectors (ETC)	Cross-flow rectangular hollow fibre VMD module with membrane area of 0.25 m ² ; Evacuated tube collectors with aperture area of 2.16 m ² and a 0.5 m ³ hot water tank; feed water was heated via a titanium plate heat exchange.	35g/L NaCl solution	-	0.008 ^g	4 ^h	750	0.84 ^l	-	-
Chafidz <i>et al.</i> [99]	2014	Riyadh, Saudi Arabia 24°38'N	Pilot Plant	ETC and PV panels	memsys V-MEMD membrane unit with 0.2µm pore size PTFE membrane ; A heat pump unit was used to cool down cooling water and preheat feed water ; ETC with CPC reflectors (CPC 1506) used as solar thermal collector, total aperture area 18m ² ; PV panels with peak power of 3.36 kW used to supply electricity.	Brackish water	645 ^e (8am ~4pm)	0.1 ^e	-	-	-	0.71 ^m	929 ^m
Kim <i>et al.</i> [106]	2013	Saudi Arabia	Mathematical model	ETC and external heat	50 shell-and –tube type hollow fibre DCMD modules; 3360 m ² ETC with 160 m ³ water storage tank. Plate heat exchangers used to obtain heat from solar collector and also to recover heat from brine and permeate; 24 hours operation with both solar energy and other external heat supply, annual solar fraction 0.77.	Seawater	-	31 ^f	51.14 ⁱ	436	1.50 ^l	-	-

Authors	year	location	Plant Type	Energy source	System Description	Feed water	Solar Radiation (W/m ²)	Capacity (m ³ /d)	Permeate flux L/m ² h	STEC (kWh/m ³)	GOR	GOR _{so}	SSEC kWh/m ³
Gabsi <i>et al.</i> [107]	2013	Tunisia	Pilot plant	Flat plate collector (FPC) and PV panels	VMD system with 5 m ² hollow fibre PVDF module; 51m ² FPC; flat plate heat exchanger used to obtain heat from solar collector; PV panels with peak power 1.5kW and batteries were used to supply power for pumps.	Seawater	-	0.21 ^e	5.25 ^h	-	-	-	-
Frikha <i>et al.</i> [108]	2013	Mahare, Tunisia 34°32'N	Mathematical model	FPC and PV panels	DCMD system with 4 m ² PVDF hollow fibre membrane module; solar collector with total aperture area of 70m ² ; titanium plate heat exchanger used to obtain heat from solar collector; PV modules with peak power of 2.1KW used to supply electricity.	Seawater	-	0.75 ^e	14 ^h	-	-	-	-
Abdallah <i>et al.</i> [109]	2013	Tunisia	Plant Design	FPC and PV panels	VMD system with 4m ² hollow fibre PVDF membrane module; 35 flat plate solar collector, each with 2m ² aperture area; 16 m ² PV field used to supply 2.1 KW electricity energy.	Seawater	700 ^f	0.8 ^f	25 ^h	-	-	-	-
Raluy <i>et al.</i> [100]	2012	Gran Canary Island, Spain 27°58'N	Pilot Plant	FPC and PV panels	PGMD system with 10 m ² module 6.96 m ² flat plate solar collectors; PV system with peak power of 80W for electricity supply	seawater	-	0.12 ^e	1.5 ^h	140~500 ^k	0.5 ^k ~5.1	-	-
Guillén-Burrieza <i>et al.</i> [110]	2011	Almeria, Spain 36°50'N	Pilot Plant	Compound Parabolic Collector (CPC)	Flat sheet AGMD module, with total membrane surface area of 2.8 m ² ; 500m ² CPC with 24 m ³ thermal storage system (designed for former solar MED project)	Marine salt solution	-	0.15 ^g	6.5 ⁱ	810	0.79	-	-
Banat <i>et al.</i> [94]	2010	Aqaba, Jordan 29°31'N	Pilot Plant	FPC and PV panels	Four spiral-wound AGMD membrane modules with membrane area of 10 m ² each; 72m ² FPC 3 m ³ heat storage tank; a titanium heat exchanger used to transfer heat from the collector to seawater; power supplied from 12 PV modules with total peak power of 1.44 kW.	Seawater	-	0.9 ^f	2.8 ^h	-	-	-	-

Authors	year	location	Plant Type	Energy source	System Description	Feed water	Solar Radiation (W/m ²)	Capacity (m ³ /d)	Permeate flux L/m ² h	STEC (kWh/m ³)	GOR	GOR _{so}	SSEC kWh/m ³
Dow <i>et al.</i> [111]	2010	Edenhope, Australia 37°03'S	Pilot Plant	ETC	DCMD system with total membrane area of 1.4m ² ; 8 ETC collector with a total aperture area of 18m ² used to heat up the feed water.	RO brines from brackish water desalination plant	-	0.12 ^f	7.14 ⁱ	-	-	-	-
Wang <i>et al.</i> [112]	2009	Hang Zhou, China 30°15'N	Lab Scale	FPC	VMD system with hollow fibre membrane module with total membrane area of 0.09m ² ; 8 m ² FPC to supply thermal energy.	Ground-water	-	0.016 ^e	29.7 ⁱ	-	-	-	-
Koschikowski <i>et al.</i> [95]	2009	Gran Canary Island, Spain 27°58'N	Pilot Plant	FPC and PV panels	5 AGMD membrane modules with internal heat recovery; 90m ² FPC used to supply thermal energy; PV modules with 1.92kW peak power to supply electricity.	Seawater	-	1.6 ^f	-	100~200	3~6	-	-
Fath <i>et al.</i> [96]	2008	Alexandria, Egypt 31°12'N	Pilot Plant	FPC and PV panels	AGMD spiral-wound membrane module ;Three corrosion-free solar collectors with a total aperture area of 5.73m ² connected in series used to supply thermal energy	-	604 ^e (7am ~7pm)	0.064 ^e	-	-	-	0.9	728 ^m
Banat <i>et al.</i> [98]	2007	Irbid, Jordan 32°33'N	Pilot Plant	FPC and PV panels	AGMD membrane module with effective area of 10m ² ; 5.73m ² corrosion-free solar collector used to heat the feed directly; PV modules with peak power of 850W used to supply electricity.	-	875 ^e	0.11 ^e	2.5 ⁱ	200~300	2.2 ^l ~3.3	1~2	327~655 ^m

a. GOR_{so} (gain-output ratio-solar) in this table is defined as the energy ratio of total latent heat of distillate to the total input solar energy to the solar MD system. It can be determined by the equation (1). Aa in the equation refers to total aperture area of solar collectors.

b. SSEC (specific solar energy consumption) refers to the amount of solar energy (that reached the aperture area of solar thermal collectors) consumed per m³ fresh water production. The relationship between SSEC and GOR_{so} is shown by equation (2). $\Delta H_v = 2360$ kJ/kg will be used for calculation of GOR_{so} and SSEC when the values are not available in literature. All SSEC and GOR_{so} values in this table were calculated by the authors.

c. GOR in this table refers to the gain output ratio of the membrane module, which is defined as the energy ratio of total latent heat of distillate to the total input thermal energy into the membrane distillation system. It can be calculated with the following equation for a membrane module without internal heat recovery.

$$GOR = \frac{m_d \Delta H_v}{m_f Cp(T_i - T_o)} \quad (4)$$

m_d , average mass flow rate of distilled water, kg/h; ΔH_v , latent heat for evaporation, kJ/kg; m_f , membrane feed mass flow rate, kg/h; Cp heat capacity of water, kJ/kg °C;

T_i and T_o refers to feed flow temperature at inlet and outlet of the membrane module, respectively.

- d. STEC (specific thermal energy consumption) refers to the amount of directly input thermal energy the MD system consumed per m³ fresh water production. STEC can be calculated with GOR value with equation (3).
- e. In these reference, the solar radiations refers to daily average values between certain period of time when data is available or average value by assuming 8h daylight time. The capacity of plant refers to daily production on a specific test day (maximum daily values were selected).
- f. Capacity and solar radiation values in theses reference are all based on designed condition. 8h operation was assumed when only designed mass flow rate was given.
- g. Capacity values in these reference are calculated based on the permeate flux values by assuming 8h operation.
- h. The permeate flux values in these reference are daily average values based on the capacity. 8h operation was assumed when actual operating time was not available.
- i. The permeate flux values in these reference are maximum flux observed during the operation or flux at optimized experimental conditions.
- j. The STEC and GOR values are the reported minimum energy consumption and highest GOR under optimized experimental conditions.
- k. These are the range of daily average values during the long term operation between the year 2009 and 2010.
- l. The GOR values are calculated with the available STEC values, $\Delta H_{v,T}$ at 60°C (2358 kJ/kg) was used in the calculation.
- m. The GOR values or SSEC values are calculated based on equation (1) or (2), $\Delta H_{v,T}$ at 60°C (2358 kJ/kg) was used in the calculation.

2.2.5 Solar-powered RO

Reverse Osmosis is regarded by far the most efficient desalination technology due to its low specific energy consumption ($2\sim5 \text{ kWh}_e/\text{m}^3$) while bearing the largest desalination installation capacities with around 65% share in the world [64]. In RO, saline water is fed to the membrane with high pressure to overcome the osmotic pressure of the feed water. Freshwater is collected at the permeate side while the concentrated brine is rejected. Feed pressure of RO systems usually range from 6~8 MPa for seawater applications and 0.6~3MPa for brackish water applications [113]. The productivity and recovery ratio of RO is largely affected by the properties of used membrane, salinity of feed water, feed pressure and feed flow rate, etc. The well-established energy recovery devices in modern RO plants contributed significantly to the high energy efficiency of the process. Much work and research have been conducted in terms of solar driven RO desalination systems. When combined with solar energy, RO can be either driven by electrical power that is generated by photovoltaic (PV) cells or solar thermal power plants, or by mechanical power that is converted from solar thermal energy by thermodynamic cycle. Lists of some PV driven RO studies and solar thermal driven RO studies in recent years are given in **Table 6** and **Table 7**, respectively.

Fig. 9 Schematic diagram of PV-driven RO system

In a PV powered RO system, PV and RO subsystems work independently. Since both of them are mature commercialized technologies, technical feasibility of PV-RO plant is not much of an issue compared to its economic feasibility and reliability [13]. A considerable number of small scale or pilot PV-RO seawater/brackish water desalination plants have been built and investigated since 1980s. A comprehensive list of PV driven RO plants (1980~2008) was summarized by Ali *et al.* [65]. Thus

Table 6 just lists selected PV-RO plants and studies reported from 2009. Recently, Peñate *et al.* [114] reported the seven year uninterrupted operation (2006~2013) of a standalone PV driven RO plant in Tunisia aiming to supply freshwater for a 300 inhabitant village located in the Sahara desert. The plant successfully produced more than 15 million litres of freshwater with TDS lower than 300 mg/L from brackish groundwater (TDS 4.0~4.5g/L) at monthly average production rate in the range of 3.26~12.8 m³/d. The specific energy consumption was in the range of 1.64~3.13 kWh/m³. Qiblawey *et al.* [115] investigated the performance of a standalone PV-RO pilot plant in Jordan. When RO operating pressure was set at 0.6 MPa, the specific energy consumption was found to be 16 kWh/m³ and recovery ratio was 54%. Economic evaluation for the plant was presented in an earlier study [116]. Water cost of the PV-RO system was estimated as \$15.6 /m³ when membrane lifetime was assumed at 5 years. Reported water cost for small scale PV driven RO plants in previous literature are normally in the range of \$7~30/m³ [116]. A much lower water cost of \$0.825 /m³ was estimated by Alsheghri *et al.* [117] probably because PV system will be built with much larger capacity than RO requires to sell electricity to grid in the proposed design.

Unlike PV driven RO system which is relatively mature and commercially available in small scale, the research and studies on thermal driven RO system are mostly in modelling or laboratory stage. Solar thermal driven RO system are mostly based on the organic Rankine cycle (ORC) technology which is commonly adopted in solar thermal power generation systems. The ORC is a thermodynamic power cycle that uses organic working fluid and converts the thermal energy input to the output mechanical energy. An ORC normally consists of pressure pump, evaporator, turbine and condenser [116]. Organic working fluid is pressurized and injected into the evaporator where it is heated up to evaporate by heat exchange with high temperature fluid. And then the vapour expands through a turbine to produce mechanical work to drive the high pressure pump for RO. Meanwhile, the feed saline water could be preheated in the ORC condenser to increase the RO membrane permeability. Schematic diagram of solar ORC driven RO system is shown in **Fig.10**.

Delgado-Torres *et al.* [118] has proposed general design recommendations for solar ORC driven RO system. Information about selection of the working fluid and boundary conditions of ORC, operating temperature, suitable solar collector and configurations of solar field, etc. are present in detail. Concentrating solar collectors such as parabolic trough collector, linear Fresnel concentrators, and compound parabolic concentrators were recommended for solar ORC to maximise the overall efficiency. The organic working fluid used in ORC should be selected to match the level of heat source temperature achieved with different solar collectors. Siloxane MM was suggested for ORC driven by parabolic trough collectors and other working substances such as Solkatherm® SES36, isobutene, isopentane, R245ca and R245fa were suggested for ORC driving by stationary solar collectors [13]. Xia *et al.* [119] simulated a wind-solar ORC driven RO system by theoretical modelling. The performance and the influence of certain parameters on fresh water production were

examined, including turbine inlet pressure, feed water pressure and salinity, and condenser temperature of ORC. Water production of 1,186 m³ was achieved with the solar ORC alone in a sunny summer day with specific solar energy consumption (SSEC) of 69 kWh/m³, which is fairly close to the specific thermal energy consumption (STEC) of conventional fossil-fuel based thermal desalination plants. And it was found that turbine inlet pressure and condenser temperature had significant influence on the nett work output of ORC and fresh water production.

Fig. 10 Schematic diagram of solar ORC driven RO system

As shown in **Table 6** and **Table 7**, reported PV-RO plants in recent years are mostly small to medium scale with the capacity of 0.2~200 m³/d for seawater or brackish groundwater treatment. In contrast, solar thermal RO applications are studied only for large scale seawater desalination plants with the capacity of 1186~50,000 m³/d although no real plant has been reported. Specific energy consumption (SEC) of RO process lies in the range of 1.2~16 kWh/m³. Water cost of PV-RO system was reported as \$0.825~15.6/m³, while the water cost of a large scale solar thermal RO plant was estimated as \$2.18/m³ [120].

Currently, the operation of PV-RO system relies largely on lead acid batteries for energy storage. The long term performance stability and maintenance remains an issue in remote area. Cost effective approaches for energy storage to supply RO operation should be developed for future application. Besides, brine disposal is another big challenge for RO application in inland regions. Increasing recovery ratio by optimization of RO process or integration with other technology like MD, or developing zero liquid discharge schemes may be the potential solution of this issue. Solar thermal RO is still immature at present. Further experimental or modelling studies need to be done to demonstrate the technical and economic feasibility of this technology.

Table 6 Summary of selected PV driven RO studies

Authors	year	location	Plant type	Energy source	System description	Feed water	Capacity (m ³ /d)	Work Pressure (MPa)	Recovery Ratio %	SEC (kWh /m ³)	Water cost US \$/m ³
Alsheghri <i>et al.</i> [117]	2015	Abu Dhabi, UAE 24°28'N	Plant Design	PV /grid	720kW PV system to export electricity to the grid 1757.8 MWh/annual; RO operation directly powered by grid electricity.	Seawater	200	-	40	6.99	0.825
Penate <i>et al.</i> [114]	2014	Kebili, Tunisia 33°42'N	Small Scale Plant	PV	Solar PV modules with peak power of 10.5 kW and a 660Ah battery bank. Pretreatment of RO consisted of a sand filter, chemical dosing, an activated carbon filter and a cartridge filter. Brine was used for irrigation after mixing with raw water.	Brackish ground water	50	1.24~1.38	70	1.64~3.13	-
Qiblawey <i>et al.</i> [115]	2011	Hartha Village, Jordan 32°33'N	Pilot Plant	PV	PV module with peak power output of 433W and 460 Ah battery pack. Pretreatment of RO consisted of softener, 5-micron sediment filter, granular activated carbon filter (GAC) and 1-micron sediment filter.	Brackish ground water	0.5	0.6	54	16	15.6
Khayet <i>et al.</i> [121]	2010	Madrid, Spain 40°23'N	Pilot Plant	PV	The RO plant was coupled to a solar heat spherical collector and PV panels. Tubular RO membrane module with an effective surface area of 1.2m ² was used.	Brackish water with TDS 6g/L	0.2	0.77	-	1.2~1.3	-
Munari <i>et al.</i> [122]	2009	Cooper Pedy, Australia 29°0'S	Pilot Plant	PV	UF-NF/RO hybrid membrane system; PV modules with peak power output of 300W without batteries; system operated at variable flow and pressure.	Brackish Groundwater	1	0~1.2	10	3~5.5	-

Note:

a. SEC (specific energy consumption) in this table refers to the amount of electrical energy consumed by per m³ fresh water production in the reverse osmosis process.

Table 7 Summary of selected solar thermal driven RO studies

Authors	year	location	Plant type	Energy source	System description	Feed water	Solar Radiation W/m ²	Capacity (m ³ /d)	Work Pressure (MPa)	Recovery Ratio %	SEC (kWh /m ³)	SSEC (kWh /m ³)	Water cost US \$/m ³
Xia <i>et al.</i> [119]	2015	Qingdao, China 36°04'N	Mathematical Model	Compound Parabolic Collectors (CPC) and Wind Turbines	RO system with pressure recovery driven by hybrid energy source: solar powered ORC and wind energy (electricity). 210 CPC thermal collectors with aperture area of 48m ² each; 5 wind turbine with diameter of 10m each.	Seawater	813 ^c	1,186 (solar) 1,325 (wind)	8	-	3.2	69	
Penate <i>et al.</i> [123]	2012	Spain	Plant Design	Parabolic trough collector (PTC)	A solar ORC power plant used to supply electricity to drive the RO seawater desalination system. Total effective membrane area 7283m ² with an average flux of 14.30 L/m ² ·h; solar collector area 2099 m ² .	Seawater	-	2,500	6.9	40	2.99	-	
Salcedo <i>et al.</i> [120]	2012	Tarragona, Spain 41°06'N	Mathematical Model	PTC and natural gas fired heater as backup	The desalination system included 7 RO trains each with 37 m ² spiral-wound membrane; driven by solar Rankine cycle with gas fired heater as backup. Annual solar fraction is 43.4%.	Seawater	-	50,000	6.3	-	3.53	-	2.18 ^d

Note:

a. SEC (specific energy consumption) in this table refers to the amount of energy consumed by per m³ fresh water production in the reverse osmosis process. It can be in the form of electrical energy or mechanical energy when the high pressure pump is directly driven by electrical power or the mechanical work output by ORC, respectively.

b. SSEC (specific solar energy consumption) refers to the amount of solar energy (that reached the aperture area of solar thermal collectors) consumed per m³ fresh water production.

c. This is daily average value by assuming 10h operation per day.

d. The water cost is converted from Euro to US dollars with exchange rate 1.4 (historical value for the article received date).

2.2.6 Solar-powered ED

In electrodialysis (ED) process, saline water is pumped through an ED stack where anions and cations move toward opposite side while an electric potential difference is applied across the cathode and anode. The ion exchange membranes between them enable the desalination of saline water and concentration of ions in separate parts [124]. ED systems are more favourable in desalination of brackish water with relatively low TDS as it is normally regarded as not economically competitive for seawater desalinations due to the expensive ion exchange membranes, costly electrodes, and relatively short lifetime while working in high-density electric field [13]. Electrodialysis Reversal (EDR) is widely used in the application of ED, in which periodic reversal of DC electric field polarity was conducted to reduce membrane scaling and fouling. In ED, the water quality after treatment and the productivity will be affected by feed water salinity, retention time, DC voltage and the time interval between polarity changes in EDR, etc [125]. As an electricity-driven process, ED is suitable to be combined with PV system.

Fig.11 Schematic diagram of PV-driven ED system

Table 8 provides a summary of selected solar ED studies in recent years. Although the largest PV-ED plant reported in the 1990s had distillate production of 200 m³/d [65], studies reported in recent years are mostly laboratory scale batch studies or small scale plants with less than 50 m³/d capacity. In terms of renewable energy driven desalination, ED is highly valued for its adaptability for variable energy conditions as ED could work at a wide range of DC voltages. Thus ED directly powered by PV has received researchers' interests. Peñate *et al.* [125] reported the performance tests of a PV-driven ED plant with a nominal production flow of 4 m³/h. A PV field with battery and DC/AC

inverter was used for power supply of pumps, valves and control unit, etc. while the EDR unit was directly powered by two other PV fields under variable conditions without battery. The operation of the EDR plant was controlled by a PLC controller which could change between 5 different PV field modulation modes to obtain favourable power supply at a wide range of solar radiations. In a 5h automatic operation during a sunny day, 16.9 m³ water with 1050 μ S/cm average conductivity was produced from 5300 μ S/cm feed brackish water. The specific energy consumption (SEC) of the EDR unit was 0.79 kWh/m³. One of the major draw backs of ED is its inefficiency in removing organic compounds. Only a small amount of charged organic compounds will be removed while most uncharged organic matters will stay in the water, which make it less favorable for desalination of contaminated source water with organic pollutants. In a recent study, Zhang *et al.* [126] proposed a PV powered hybrid system of forward osmosis (FO) and ED for brackish and wastewater treatment, in which feed water first went through the FO membrane to remove the contaminants and then ED was used for desalination of draw solution (NaCl solution). Reasonable TOC and salt removal efficiency was achieved in the produced water which met potable water standard in general. An economic analysis was done for a small potable water production system with 130 L/d capacity. The water production cost was estimated at 3.32~4.92 Euro /m³ (about USD 4.42~6.54). Economic evaluation has also been done by Ortiz [127] for a 15m³/d PV-driven ED plant for brackish water (2300~5100mg/L) desalination based on the result from laboratory scale demonstration. The cost of produced water was in the range of 0.14~0.23 Euro/m³ (about USD 0.20~0.34) for irrigation purpose and 0.17~0.32 Euro/m³ (about USD 0.26~0.48) for drinking purpose.

In terms of brackish water treatment, as shown in Table 8, the reported SEC of ED is 0.72~4.05 kWh/m³, which lies in the range 0.4~4 kWh/m³ summarized by Fernandez-Gonzalez et al [128]. The energy consumption is even lower than RO for brackish water with low salinity, i.e. TDS<5000mg/L. Accordingly, PV-ED should be economically competitive with PV-RO. Water production cost from brackish groundwater under 5000mg/L TDS have been reported in the range of \$0.19~16.0/m³ [128] with lower bound less than that of PV-RO (see section 2.2.5). The potential of ED in running directly with PV arrays is a particular advantage over RO. Less reliance on batteries results in less capital cost of the PV system. Thus, the research on battery free ED system should be a future focus. The capability of PV-ED system in operating with variable feed water quality and weather conditions should be further investigated [124].

Table 8 Summary of selected PV driven ED studies

Authors	year	location	Plant type	System description	Feed water	Capacity (m ³ /d)	SEC (kWh/m ³)	Water cost US \$/m ³
Zhang <i>et al.</i> [126]	2013	Heverlee, Belgium 50°51'N	Lab scale	FO-ED hybrid membrane system; feed water first come through FO with NaCl as draw solute, then ED is used to desalinate the NaCl solution. ED stack consisted of 5 cell pairs with total effective surface area of 0.029m ² . PV panels with 0.0648m ² surface area and 8~9 V voltage output used as power supply	Wastewater treatment plant effluent	Batch test	-	4.42~6.54 ^b
Penate <i>et al.</i> [125]	2013	Gran Canaria island, Spain 27°58'N	Small plant	EDR unit with 340 cell pairs, 2 electrical stages and a nominal product flow of 4m ³ /h. A PV field with battery and 5.8kW peak power was used to power pumps, valves and PLC control unit, etc. 2 other batteryless PV fields with 2.45kW and 1.24kW peak power were used to power two different electrical stages of EDR pack, respectively. A PLC control unit was used to change the operational mode according to solar radiation.	Brackish water with conductivity of 5300 µS/cm	16.9 ^d	0.79	-
Cirez <i>et al.</i> [129]	2013	Spain	Lab scale	ED unit with 10 cell pairs and total effective membrane area of 0.2m ² ; special designed PV module providing open circuit voltage up to 13.7V and peak power up to 30W.	Simulated brackish water with 5000mg/L NaCl solutions	Batch test	4.05	-
Ortiz <i>et al.</i> [127]	2008	Alicante, Spain 38°24'N	Lab scale	ED unit with 70 cells and total effective membrane area of 3.5m ² . PV panels with peak power of 154W	Brackish groundwater with TDS 2300~5100mg/L	Batch test	0.92~1.69 drinking; 0.72~1.43 irrigation	^c 0.26~0.48 drinking; 0.20~0.34 irrigation
AlMadani <i>et al.</i> [130]	2003	Isa Town, Bahrain 26°10'N	Lab scale	ED unit consisted of 24 ionic cell pairs arranged with two electrical stages; 4 PV panels with total peak power of 132 W.	Brackish groundwater with 3300mg/L	0.19~1.14	-	-

Note: a. SEC (specific energy consumption) in this table refers to the amount of electrical energy consumed per m³ fresh water production.

b. The cost was estimated for a 130 L/d plant based on optimized operational condition examined in the lab scale study. The value was converted from Euro with an exchange rate of 1.33 (exchange rate at paper received time obtained from Internet).

c. The cost was estimated for a 15m³/d plant based on mathematical simulation. The value was converted from Euro with an exchange rate of 1.50 (exchange rate at paper received time obtained from Internet).

d. This refers to the fresh water production for a specific testing day.

2.3 Summary of solar desalination technologies

Fig.12 is a summary of potential combinations of solar technologies and desalination processes. Among all the indirect desalination technologies, RO and ED could be directly powered by electricity from PV system or CSP plant. Solar thermal collectors are used to drive other indirect solar desalination processes HDH, MD, MSF and MED after converting solar radiation into thermal energy. Meanwhile, mechanical energy that drives the high pressure pump in RO process can also be indirectly derived from solar thermal collectors through solar organic Rankine cycle (SORC). Heat pumps (TVC, AHP, ADHP, MVC) are generally adopted to enhance the energy efficiency of MED process. These heat pumps are normally driven by thermal energy from the solar thermal collectors with MVC as an exception which could be powered by the electricity from PV or CSP plant. The auxiliary equipment used in those solar thermal desalination processes such as circulation pumps also can be powered by the electricity from PV or CSP plant. The integration of CSP plant and solar desalination has been proposed for large scale applications, where CSP either export electricity to drive RO, ED, MVC or export exhaust/motive steam that can be used to power MED and MSF process.

Fig.12 Potential integration of solar technologies and desalination processes

Michael *et al.* [131] have defined four capacity ranges for renewable energy powered desalination plants based on the requirement of different types of markets. These ranges are: very small scale plants (<1 m³/d) targeting at end-users such as households, families living in isolated areas; small scale plants (<10 m³/d) which could provide the daily water needs for more than 100 people, suitable

for small villages, small islands or hotels; medium scale plants (10~1000 m³/d) that can supply water for large users like towns, villages in water stressed areas; and large scale plants (>1000 m³/d) which can be used for municipal water supply. As shown in **Table 9**, the various solar desalination technologies discussed above are favourable for different capacity applications. Reported water costs of these technologies at different plant scales are also shown in the Table. According to Ioannis *et al.* [132], water cost for small desalination plants using conventional energy source ranges between \$0.2~1.3/m³ for brackish water desalination and between \$0.4~3.4/m³ for seawater desalination. Compared to this, the water cost for small to medium scale solar desalination plants are quite high. On the other hand, the estimated water costs for large scale plants could be comparable with the conventional large scale commercial desalination processes, which were reported as \$0.5~1.5/m³ for seawater desalination [83]. However, it should be noted that the cost estimation are mainly based on simulation as no large scale solar desalination plant has been built yet.

Table 9 Suitable plant capacities of different solar desalination technologies and their reported water costs.

	Very Small Scale	Small Scale	Medium Scale	Large Scale
Solar Still	\$6.0~65.0 /m ³	N/A		
Solar HDH	\$4.4 /m ³	\$2.9~22.1 /m ³	N/A	
Solar MD	\$12.0~18.0 /m ³	N/A	N/A	
Solar MSF			N/A	\$ 1.4~1.6 /m ³
Solar MED		\$18.0~22.0 /m ³	\$4.1~8.0 /m ³	\$0.9~1.3 /m ³
PV-RO	\$15.6 /m ³	\$6.5~12.8 /m ³	\$0.8~8.4 /m ³	
PV-ED		\$ 0.2~16.0 /m ³	\$5.7~12.1 /m ³	
Solar Thermal RO				\$2.2 /m ³
CSP+RO/MED/MSF				\$0.9~1.2 /m ³ (MED)

Note:

- 1) The water cost values are derived by combining data collected in Table 1~8 and reference [101], [102], [116], [128]
- 2) The highlighted columns in each row represent the recommended capacity of each technology.

3. Solar photocatalysis and disinfection

3.1 Solar water photocatalytic application

Photocatalysis is one of the most effective technology for the mineralization of refractory organic compounds and water pathogens among AOPs (Advanced oxidation processes). Major types of photocatalysis in terms of fundamentals include heterogeneous photocatalysis which employs semiconductor catalysts for water treatment and homogeneous photocatalysis which mainly refers to photo Fenton process [133].

In heterogeneous photocatalysis process, the degradation of recalcitrant organics is governed by the combined action of a semiconductor photocatalyst, an energetic radiation source and a highly reactive oxygen species [134]. Among those semiconductor catalysts (TiO_2 , ZnO , Fe_2O_3 , CdS , GaP and ZnS), TiO_2 has received the most interests. The Principle of heterogeneous photocatalyst of semiconductor is often explained based on band model. An electron (e^-) in an electron-filled valence band (VB) will be excited to a vacant conduction band (CB) when the semiconductor catalyst absorbed a photon with energy $h\nu$ equal to or greater than its band gap energy [135]. Meanwhile a positive hole (h^+) is left in the VB. The photo-generated electrons and positive holes cause the reduction and oxidation of different compounds, respectively. In the case of TiO_2 photocatalysis, the photo-generated electron-hole pair in the surface of TiO_2 triggers a series of chain oxidative-reductive reactions normally in the presence of water and dissolved oxygen [133]. Some highly reactive species formed in this process such as $\text{OH}^\cdot$ radicals and $\text{H}_2\text{O}^\cdot$ radicals are regarded as major oxidants, which react with the majority of organic substances. There are basically two main configurations of heterogeneous photocatalytic reactors based on the state of photocatalysts [136]: reactors with suspended photocatalyst particles and reactors with immobilized photocatalysts. The first configuration needs additional separation process for recovery of photocatalytic particles such as sedimentation and filtration, while the second configuration permits a continuous operation owing to the fixation of photocatalysts onto activated carbon, mesoporous clays, fibres and membranes [133].

The most commonly used homogeneous solar photocatalytic process in water/wastewater treatment is photo-Fenton. Fenton oxidation process is a widely used AOP technology which relies on the catalytic reaction of H_2O_2 with iron ions that produces $\text{OH}^\cdot$ radicals as the major oxidizing species (as shown in Eq. (5)(6)), while Photo-Fenton (ph-F) process combines Fenton reagents (H_2O_2 and Fe^{2+}) with UV-vis radiation ($\lambda < 600\text{nm}$) which will increase the production of $\text{OH}^\cdot$ radicals by additional reactions (see Eq.(7) (8)) [137]. Compared to conventional Fenton oxidation, Ph-F embraces a higher oxidation rate, less iron utilization and as a consequence less sludge generation. Both solar and UV light can be used for Ph-F and the radiation has significant effects on inactivation of microorganisms.

Photoreactors are required in industrial applications of solar photocatalytic process to harness solar radiation efficiently. The most commonly used photoreactors are [135, 138]: Parabolic Trough Collectors (PTC), Compound Parabolic Collectors (CPC) and Inclined Plate Collectors (IPC).

Fig.13 Typical layout for 3 different photoreactors: (a) Parabolic Trough Collectors (PTC), (b) Compound Parabolic Collectors (CPC) and (c) Inclined Plate Collectors (IPC) [138].

PTC and CPC reactors are based on the well-established concentrating solar thermal collectors. In a PTC reactor, long, reflective parabolic surface is used to concentrate incident solar radiation on the focal line where a transparent tube through which the reactant fluid flows is placed. In the case of heterogeneous photocatalytic process, suspended photocatalysts are mostly investigated with PTC reactors [138]. PTC can only capture direct sunlight which is regarded as a disadvantage. Either single-axis or dual axis sun tracking systems should be used in PTC reactors. In CPC reactors, two sections of parabola facing each other were used to concentrate the sunlight onto absorber tube at the focal line. CPC can harness solar radiation more efficiently than PTC as both direct and diffuse sunlight will be reflected onto the absorber tube. Meanwhile, incident sunlight is distributed evenly on the entire absorber tube surface, making it suitable for use with both suspended photocatalysts and immobilized photocatalysts [138].

Inclined plate collector (IPC) is a flat or a corrugated inclined black plate over which the reactant fluid flows in a thin film. It is simple in construction and especially suitable for use with photocatalysts supported on the surface of inclined plate, which have been named as 'thin film fixed bed reactor (TFFBR)' [139]. A very low flow rate on the bottom surface (normally 0.15~1.0 L/min) is required to maintain the 'thin film' (typically 100~200 μm) [135]. Thus IPC requires larger surface area than the PTC and CPC. It is regarded as more suitable for small scale applications.

The influence of operating conditions on photocatalytic processes have been studied extensively by researchers. Major influencing factors include solar radiation and weather conditions, catalyst load, dissolved oxygen concentrations, pH, temperature, contaminants type and load, etc. [133, 135]

Lists of pilot studies of heterogeneous and photocatalytic processes reported in recent years are summarized in **Table 10** and **Table 11**, respectively. Special research focus has been placed on degradation of persistent organic pollutants such as pesticides and PPCPs (Pharmaceuticals and Protective Care Products) with heterogeneous photocatalytic process. Several pilot studies have been conducted for treatment of municipal WWTP effluent [140, 141]. Meanwhile solar photocatalytic processes with TiO_2 have also been studied for application in drinking water disinfection, which is an improvement from simple solar disinfection (SODIS). Some microorganisms which are resistant to UV-A irradiation have been successfully inactivated by TiO_2 photocatalysis [142]. Photo-Fenton technology is mostly investigated for industrial wastewater treatment. Michael *et al.* [143] investigated the performance of a solar photo-Fenton process in treating olive mill wastewater (OMW) with a CPC photoreactor. Flocculation/coagulation was selected as pretreatment method to reduce turbidity of raw water. In the optimal dosage of Fe^{2+} , H_2O_2 , 87% COD removal was achieved after 240 min of solar radiation while dark Fenton at same operating conditions only achieved 55% removal. An economic evaluation has been done to assess the economic feasibility of this technology. The investment and operational cost of a $50\text{m}^3/\text{d}$ OMW treatment plant was estimated on a five year basis. The wastewater treatment cost was estimated at 2.11 Euro/ m^3 (USD 2.9 with exchange rate of 1.373). Although solar photocatalytic technology has exhibited good results in treating a variety of wastewater, the present research are still limited to small scale batch studies. Except for optimization of operating conditions to achieve better performance, the design of efficient photoreactors to be used in variable feed water and weather conditions is also of vital importance for the future scaling up. Besides, in-situ long term experiments need to be conducted for certain applications to further investigate the reliability of this technology [135].

Table 10 Summary of selected heterogeneous photocatalytic pilot studies for water/wastewater treatment

Authors	Year	Raw Water	Capacity	Major Contaminants and concentrations	Photocatalyst type and load	Reactor type	Reactor/Process details	Optimal Performance
Sousa <i>et al.</i> [140]	2012	Municipal wastewater treatment plant (WWTP) effluent	25L Batch	Emerging contaminants with special focus on pharmaceutical compounds DOC of 12.1mg/L	Suspended TiO ₂ P25,	CPC	0.91m ² CPC unit with four borosilicate tubes	19 out of 22 pharmaceutical compounds in the effluent were completely removed with total accumulated UV energy of 32KJ/L. 35~77% removal efficiency achieved for the rest three compounds. DOC removal efficiency was around 60%.
Fenoll <i>et al.</i> [144]	2012	Drinking water with pesticides spike	250L Batch	eight miscellaneous pesticides (ethoprophos, isoxaben, metalaxyl, metribuzin, pencycuron, pendimethalin, propanil and tolclofosmethyl) 65~115 µg/L	Suspended ZnO, TiO ₂ , SnO ₂ , WO ₃ , and ZnS 150mg/L	CPC	1.27m ² photoreactor module with 8 borosilicate tubes	ZnO shows the best performance. 29~126min reaction time required for 90% degradation for the pesticides
Miranda-Garcia <i>et al.</i> [141]	2011	Municipal wastewater treatment plant (WWTP) effluent	10L Batch	emerging contaminants (acetaminophen, antipyrine, atrazine, carbamazepine, diclofenac, flumequine, hydroxybiphenyl, ibuprofen, isoproturon, ketorolac, ofloxacin, progesterone, sulfamethoxazole and triclosan) DOC 13mg/L	Immobilized TiO ₂ P25 supported by borosilicate glass spheres synthesized by sol-gel	CPC	Two CPC modules with total illumination area of 0.30m ² and twelve Pyrex glass tube mounted on a fixed platform tilted as local latitude	85% compounds degraded within 120min of illumination time
Zayani <i>et al.</i> [145]	2009	Commercial azo dye solution	2 m ³ batch	Yellow Cibacron FN-2R (YC) TOC 30mg/L	Immobilized TiO ₂ P25 10g/m ²	IPC	Thin-film fixed bed reactor with an area of 25m ² , 20 degree inclined angle. Flow rate 3 m ³ /h	Up to 80% removal of TOC achieved after 8h treatment (a day)

Table 11 Summary of selected photo- Fenton pilot studies for wastewater treatment

Authors	Year	Raw Water	Capacity	Major Contaminant and concentrations	Reactor Type	Operational Conditions			Optimal Performance
						H ₂ O ₂ dosage mg/L	Fe ²⁺ dosage mg/L	Initial pH	
Velegraki <i>et al.</i> [146]	2015	Winery wastewater	200L batch mode	Organic matters including soluble sugars, organic acids, alcohols and high-molecular-weight compounds, such as esters, polyphenols, tannins and lignin Initial COD about 1200mg/L Initial DOC 435 mg C/L	CPC	Initial 500; stepwise additions to maintain at 100~500	5	2.8	80% COD and DOC after 402min reaction time with 63KJ/L accumulated UV energy
Michael <i>et al.</i> [143]	2014	Olive mill wastewater (coagulation /flocculation used as pretreatment for removing suspended solids)	100L batch mode	Organic wastewater with high levels of phenolic compounds, Diluted sample used for photo-Fenton study Initial COD 350mg/L	CPC	1000	80	2.8~2.9	COD removal 87.3% after 240min irradiation
Hernandez-Rodriguez <i>et al.</i> [147]	2014	Synthetic wool dyeing wastewater with dye solution	5L Batch	Different dye solutions (Yellow, Blue and Red) with COD 2089~2388mg/L TOC 973~1070 mg/L	CPC	4540~6050	120~240	3.0	75% ~79% TOC removal after 139min illumination time with 20KJ/L accumulated energy

3.2 Solar Disinfection of water (SODIS)

Fig.14 Schematic diagram of SODIS

Solar disinfection (SODIS) of drinking water is a simple, low-cost household water treatment technology promoted by WHO (World Health Organization) which is suitable for developing countries that lack access to safe drinking water supply but receive abundant solar radiation. SODIS only requires that water is stored in transparent containers (usually PET bottles) in which they are exposed to direct sunlight for continuous periods to enable waterborne pathogens be inactivated by sunlight [148]. In SODIS, both thermal and optical inactivation (with UV radiation) occurs and they have a strong synergistic effect at temperatures over 45°C [149]. Considerable studies and field works have been done on SODIS since the 1880s. The efficacy of SODIS has been well proved. Being effective against almost all waterborne microbial species, SODIS can significantly reduce rates of childhood dysentery and infant diarrhoea by 45% as indicated by clinical trials [150]. Factors that affect the SODIS process are widely investigated by researchers, including received UV radiation, bottle properties, water quality, water temperature, and the external configurations, etc. [151]. The cost of SODIS has been estimated as \$0.63 per person per year by Clasen *et al.* [152], being the lowest household based disinfection intervention when compared with chlorination, filtration, flocculation/disinfection, etc. Currently, SODIS is used by more than 4.5 million people for drinking water disinfection in more than 50 countries all over the world [150]. The future research of SODIS should be focused on enhancing the performance with physical or chemical approaches that utilize locally available resources and better not involve additional cost, as well as promoting the technology among local people with acceptable educational effort.

4. Conclusions

In the context of global water scarcity and future energy crisis, water treatment technologies driven by solar energy are sustainable alternatives to address the worldwide water problem and reduce the harmful impact of burning fossil fuels. The selection of solar water technologies can be very site specific. Among the various technologies, there are simple, low-tech, low investment technologies such as solar still and SODIS, which is especially suitable for remote regions in developing countries that lack abundant financial support and access to high technology and skilled workers. Although some of them are not commercially available, indirect desalination technologies and solar photocatalysis technologies are becoming more reliable and technically mature with the developments and technical improvement in both solar technologies and the water treatment processes. Compared to conventional fossil-fuel based desalination plants, water production cost from solar based desalination processes are still relatively high largely due to the costly solar collectors, which is a major reason that restricted the commercialization speed. However, in most cases, the environmental cost of using non-renewable energy has been awfully ignored. The depletion of fossil fuel energy, the emission of greenhouse gases and air pollution should all be taken into consideration in the energy market in order to have a sustainable future. Besides, estimated costs of large scale solar desalination plants showed that they could be economically comparable with conventional plants although no real large scale plant has been built yet. Furthermore, there is still much room for price decline of solar collectors with the development of solar technologies. Solar based desalination will be more competitive in the near future.

In terms of the current research on different solar water treatment technologies, a serious issue is, most researchers speak highly of the technology of their own focus while ignoring the limitations and problems exists in the area. This makes it even difficult to evaluate and compare different technologies. Meanwhile, most technologies are still under research and development, therefore very rare studies are based on real plants. Further demonstration and modelling studies need to be conducted for most of the processes for scaling up and commercialization purpose. Furthermore, two other common economic-technical issues for most of the technologies include: 1) how to match the intermittence of solar energy with the continuous water treatment demand; 2) the economical, low environmental impact disposal of residues (eg. brines for solar desalination and chemical sludge for solar Fenton). For the first issue, either energy storage or water storage measures should be taken, which may involves much higher investment cost (such as batteries for PV electricity). The disposal of residues can account for a large portion of the water cost and have potentially negative impact on the environment. Therefore, besides the efforts that aim at improving the efficiency and reducing the cost of the solar technologies and the water treatment processes, developing novel solutions for these two issues should also be a focus of future research.

Acknowledgement

The authors wish to thank China Scholarship Council and University of Wollongong for their financial support towards a postgraduate scholarship to the first author.

References

- [1] M. Shatat, M. Worall, S. Riffat, Opportunities for solar water desalination worldwide: Review, *Sustainable cities and society*, 9 (2013) 67-80.
- [2] I.E. Agency, Key world energy statistics, International Energy Agency, 2014.
- [3] N. Abas, A. Kalair, N. Khan, Review of fossil fuels and future energy technologies, *Futures*, 69 (2015) 31-49.
- [4] J. Blanco, S. Malato, P. Fernández-Ibañez, D. Alarcón, W. Gernjak, M.I. Maldonado, Review of feasible solar energy applications to water processes, *Renewable and Sustainable Energy Reviews*, 13 (2009) 1437-1445.
- [5] G. Masson, M. Latour, D. Biancardi, Global market outlook for photovoltaics until 2016, European Photovoltaic Industry Association, 5 (2012).
- [6] I.E. Agency, Technology Roadmap: Solar Photovoltaic Energy, in, France, 2014.
- [7] S. Manju, N. Sagar, Renewable energy integrated desalination: A sustainable solution to overcome future fresh-water scarcity in India, *Renewable and Sustainable Energy Reviews*, 73 (2017) 594-609.
- [8] A. Pugsley, A. Zacharopoulos, J.D. Mondol, M. Smyth, Global applicability of solar desalination, *Renewable Energy*, 88 (2016) 200-219.
- [9] I.J. Esfahani, J. Rashidi, P. Ifaei, C. Yoo, Efficient thermal desalination technologies with renewable energy systems: A state-of-the-art review, *Korean Journal of Chemical Engineering*, 33 (2016) 351-387.
- [10] H. Sharon, K.S. Reddy, A review of solar energy driven desalination technologies, *Renewable and Sustainable Energy Reviews*, 41 (2015) 1080-1118.
- [11] J.H. Reif, W. Alhalabi, Solar-thermal powered desalination: Its significant challenges and potential, *Renewable and Sustainable Energy Reviews*, 48 (2015) 152-165.
- [12] S. Gorjian, B. Ghobadian, Solar desalination: A sustainable solution to water crisis in Iran, *Renewable and Sustainable Energy Reviews*, 48 (2015) 571-584.
- [13] C. Li, Y. Goswami, E. Stefanakos, Solar assisted sea water desalination: A review, *Renewable and Sustainable Energy Reviews*, 19 (2013) 136-163.
- [14] A. Al-Karaghoul, L.L. Kazmerski, Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes, *Renewable and Sustainable Energy Reviews*, 24 (2013) 343-356.
- [15] J. Kucera, Desalination: water from water, John Wiley & Sons, 2014.
- [16] G.N. Tiwari, H.N. Singh, R. Tripathi, Present status of solar distillation, *Solar Energy*, 75 (2003) 367-373.
- [17] P. Prakash, V. Velmurugan, Parameters influencing the productivity of solar stills – A review, *Renewable and Sustainable Energy Reviews*, 49 (2015) 585-609.
- [18] G. Xiao, X. Wang, M. Ni, F. Wang, W. Zhu, Z. Luo, K. Cen, A review on solar stills for brine desalination, *Applied Energy*, 103 (2013) 642-652.
- [19] V. Sivakumar, E. Ganapathy Sundaram, Improvement techniques of solar still efficiency: A review, *Renewable and Sustainable Energy Reviews*, 28 (2013) 246-264.
- [20] T. Rajaseenivasan, K.K. Murugavel, T. Elango, R.S. Hansen, A review of different methods to enhance the productivity of the multi-effect solar still, *Renewable and Sustainable Energy Reviews*, 17 (2013) 248-259.

- [21] G.M. Ayoub, L. Malaeb, Developments in solar still desalination systems: A critical review, *Critical Reviews in Environmental Science and Technology*, 42 (2012) 2078-2112.
- [22] V. Velmurugan, K. Srithar, Performance analysis of solar stills based on various factors affecting the productivity—A review, *Renewable and Sustainable Energy Reviews*, 15 (2011) 1294-1304.
- [23] A.E. Kabeel, S.A. El-Agouz, Review of researches and developments on solar stills, *Desalination*, 276 (2011) 1-12.
- [24] A. Ahsan, M. Imteaz, U.A. Thomas, M. Azmi, A. Rahman, N.N. Nik Daud, Parameters affecting the performance of a low cost solar still, *Applied Energy*, 114 (2014) 924-930.
- [25] T. Elango, A. Kannan, K.K. Murugavel, Performance study on single basin single slope solar still with different water nanofluids, *Desalination*, 360 (2015) 45-51.
- [26] A.E. Kabeel, Z.M. Omara, F.A. Essa, Enhancement of modified solar still integrated with external condenser using nanofluids: An experimental approach, *Energy Conversion and Management*, 78 (2014) 493-498.
- [27] A. Ahsan, M. Imteaz, A. Rahman, B. Yusuf, T. Fukuhara, Design, fabrication and performance analysis of an improved solar still, *Desalination*, 292 (2012) 105-112.
- [28] G.M. Ayoub, L. Malaeb, Economic feasibility of a solar still desalination system with enhanced productivity, *Desalination*, 335 (2014) 27-32.
- [29] R.S. Hansen, C.S. Narayanan, K.K. Murugavel, Performance analysis on inclined solar still with different new wick materials and wire mesh, *Desalination*, 358 (2015) 1-8.
- [30] Y.A.F. El-Samadony, A.S. Abdullah, Z.M. Omara, Experimental study of stepped solar still integrated with reflectors and external condenser, *Experimental Heat Transfer*, 28 (2015) 392-404.
- [31] M. El-Naggar, A.A. El-Sebaei, M.R.I. Ramadan, S. Aboul-Enein, Experimental and theoretical performance of finned-single effect solar still, *Desalination and Water Treatment*, (2015) 1-16.
- [32] S.A. El-Agouz, Experimental investigation of stepped solar still with continuous water circulation, *Energy Conversion and Management*, 86 (2014) 186-193.
- [33] T. Rajaseenivasan, K. Kalidasa Murugavel, T. Elango, Performance and exergy analysis of a double-basin solar still with different materials in basin, *Desalination and Water Treatment*, (2014) 1-9.
- [34] Z.M. Omara, A.E. Kabeel, M.M. Younes, Enhancing the stepped solar still performance using internal reflectors, *Desalination*, 314 (2013) 67-72.
- [35] F.F. Tabrizi, M. Dashtban, H. Moghaddam, Experimental investigation of a weir-type cascade solar still with built-in latent heat thermal energy storage system, *Desalination*, 260 (2010) 248-253.
- [36] A.A. El-Sebaei, A.A. Al-Ghamdi, F.S. Al-Hazmi, A.S. Faidah, Thermal performance of a single basin solar still with PCM as a storage medium, *Applied Energy*, 86 (2009) 1187-1195.
- [37] S. Kumar, G.N. Tiwari, Life cycle cost analysis of single slope hybrid (PV/T) active solar still, *Applied Energy*, 86 (2009) 1995-2004.
- [38] A.E. Kabeel, Performance of solar still with a concave wick evaporation surface, *Energy*, 34 (2009) 1504-1509.
- [39] S. Abdallah, O.O. Badran, Sun tracking system for productivity enhancement of solar still, *Desalination*, 220 (2008) 669-676.
- [40] Z.S. Abdel-Rehim, A. Lasheen, Experimental and theoretical study of a solar desalination system located in Cairo, Egypt, *Desalination*, 217 (2007) 52-64.
- [41] H.E.S. Fath, M. El-Samanoudy, K. Fahmy, A. Hassabou, Thermal-economic analysis and comparison between pyramid-shaped and single-slope solar still configurations, *Desalination*, 159 (2003) 69-79.
- [42] E.E. Delyannis, V. Belessiotis, Solar application in desalination: the Greek Islands experiment, *Desalination*, 100 (1995) 27-34.
- [43] G.N. Tiwari, Demonstration plant of a multi wick solar still, *Energy Conversion and Management*, 24 (1984) 313-316.

- [44] F.A. Al-Sulaiman, M.I. Zubair, M. Atif, P. Gandhidasan, S.A. Al-Dini, M.A. Antar, Humidification dehumidification desalination system using parabolic trough solar air collector, *Applied Thermal Engineering*, 75 (2015) 809-816.
- [45] B. Seifert, A. Kroiss, M. Spinnler, T. Sattelmayer, About the history of humidification–dehumidification desalination systems, in, 2013.
- [46] W. Abdelmoez, M.S. Mahmoud, T.E. Farrag, Water desalination using humidification/dehumidification (HDH) technique powered by solar energy: a detailed review, *Desalination and Water Treatment*, 52 (2014) 4622-4640.
- [47] A. Giwa, N. Akther, A.A. Housani, S. Haris, S.W. Hasan, Recent advances in humidification dehumidification (HDH) desalination processes: Improved designs and productivity, *Renewable and Sustainable Energy Reviews*, 57 (2016) 929-944.
- [48] M. Zamen, S.M. Soufari, S.A. Vahdat, M. Amidpour, M.A. Zeinali, H. Izanloo, H. Aghababaie, Experimental investigation of a two-stage solar humidification–dehumidification desalination process, *Desalination*, 332 (2014) 1-6.
- [49] G.P. Narayan, M.H. Sharqawy, E.K. Summers, J.H. Lienhard, S.M. Zubair, M.A. Antar, The potential of solar-driven humidification–dehumidification desalination for small-scale decentralized water production, *Renewable and Sustainable Energy Reviews*, 14 (2010) 1187-1201.
- [50] X. Li, G. Yuan, Z. Wang, H. Li, Z. Xu, Experimental study on a humidification and dehumidification desalination system of solar air heater with evacuated tubes, *Desalination*, 351 (2014) 1-8.
- [51] E.K. Summers, M.A. Antar, J.H. Lienhard V, Design and optimization of an air heating solar collector with integrated phase change material energy storage for use in humidification–dehumidification desalination, *Solar Energy*, 86 (2012) 3417-3429.
- [52] E.K. Summers, J.H. Lienhard, S.M. Zubair, Air-heating solar collectors for humidification-dehumidification desalination systems, *Journal of Solar Energy Engineering*, 133 (2011) 011016.
- [53] E.K. Summers, High efficiency solar air heaters with novel built-in heat storage for use in a humidification-dehumidification desalination cycle, (2010).
- [54] S.M. Soufari, M. Zamen, M. Amidpour, Experimental validation of an optimized solar humidification-dehumidification desalination unit, *Desalination and Water Treatment*, 6 (2009) 244-251.
- [55] K. Zhani, H. Ben Bacha, Experimental investigation of a new solar desalination prototype using the humidification dehumidification principle, *Renewable Energy*, 35 (2010) 2610-2617.
- [56] A.M.A. Dayem, Efficient Solar Desalination System Using Humidification/Dehumidification Process, *Journal of Solar Energy Engineering*, 136 (2014) 041014.
- [57] A.M.A. Dayem, Pioneer solar water desalination system: Experimental testing and numerical simulation, *Energy Science and Technology*, 1 (2011) 33-48.
- [58] A.E. Kabeel, E.M.S. El-Said, A hybrid solar desalination system of air humidification, dehumidification and water flashing evaporation: Part II. Experimental investigation, *Desalination*, 341 (2014) 50-60.
- [59] Z. Chang, H. Zheng, Y. Yang, Y. Su, Z. Duan, Experimental investigation of a novel multi-effect solar desalination system based on humidification–dehumidification process, *Renewable Energy*, 69 (2014) 253-259.
- [60] G. Yuan, Z. Wang, H. Li, X. Li, Experimental study of a solar desalination system based on humidification–dehumidification process, *Desalination*, 277 (2011) 92-98.
- [61] E. Mathioulakis, G. Panaras, V. Belessiotis, Experience gained through the implementation and operation of a solar humidification—dehumidification desalination plant, *Desalination and water treatment*, 21 (2010) 375-381.
- [62] C. Yamali, İ. Solmus, A solar desalination system using humidification–dehumidification process: experimental study and comparison with the theoretical results, *Desalination*, 220 (2008) 538-551.
- [63] I. Houcine, M. BenAmara, A. Guizani, M. Maâlej, Pilot plant testing of a new solar desalination process by a multiple-effect-humidification technique, *Desalination*, 196 (2006) 105-124.

- [64] S. Burn, M. Hoang, D. Zarzo, F. Olewniak, E. Campos, B. Bolto, O. Barron, Desalination techniques — A review of the opportunities for desalination in agriculture, *Desalination*, 364 (2015) 2-16.
- [65] M.T. Ali, H.E.S. Fath, P.R. Armstrong, A comprehensive techno-economical review of indirect solar desalination, *Renewable and Sustainable Energy Reviews*, 15 (2011) 4187-4199.
- [66] S.M.A. Moustafa, D.I. Jarrar, H.I. El-Mansy, Performance of a self-regulating solar multistage flash desalination system, *Solar Energy*, 35 (1985) 333-340.
- [67] M.A. Sharaf Eldean, H.E. Fath, Exergy and thermo-economic analysis of solar thermal cycles powered multi-stage flash desalination process, *Desalination and Water Treatment*, 51 (2013) 7361-7378.
- [68] A.S. Nafey, M.A. Mohamad, S.O. El-Helaby, M.A. Sharaf, Theoretical and experimental study of a small unit for solar desalination using flashing process, *Energy Conversion and Management*, 48 (2007) 528-538.
- [69] H. Lu, J.C. Walton, H. Hein, Thermal desalination using MEMS and salinity-gradient solar pond technology, *NASA STI/Recon Technical Report N*, 3 (2002) 00498.
- [70] A.S. Nafey, M.A. Sharaf, L. García-Rodríguez, A new visual library for design and simulation of solar desalination systems (SDS), *Desalination*, 259 (2010) 197-207.
- [71] P. Palenzuela, A.S. Hassan, G. Zaragoza, D.-C. Alarcón-Padilla, Steady state model for multi-effect distillation case study: Plataforma Solar de Almería MED pilot plant, *Desalination*, 337 (2014) 31-42.
- [72] M. Al-Shammiri, M. Safar, Multi-effect distillation plants: state of the art, *Desalination*, 126 (1999) 45-59.
- [73] M.A. Sharaf, A.S. Nafey, L. García-Rodríguez, Thermo-economic analysis of solar thermal power cycles assisted MED-VC (multi effect distillation-vapor compression) desalination processes, *Energy*, 36 (2011) 2753-2764.
- [74] D.-C. Alarcón-Padilla, L. García-Rodríguez, Application of absorption heat pumps to multi-effect distillation: a case study of solar desalination, *Desalination*, 212 (2007) 294-302.
- [75] M.D. Stuber, C. Sullivan, S.A. Kirk, J.A. Farrand, P.V. Schillaci, B.D. Fojtasek, A.H. Mandell, Pilot demonstration of concentrated solar-powered desalination of subsurface agricultural drainage water and other brackish groundwater sources, *Desalination*, 355 (2015) 186-196.
- [76] D.-C. Alarcón-Padilla, J. Blanco-Gálvez, L. García-Rodríguez, W. Gernjak, S. Malato-Rodríguez, First experimental results of a new hybrid solar/gas multi-effect distillation system: the AQUASOL project, *Desalination*, 220 (2008) 619-625.
- [77] D.-C. Alarcón-Padilla, L. García-Rodríguez, J. Blanco-Gálvez, Assessment of an absorption heat pump coupled to a multi-effect distillation unit within AQUASOL project, *Desalination*, 212 (2007) 303-310.
- [78] B. Milow, E. Zarza, Advanced MED solar desalination plants. Configurations, costs, future—seven years of experience at the Plataforma Solar de Almeria (Spain), *Desalination*, 108 (1997) 51-58.
- [79] P. Palenzuela, G. Zaragoza, D.-C. Alarcón-Padilla, Characterisation of the coupling of multi-effect distillation plants to concentrating solar power plants, *Energy*, 82 (2015) 986-995.
- [80] S. Casimiro, J. Cardoso, C. Ioakimidis, J.F. Mendes, C. Mineo, A. Cipollina, MED parallel system powered by concentrating solar power (CSP). Model and case study: Trapani, Sicily, (2014).
- [81] R. Olwig, T. Hirsch, C. Sattler, H. Glade, L. Schmeken, S. Will, A. Ghermandi, R. Messalem, Techno-economic analysis of combined concentrating solar power and desalination plant configurations in Israel and Jordan, *Desalination and Water Treatment*, 41 (2012) 9-25.
- [82] M.A. Sharaf, A.S. Nafey, L. García-Rodríguez, Exergy and thermo-economic analyses of a combined solar organic cycle with multi effect distillation (MED) desalination process, *Desalination*, 272 (2011) 135-147.
- [83] N. Ghaffour, T.M. Missimer, G.L. Amy, Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability, *Desalination*, 309 (2013) 197-207.

- [84] X. Liu, W. Chen, M. Gu, S. Shen, G. Cao, Thermal and economic analyses of solar desalination system with evacuated tube collectors, *Solar Energy*, 93 (2013) 144-150.
- [85] Y.-D. Kim, K. Thu, A. Myat, K.C. Ng, Numerical simulation of solar-assisted multi-effect distillation (SMED) desalination systems, *Desalination and Water Treatment*, 51 (2013) 1242-1253.
- [86] J. Leblanc, J. Andrews, A. Akbarzadeh, Low - temperature solar - thermal multi - effect evaporation desalination systems, *International Journal of Energy Research*, 34 (2010) 393-403.
- [87] D.C. Alarcón-Padilla, L. García-Rodríguez, J. Blanco-Gálvez, Design recommendations for a multi-effect distillation plant connected to a double-effect absorption heat pump: A solar desalination case study, *Desalination*, 262 (2010) 11-14.
- [88] A. Alkhudhiri, N. Darwish, N. Hilal, Membrane distillation: A comprehensive review, *Desalination*, 287 (2012) 2-18.
- [89] W. Heinzl, S. Büttner, G. Lange, Industrialized modules for MED Desalination with polymer surfaces, *Desalination and Water Treatment*, 42 (2012) 177-180.
- [90] K. Zhao, W. Heinzl, M. Wenzel, S. Büttner, F. Bollen, G. Lange, S. Heinzl, N. Sarda, Experimental study of the memsys vacuum-multi-effect-membrane-distillation (V-MEMD) module, *Desalination*, 323 (2013) 150-160.
- [91] E. Drioli, A. Ali, F. Macedonio, Membrane distillation: Recent developments and perspectives, *Desalination*, 356 (2015) 56-84.
- [92] M. Essalhi, M. Khayet, Application of a porous composite hydrophobic/hydrophilic membrane in desalination by air gap and liquid gap membrane distillation: A comparative study, *Separation and Purification Technology*, 133 (2014) 176-186.
- [93] G. Naidu, S. Jeong, Y. Choi, E. Jang, T.-M. Hwang, S. Vigneswaran, Application of vacuum membrane distillation for small scale drinking water production, *Desalination*, 354 (2014) 53-61.
- [94] F. Banat, N. Jwaied, Autonomous membrane distillation pilot plant unit driven solar energy: Experiences and lessons learned, *Int. J. Sustain. Water Environ. Syst*, 1 (2010) 21-24.
- [95] J. Koschikowski, M. Wieghaus, M. Rommel, V.S. Ortin, B.P. Suarez, J.R. Betancort Rodríguez, Experimental investigations on solar driven stand-alone membrane distillation systems for remote areas, *Desalination*, 248 (2009) 125-131.
- [96] H.E.S. Fath, S.M. Elsherbiny, A.A. Hassan, M. Rommel, M. Wieghaus, J. Koschikowski, M. Vatansever, PV and thermally driven small-scale, stand-alone solar desalination systems with very low maintenance needs, *Desalination*, 225 (2008) 58-69.
- [97] F. Banat, N. Jwaied, M. Rommel, J. Koschikowski, M. Wieghaus, Performance evaluation of the "large SMADES" autonomous desalination solar-driven membrane distillation plant in Aqaba, Jordan, *Desalination*, 217 (2007) 17-28.
- [98] F. Banat, N. Jwaied, M. Rommel, J. Koschikowski, M. Wieghaus, Desalination by a "compact SMADES" autonomous solarpowered membrane distillation unit, *Desalination*, 217 (2007) 29-37.
- [99] A. Chafidz, S. Al-Zahrani, M.N. Al-Otaibi, C.F. Hoong, T.F. Lai, M. Prabu, Portable and integrated solar-driven desalination system using membrane distillation for arid remote areas in Saudi Arabia, *Desalination*, 345 (2014) 36-49.
- [100] R.G. Raluy, R. Schwantes, V.J. Subiela, B. Peñate, G. Melián, J.R. Betancort, Operational experience of a solar membrane distillation demonstration plant in Pozo Izquierdo-Gran Canaria Island (Spain), *Desalination*, 290 (2012) 1-13.
- [101] F. Banat, N. Jwaied, Economic evaluation of desalination by small-scale autonomous solar-powered membrane distillation units, *Desalination*, 220 (2008) 566-573.
- [102] R.B. Saffarini, E.K. Summers, H.A. Arafat, J.H. Lienhard V, Economic evaluation of stand-alone solar powered membrane distillation systems, *Desalination*, 299 (2012) 55-62.
- [103] W.G. Shim, K. He, S. Gray, I.S. Moon, Solar energy assisted direct contact membrane distillation (DCMD) process for seawater desalination, *Separation and Purification Technology*, 143 (2015) 94-104.

- [104] G. Zaragoza, A. Ruiz-Aguirre, E. Guillén-Burrieza, Efficiency in the use of solar thermal energy of small membrane desalination systems for decentralized water production, *Applied Energy*, 130 (2014) 491-499.
- [105] Y. Wang, Z. Xu, N. Lior, H. Zeng, An experimental study of solar thermal vacuum membrane distillation desalination, *Desalination and Water Treatment*, (2014) 1-11.
- [106] Y.-D. Kim, K. Thu, N. Ghaffour, K. Choon Ng, Performance investigation of a solar-assisted direct contact membrane distillation system, *Journal of Membrane Science*, 427 (2013) 345-364.
- [107] S. Gabsi, N. Frikha, B. Chaouachi, Performance of a Solar Vacuum Membrane Distillation Pilot Plant, for Seawater Desalination in Mahares, Tunisia, (2013).
- [108] N. Frikha, R. Matlaya, B. Chaouachi, S. Gabsi, Simulation of an autonomous solar vacuum membrane distillation for seawater desalination, *Desalination and Water Treatment*, 52 (2013) 1725-1734.
- [109] S. Ben Abdallah, N. Frikha, S. Gabsi, Design of an autonomous solar desalination plant using vacuum membrane distillation, the MEDINA project, *Chemical Engineering Research and Design*, 91 (2013) 2782-2788.
- [110] E. Guillén-Burrieza, J. Blanco, G. Zaragoza, D.-C. Alarcón, P. Palenzuela, M. Ibarra, W. Gernjak, Experimental analysis of an air gap membrane distillation solar desalination pilot system, *Journal of Membrane Science*, 379 (2011) 386-396.
- [111] N. Dow, M. Duke, J. Zhang, T. O’Rielly, J.D. Li, S. Gray, E. Ostarcevic, P. Atherton, Demonstration of solar driven membrane distillation in remote Victoria, in, 2010, pp. 8-10.
- [112] X. Wang, L. Zhang, H. Yang, H. Chen, Feasibility research of potable water production via solar-heated hollow fiber membrane distillation system, *Desalination*, 247 (2009) 403-411.
- [113] A. Al-Karaghoul, D. Renne, L.L. Kazmerski, Technical and economic assessment of photovoltaic-driven desalination systems, *Renewable Energy*, 35 (2010) 323-328.
- [114] B. Peñate, V.J. Subiela, F. Vega, F. Castellano, F.J. Domínguez, V. Millán, Uninterrupted eight-year operation of the autonomous solar photovoltaic reverse osmosis system in Ksar Ghilène (Tunisia), *Desalination and Water Treatment*, (2014) 1-8.
- [115] H. Qiblawey, F. Banat, Q. Al-Nasser, Performance of reverse osmosis pilot plant powered by Photovoltaic in Jordan, *Renewable Energy*, 36 (2011) 3452-3460.
- [116] F. Banat, H. Qiblawey, Q. Al-Nasser, Economic evaluation of a small RO unit powered by PV installed in the village of Hartha, Jordan, *Desalination and Water Treatment*, 3 (2009) 169-174.
- [117] A. Alsheghri, S.A. Sharief, S. Rabbani, N.Z. Aitzhan, Design and Cost Analysis of a Solar Photovoltaic Powered Reverse Osmosis Plant for Masdar Institute, *Energy Procedia*, 75 (2015) 319-324.
- [118] A.M. Delgado-Torres, L. García-Rodríguez, Design recommendations for solar organic Rankine cycle (ORC)-powered reverse osmosis (RO) desalination, *Renewable and Sustainable Energy Reviews*, 16 (2012) 44-53.
- [119] G. Xia, Q. Sun, J. Wang, X. Cao, Y. Yu, L. Wang, Theoretical analysis of a reverse osmosis desalination system driven by solar-powered organic Rankine cycle and wind energy, *Desalination and Water Treatment*, 53 (2015) 876-886.
- [120] R. Salcedo, E. Antipova, D. Boer, L. Jiménez, G. Guillén-Gosálbez, Multi-objective optimization of solar Rankine cycles coupled with reverse osmosis desalination considering economic and life cycle environmental concerns, *Desalination*, 286 (2012) 358-371.
- [121] M. Khayet, M. Essalhi, C. Armenta-Déu, C. Cojocar, N. Hilal, Optimization of solar-powered reverse osmosis desalination pilot plant using response surface methodology, *Desalination*, 261 (2010) 284-292.
- [122] A. De Munari, D.P.S. Capão, B.S. Richards, A.I. Schäfer, Application of solar-powered desalination in a remote town in South Australia, *Desalination*, 248 (2009) 72-82.
- [123] B. Peñate, L. García-Rodríguez, Seawater reverse osmosis desalination driven by a solar Organic Rankine Cycle: Design and technology assessment for medium capacity range, *Desalination*, 284 (2012) 86-91.

- [124] N.C. Wright, A.G. Winter V, Justification for community-scale photovoltaic-powered electrodialysis desalination systems for inland rural villages in India, *Desalination*, 352 (2014) 82-91.
- [125] B. Peñate, F. Círez, F.J. Domínguez, V.J. Subiela, L. Vera, Design and testing of an isolated commercial EDR plant driven by solar photovoltaic energy, *Desalination and Water Treatment*, 51 (2013) 1254-1264.
- [126] Y. Zhang, L. Pinoy, B. Meesschaert, B. Van der Bruggen, A natural driven membrane process for brackish and wastewater treatment: photovoltaic powered ED and FO hybrid system, *Environmental science & technology*, 47 (2013) 10548-10555.
- [127] J.M. Ortiz, E. Expósito, F. Gallud, V. García-García, V. Montiel, A. Aldaz, Desalination of underground brackish waters using an electrodialysis system powered directly by photovoltaic energy, *Solar Energy Materials and Solar Cells*, 92 (2008) 1677-1688.
- [128] C. Fernandez-Gonzalez, A. Dominguez-Ramos, R. Ibañez, A. Irabien, Sustainability assessment of electrodialysis powered by photovoltaic solar energy for freshwater production, *Renewable and Sustainable Energy Reviews*, 47 (2015) 604-615.
- [129] F. Círez, J. Uche, A.A. Bayod, A. Martínez, Batch ED fed by a PV unit: a reliable, flexible, and sustainable integration, *Desalination and Water Treatment*, 51 (2013) 673-685.
- [130] H.M.N. AlMadani, Water desalination by solar powered electrodialysis process, *Renewable Energy*, 28 (2003) 1915-1924.
- [131] I.C. Karagiannis, P.G. Soldatos, Water desalination cost literature: review and assessment, *Desalination*, 223 (2008) 448-456.
- [132] M. Papapetrou, C. Biercamp, M. Wiegand, Roadmap for the Development of Desalination Powered by Renewable Energy: Promotion for Renewable Energy for Water Production Through Desalination, *Fraunhofer Verlag*, 2010.
- [133] M.N. Chong, B. Jin, C.W.K. Chow, C. Saint, Recent developments in photocatalytic water treatment technology: A review, *Water Research*, 44 (2010) 2997-3027.
- [134] S. Ahmed, M.G. Rasul, W.N. Martens, R. Brown, M.A. Hashib, Heterogeneous photocatalytic degradation of phenols in wastewater: A review on current status and developments, *Desalination*, 261 (2010) 3-18.
- [135] D. Spasiano, R. Marotta, S. Malato, P. Fernandez-Ibañez, I. Di Somma, Solar photocatalysis: Materials, reactors, some commercial, and pre-industrialized applications. A comprehensive approach, *Applied Catalysis B: Environmental*, 170-171 (2015) 90-123.
- [136] R.L. Pozzo, J.L. Giombi, M.A. Baltanás, A.E. Cassano, The performance in a fluidized bed reactor of photocatalysts immobilized onto inert supports, *Catalysis Today*, 62 (2000) 175-187.
- [137] S. Rahim Pouran, A.R. Abdul Aziz, W.M.A. Wan Daud, Review on the main advances in photo-Fenton oxidation system for recalcitrant wastewaters, *Journal of Industrial and Engineering Chemistry*, 21 (2015) 53-69.
- [138] R.J. Braham, A.T. Harris, Review of Major Design and Scale-up Considerations for Solar Photocatalytic Reactors, *Industrial & Engineering Chemistry Research*, 48 (2009) 8890-8905.
- [139] D. Bahnemann, Photocatalytic water treatment: solar energy applications, *Solar Energy*, 77 (2004) 445-459.
- [140] M.A. Sousa, C. Gonçalves, V.J.P. Vilar, R.A.R. Boaventura, M.F. Alpendurada, Suspended TiO₂-assisted photocatalytic degradation of emerging contaminants in a municipal WWTP effluent using a solar pilot plant with CPCs, *Chemical Engineering Journal*, 198-199 (2012) 301-309.
- [141] N. Miranda-García, S. Suárez, B. Sánchez, J.M. Coronado, S. Malato, M.I. Maldonado, Photocatalytic degradation of emerging contaminants in municipal wastewater treatment plant effluents using immobilized TiO₂ in a solar pilot plant, *Applied Catalysis B: Environmental*, 103 (2011) 294-301.
- [142] S. Malato, P. Fernández-Ibañez, M.I. Maldonado, J. Blanco, W. Gernjak, Decontamination and disinfection of water by solar photocatalysis: Recent overview and trends, *Catalysis Today*, 147 (2009) 1-59.

- [143] I. Michael, A. Panagi, L.A. Ioannou, Z. Frontistis, D. Fatta-Kassinos, Utilizing solar energy for the purification of olive mill wastewater using a pilot-scale photocatalytic reactor after coagulation-flocculation, *Water Research*, 60 (2014) 28-40.
- [144] J. Fenoll, P. Flores, P. Hellín, C.M. Martínez, S. Navarro, Photodegradation of eight miscellaneous pesticides in drinking water after treatment with semiconductor materials under sunlight at pilot plant scale, *Chemical Engineering Journal*, 204–206 (2012) 54-64.
- [145] G. Zayani, L. Bousselmi, F. Mhenni, A. Ghrabi, Solar photocatalytic degradation of commercial textile azo dyes: Performance of pilot plant scale thin film fixed-bed reactor, *Desalination*, 246 (2009) 344-352.
- [146] T. Velegraki, D. Mantzavinos, Solar photo-Fenton treatment of winery effluents in a pilot photocatalytic reactor, *Catalysis Today*, 240, Part A (2015) 153-159.
- [147] M.J. Hernández-Rodríguez, C. Fernández-Rodríguez, J.M. Doña-Rodríguez, O.M. González-Díaz, D. Zerbani, J. Pérez Peña, Treatment of effluents from wool dyeing process by photo-Fenton at solar pilot plant, *Journal of Environmental Chemical Engineering*, 2 (2014) 163-171.
- [148] M.B. Keogh, M. Castro-Alfárez, M.I. Polo-López, I. Fernández Calderero, Y.A. Al-Eryani, C. Joseph-Titus, B. Sawant, R. Dhodapkar, C. Mathur, K.G. McGuigan, P. Fernández-Ibáñez, Capability of 19-L polycarbonate plastic water cooler containers for efficient solar water disinfection (SODIS): Field case studies in India, Bahrain and Spain, *Solar Energy*, 116 (2015) 1-11.
- [149] K. McGuigan, T. Joyce, R. Conroy, J. Gillespie, M. Elmore-Meegan, Solar disinfection of drinking water contained in transparent plastic bottles: characterizing the bacterial inactivation process, *Journal of applied microbiology*, 84 (1998) 1138-1148.
- [150] K.G. McGuigan, R.M. Conroy, H.-J. Mosler, M.d. Preez, E. Ubomba-Jaswa, P. Fernandez-Ibañez, Solar water disinfection (SODIS): A review from bench-top to roof-top, *Journal of Hazardous Materials*, 235–236 (2012) 29-46.
- [151] M. Vivar, M. Fuentes, J. Castro, R. García-Pacheco, Effect of common rooftop materials as support base for solar disinfection (SODIS) in rural areas under temperate climates, *Solar Energy*, 115 (2015) 204-216.
- [152] T. Clasen, S. Cairncross, L. Haller, J. Bartram, D. Walker, Cost-effectiveness of water quality interventions for preventing diarrhoeal disease in developing countries, *Journal of water and health*, 5 (2007) 599-608.