
Desalination

Paper:

Ahmed, F., Hashaikeh, R. & Hilal, N. (2019). Solar powered desalination – Technology, energy and future outlook. *Desalination, 453*, 54-76.

http://dx.doi.org/10.1016/j.desal.2018.12.002

Solar powered desalination – technology, energy and future outlook

Farah Ejaz Ahmed[1], Raed Hashaikeh[2], Nidal Hilal[1,3]*

[1] NYUAD Water Research Center, New York University Abu Dhabi, Abu Dhabi, United Arab Emirates

[2] Chemical Engineering Department. Khalifa University of Science and Technology, Masdar Institute, Masdar City, Abu Dhabi 54224, United Arab Emirates

[3] Centre for Water Advanced Technologies and Environmental Research (CWATER), College of Engineering, Swansea University, Fabian Way, Swansea SA1 8EN, UK

*n.hilal@swansea.ac.uk

Abstract

Growing water demands have led to rapidly increasing desalination installation capacity worldwide. In an attempt to lower carbon footprint resulting from high-energy consuming desalination processes, attention has shifted to using renewable energy sources to power desalination. With solar irradiation ample in regions that heavily rely on desalination, solar powered desalination provides a sustainable solution to meeting water needs. The compatibility of each desalination process with the solar technology is driven by whether the kind of energy needed is thermal or electrical, as well as its availability. With rapid advances in solar energy technologies – both photovoltaic and solar thermal, there has also been growing interest in coupling solar energy with desalination, with a focus on improving energy efficiency. In this review, the most recent developments in photovoltaic powered reverse osmosis (PV-RO), solar thermal powered reverse osmosis (ST-RO) are discussed with respect to membrane materials, process configuration, energy recovery devices and energy storage. In addition, advances in new materials for solar powered membrane distillation (MD) and solar stills in the past two years have also been reviewed. Future outlook considers the use of hybrid renewable energy systems as well as solar powered forward osmosis and dewvaporation. Solar powered desalination systems have been analysed with emphasis on technological and energy consumption aspects.

Keywords: Desalination; Solar Desalination; PV-RO; ST-RO; Solar-MD

Table of Contents

1. Introduction

1.1 Water scarcity

Increasing water stress continues to affect more and more parts of the world. According to the UN World Water Development Report, 3.7 billion people are currently affected by water scarcity. In 2050, this number could increase to up to 5.7 billion [1]. At present, 3.5 million people die annually as a result of inadequate water supply and sanitation, reinforcing the role of water as a critical global resource. **Figure 1** shows projected country-level water stress in 2040 [2].

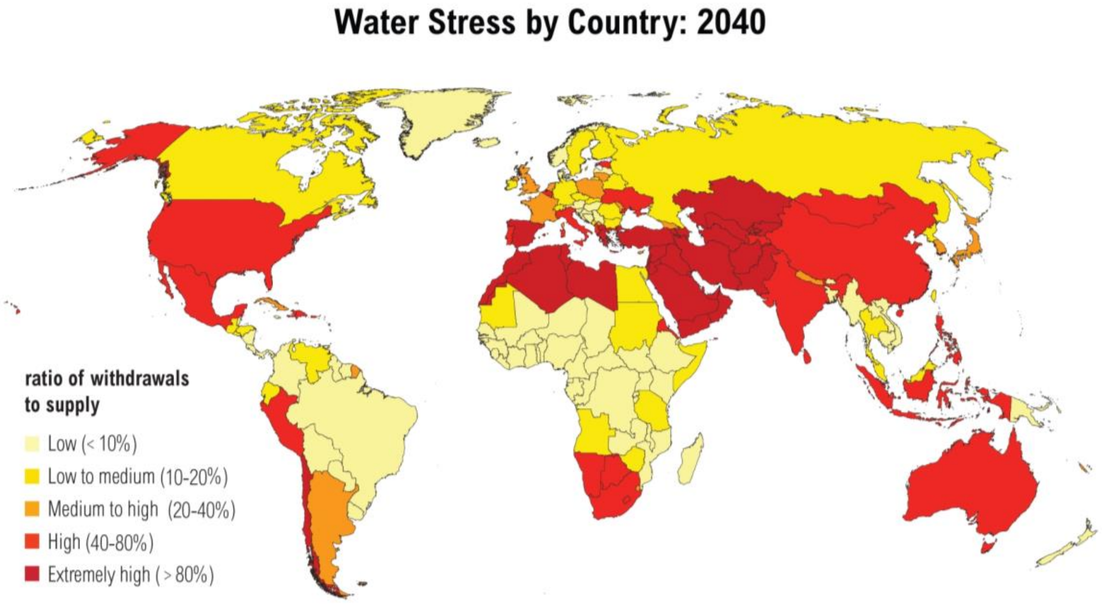

Figure 1: Projected water stress in 2040 [2]

With depleting fresh water sources causing an imminent threat, focus on desalination as a means to meet global water demand has never been greater. Increase in population and subsequent rise in demand for consumable water have been cited as the top drivers for the global desalination market. To give an insight, the global desalination market is projected to accelerate at a rate of 9% from 2018 to 2022, with 74% of the growth coming from the Europe, Middle East and Africa (EMEA) region [3].

Desalination is the process by which salts are removed from saline feed-water to render it useful for other use, including as drinking water [4]. Desalination processes can generally be divided into two technology types: thermal desalination and membrane technology. The former as the name suggests use heat to separate distillate from saline water. Multi-stage flash (MSF) and Multiple Effect Distillation (MED) have traditionally been the most widely used thermal desalination technologies. However, in recent years membrane technology has taken over with the global cumulative installed and online capacity at the end of 2016 consisting of 73% membrane-based desalination and 27% thermal (**Figure 2**) [5]. Ever since the development of reverse osmosis (RO) membranes in the 1960s, advancements in membrane separation have caused RO to dominate the desalination market, with the largest share of installation capacity in recent years, especially outside the Middle East [6]. In the Middle East and North Africa, the transition from thermal to membrane-based desalination processes is slower than elsewhere owing to availability of lower-cost fuel and co-generation plants [7]. Another membrane-based process with a significant market share of installed desalination capacity in the past ten years is electrodialysis (ED). Other desalination processes that are set to grow include forward osmosis (FO) and membrane distillation (MD).

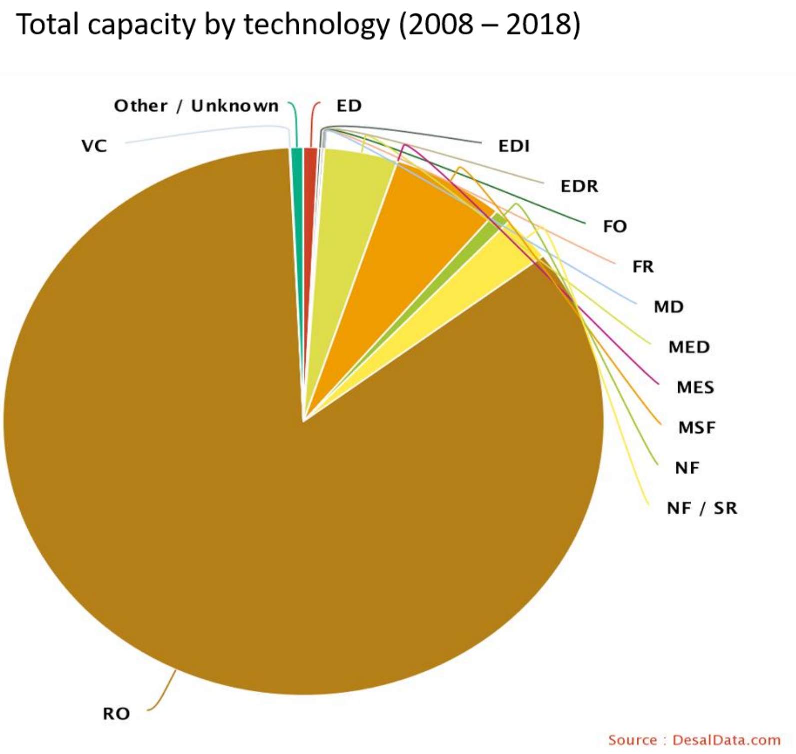

Figure 2: Global installation capacity by desalination technology between 2010 – 2018 [8]

1.1 Renewable energy desalination

Despite the technological maturity of the processes mentioned above, energy requirements for desalination processes are still significant. It is clear that growing water demand necessitates the need for installing an increasing number of high-capacity desalination plants, which use conventional and expensive fossil fuel energy sources and can cause an increase in air pollution as well as greenhouse gas (GHG) emissions [9]. Although the energy requirements of seawater reverse osmosis (SWRO) has decreased by a factor of 5 in the last 50 years owing to technological development [10, 11], total installed capacity is currently at > 60 Mt with an annual growth rate of 10-15% [12]. Energy usage by SWRO installations approaches 100 TWh/year which translates into 60 – 100 Mt CO_2 annually. Decarbonization of desalination is a necessary component of reducing CO_2 emissions and mitigating climate change while meeting the world's water demand [12]. Thermal desalination plants require 40 to 80 kWh/m^3 for their substantial heating requirements and an additional 2.5 to 5 kWh/ m^3 in electrical energy [11, 13]. The obvious solutions are lowering the energy consumption through new materials and process design and/or developing new sustainable processes or using renewable energy sources to drive desalination.

Decarbonization in the area of desalination is also motivated by the finite and expensive nature of fossil fuels. At the forefront of the transition to renewable energy sources also lies the role of regulatory bodies such as the European Commission, who have continuously guided policies to increase the share of renewable energy sources by setting targets and capping greenhouse gas emissions [14, 15]. Types of renewable energy sources are described below:

- Solar: solar energy is radiation from the sun that can be harnessed using several technologies discussed in Section 2
- Wind energy: wind power is the harnessing of airflow through wind turbines to generate mechanical power and in turn electricity through generators. In 2015, there was 20% increase in installed capacity of new wind turbines from the year before. The EU represents one third of the world's wind power [16]
- Hydroelectric energy: Energy harnessed from flowing water in a hydroelectric dam. The contribution of hydropower to the US electrical consumption reduced from 40% to 8% since 1940 due to insufficient technology improvements as compared to other energy sources [17]. **Figure 3** shows a photograph of the Hoover dam, located between Nevada and Arizona.

Figure 3: Photographs of the Hoover dam located in Southwest USA [17]

- Biomass energy: energy obtained from organic material such as wood and crops.
- Geothermal energy: heat within the earth that is used as steam or hot water for heating or to generate electricity [18]

The technological status of renewable energy desalination technologies is shown in **Figure 4** [19]. However, the production capacity for PV-RO is already drastically greater than that shown in this figure (>1000 m^3/d), as will be discussed in Section 3.1.

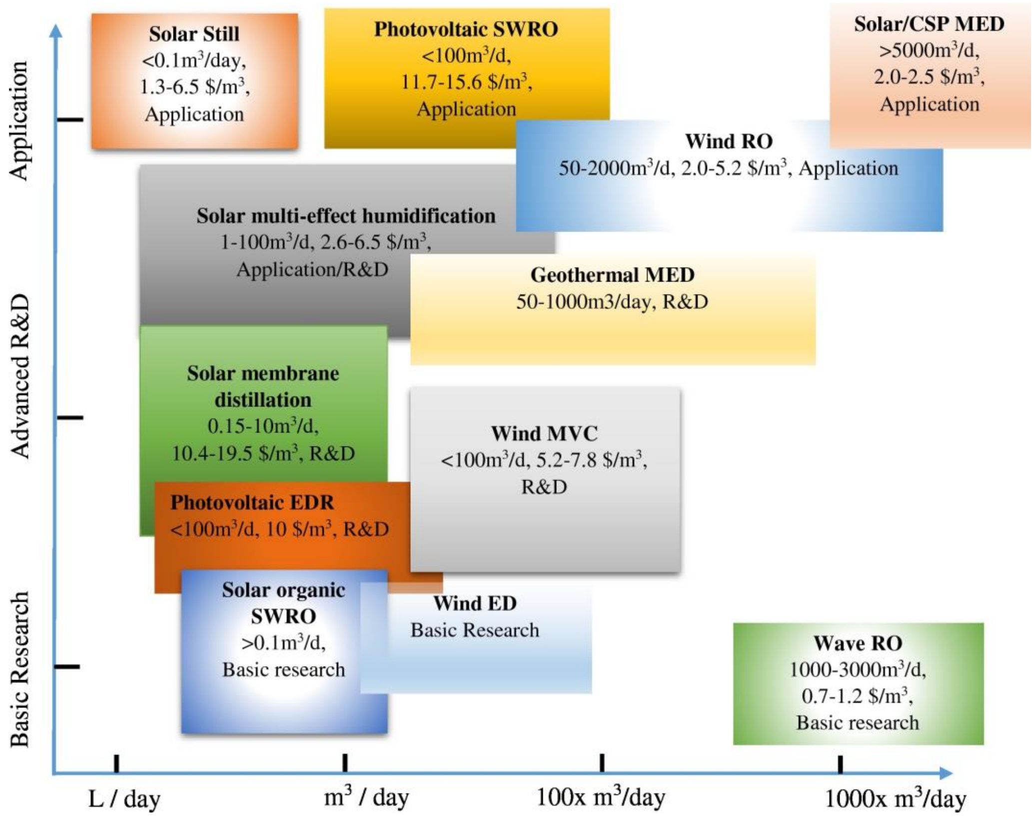

Figure 4:Technological status of renewable energy desalination technologies [19]

Although other forms of renewable energy have also been exploited for desalination processes, solar energy is of special interest as it is the most abundant permanent source of energy on earth [20]. The earth receives on average 1361 W/m^2 of radiation from the sun every year [21]. 30% of this is scattered or reflected, leaving 70% for harvesting [22, 23]. A few studies have highlighted that some of the world's most arid regions that rely on desalination to meet their water needs also have high solar irradiation. Pugsley *et al.* developed a ranking method correlating water scarcity, saline water resources and solar insolation for several countries to suggest the applicability of solar desalination [24]. They found 30 countries including those in the MENA region where solar desalination opportunities are greatest, whereas 28 more countries (including China, India, Australia, parts of the USA) also convey potential. This is why solar powered desalination technologies have been widely investigated and employed in many parts of the world, for both small and large scale systems.

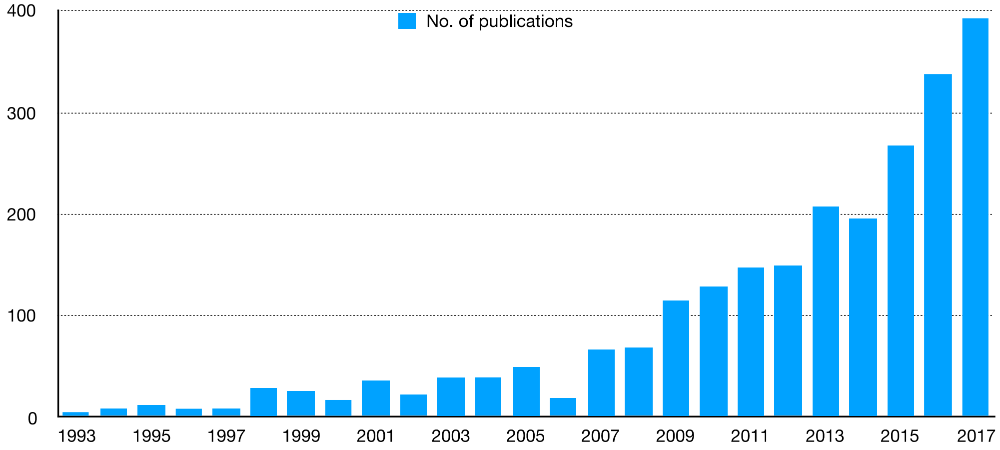

Figure 5: No. of publications with topic keywords 'solar energy' and 'desalination'

Interest in the area of solar energy for desalination has drastically increased in the last 25 years, as is indicated by the sharp increase in number of publications on this topic (**Figure 5**). Chandrashekara and Yadav focused on reviewing solar energy for thermal desalination technologies [25]. Sharon and Reddy also reviewed solar energy driven desalination technologies, and found that the limited availability of long-life efficient membranes hinders cutting maintenance cost and subsequent water production cost [26]. Zhang *et al.* reviewed recent developments in solar energy for water treatment, which included solar photocatalysis and solar disinfection in addition to solar desalination technologies [27]. Although they reviewed several desalination technologies, they did not extensively discuss solar-powered membrane distillation and advances in membrane materials. Pouyfaucon & García-Rodríguez specifically reviewed solar-thermal powered desalination from the perspective of finding a viable solution in terms of technology, depending on water demand and location [28]. Despite frequent reviews, solar energy and desalination remain growing areas of research, driven by the need to lower energy consumption and GHG.

1.2 Solar desalination

Solar desalination can either be direct, or indirect, depending on how solar energy drives the technology. Direct solar desalination systems, also known as solar stills, distillate is produced directly in the solar collector, whereas in indirect solar desalination systems, solar energy is harvested as thermal or electrical energy which in turn is used to drive desalination. Despite many advances in enhancing the productivity of solar stills as can be found in recent reviews [10, 29-33], currently available designs are still not suitable for large scale water production [34]. However, in the last two years, research in new materials for direct solar desalination has rapidly advanced, as will be seen in Section 3.1. Examples of indirect solar desalination include membrane distillation (MD), reverse osmosis (RO), humidification-dehumidification (HDH), multi-effect distillation (MED), multi-stage flash (MSF) and electrodialysis (ED). Reverse osmosis is seen as the most apt technology for large-scale solar powered desalination. Here we review recent advances in state-of-the-art solar powered desalination technologies with respect to reducing energy demand, the role of new materials in enhancing performance in emergent processes such as solar powered MD. This review comments on the industrial and research status of solar powered RO with respect to the various technological aspects including type of solar technology to be used and reducing specific energy consumption of solar powered RO systems. Section 3.2.2 discusses an emergent desalination technology, membrane distillation (MD) and its coupling with solar energy, with a focus on new membrane materials. Furthermore, Section 4 briefly describes prospects of hybrid RE systems as well as newer desalination processes such as forward osmosis and dewvaporation.

2. Solar technologies

An introduction to solar technologies, including the principle of operation, is a prerequisite examining the existing and potential role of solar power in desalination. Solar energy can be harnessed directly as electricity, or as solar thermal energy, which is either used in heating or cooling systems, or drives turbines to generate electricity. Technologies for solar energy therefore falls under two broad categories: PV and solar thermal. Solar thermal technologies are further divided into concentrated solar power (CSP), for electricity generation, or direct use in low-temperature heating applications (**Figure 6**).

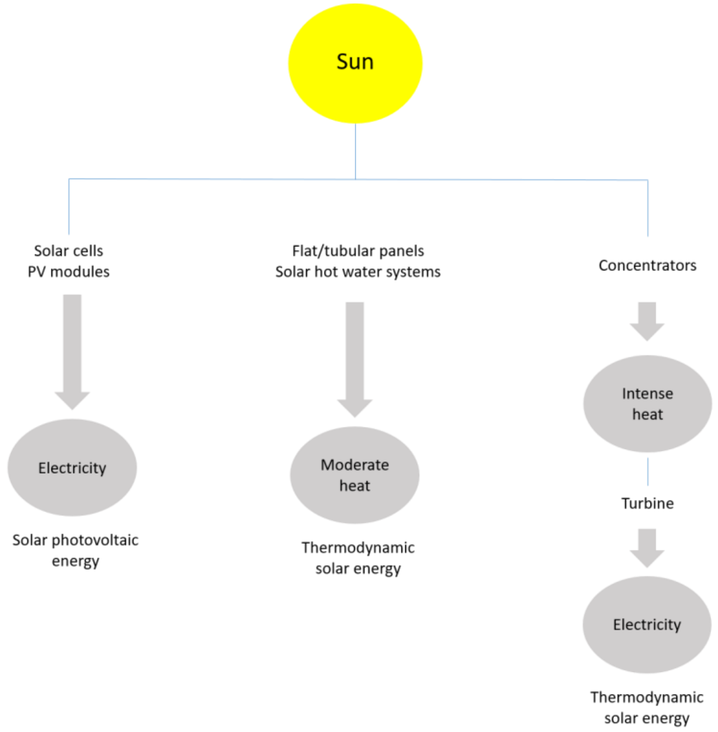

Figure 6: Methods of exploiting solar energy [35]

2.1 Solar PV

Photovoltaic technology is used to hardness solar energy from photons as electricity. The operating principal of solar PV is described extensively in literature, to which the reader is referred [35-38]. In short, solar radiation (or any light) can be converted into electricity through materials that exhibit the ‘photovoltaic’ effect. The photovoltaic effect is the appearance of a voltage difference when light is shined on a system of two electrodes with a solid or liquid system between them [39]. In a PV system, solar panels made of different layers are used to capture photons. As photons are captured, they provide sufficient energy for electrons to be released from atoms in the semiconductor. The flow of electrons between positive and negative electrodes creates an electric current. The solar panels include an anti-reflective coating to minimize photons from escaping and a semiconductor layer between two electrodes. **Figure 7** shows a schematic of the principal of operation of a typical cell.

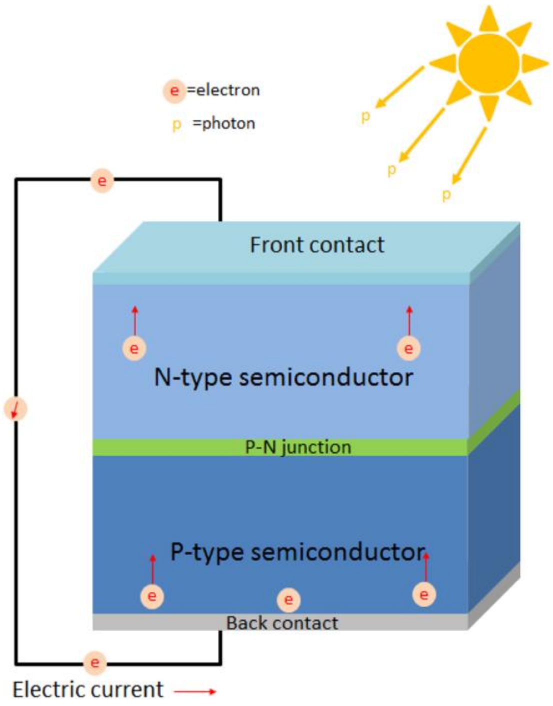

Figure 7: Typical PV cell [40]

The PV module produces a DC current, and if the PV is to supply electricity to a grid, it needs to be converted to AC through an inverter as most grids are AC [41]. PV systems usually require batteries to store energy especially if current needs to be supplied regardless of solar radiation at the moment. When neither inverter nor batteries are in place, a variable-flow pump is often used to account for seasonal fluctuations of solar radiation. The electrical output of a solar panel is determined by solar radiation that reaches the panel, its duration, PV technology in place as well as its dimensions [35]. Solar panel performance also depends on irradiance temperature, shade as well as soiling. PV power plants can be designed for a range of power capacities, from a few watts to several megawatts [41]. The performance of solar cells can depend on conversion efficiency, capacity factor, lifetime and energy consumption during cell manufacture [42]. The modularity of PV systems allows them to be designed with power capacities from a few watts to many megawatts [41, 43].

Solar cells are typically divided into three generations: crystalline silicon (c-Si), thin-film solar cells and third generation solar cells [44]. With more than 90% PV cells made with crystalline silicon (c-Si), it remains the most the dominant material [45]. However, despite extensive research, it continues to undergo changes as researchers and engineers seek to further increase the efficiency and lower the cost of c-Si solar cells [45].

2.2 Solar thermal

Solar thermal technologies extract heat energy from the sun’s radiation. The simplest solar thermal technology involves a solar thermal collector. A solar (thermal) collector absorbs solar radiation and transfers its thermal energy to a fluid passing through [46]. The captured heat is either used in low-temperature heating or is used to drive a heat engine to generate electricity.

For direct heating, flat plate and evacuated tube collectors are the most common kind available in the market today. The flat plate collector is the most common technology for solar powered hot water systems. It consists of a dark flat surface, which absorbs solar radiation and transfers the heat to fluid in the tubes. Thermal insulation and transparent screens are used to minimize heat loss. An evacuated tube collector consists of tubes made of a vacuum layer sandwiched between borosilicate glass layers. The inner tube is coated with a black coating that absorbs solar energy and transfers it to the liquid inside. The vacuum layer minimizes heat loss from the tube. Solar thermal collectors allow heat to be captured in a working fluid such as water, air, oil or CO_2.

CSP is another form of solar thermal technology that is used for electricity generation. It involves the use of mirrors to concentrate sunlight and convert it to heat, which is then used to drive a turbine and generate electricity [47] The two main collectors used in CSP are power towers and parabolic trough collectors. In a CSP system, the collector heats a heat transfer fluid. The heat can be used to drive a turbine or can be stored in a thermal energy storage (TES) system [48]. Two common types of CSP collectors are the parabolic trough (PTC) and the power tower (PT). In a PTC, a highly reflective material in parabolic shape is used to concentrate incident light onto the receiver tube along the focal line. The receiver tube is made of an absorbent material and is covered with a glass tube to minimize heat loss. The fluid inside the receiver tube is heated by the focused radiation thus converting solar radiation into heat [49]. A schematic of a PTC is shown in **Figure 8**.

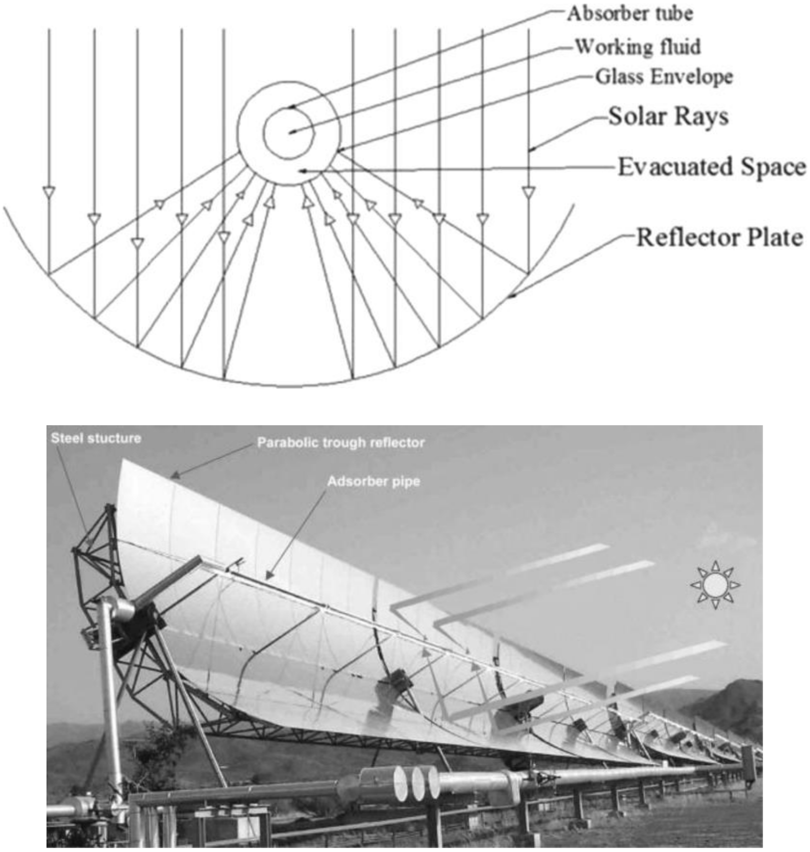

Figure 8: Schematic (top) and photograph (bottom) of a parabolic trough collector (PTC) [50, 51]

The temperature of the absorber tube can go up to 350-400 °C [50], significantly higher than that achievable by flat plate or evacuated tube collectors. Description of other solar thermal collectors can be found elsewhere [49]. The performance of the collector in a solar thermal system, measured by the conversion effiiciency of irradiation-to-heat, depends on the technology used, operating temperature of the collector fluid, ambient temperature and incident irradiation [52].

2.3 Status of solar technologies

According to a report by the International Renewable Energy Agency (IRENA), the global solar installed capacity is almost 391 GW [53], more than 27 times that in 2008, as shown in **Figure 9**. This includes electricity generated from solar photovoltaic and concentrated solar power technologies, although solar PV is the primary contributor.

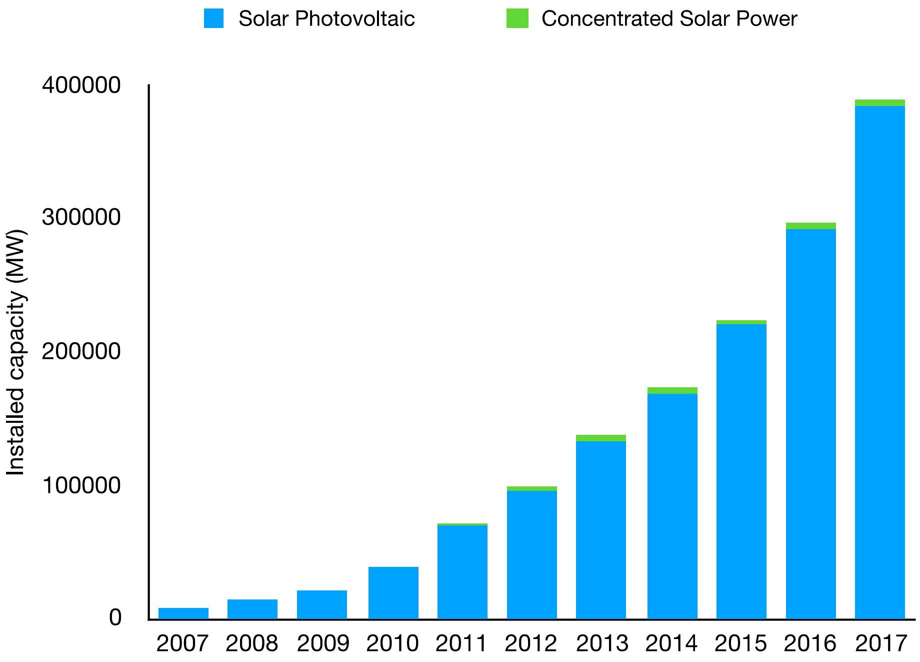

Figure 9: Global solar energy installed capacity [53]

2.3.1 Status of solar PV

The last decade has positioned solar PV as an inexpensive form of renewable energy, with the potential to surpass wind and hydropower as a critical renewable energy resource [54]. Previously, harnessing solar energy through PV was not considered economically feasible. However, rapid technological improvements have driven an 80% decline in the cost of PV modules in the last 10 years [55]. Furthermore, the cost of PV could decrease by a further 59% as compared to 2015 prices, bringing the global average down to \$0.05-\$0.06 per kWh [56]. PV is expected to contribute to 20% of the world's energy supply by 2050 with a 50 % reduction in global CO_2 emissions predicted by 2100 [40]. According to a recent Science for Policy report by the Joint Research Center [57], PV makes up more than 50% of new renewable power capacity installed in 2016, including both large scale and distributed systems. Also, the last decade has seen an increase in the production capacities of Asian countries in addition to the initial dominance of Japan and Europe. As mentioned before, public incentives were a crucial factor in the initial growth of PV, however its economic competitiveness with fossil fuels will continue to drive its growth.

2.3.2 Status of solar thermal

Technology improvements in solar thermal systems have led to recent studies on the feasibility of such systems for industrial heating. Currently, solar collectors have a thermal efficiency between 60% and 75%. The levelized cost of thermal energy (LCOEth) from solar thermal systems is \$0.05 – 0.09 per kWh_{th}, but varies strongly with collector price, efficiency, taxes and government subsidies. **Figure 10** shows a schematic of a solar thermal system for industrial applications [52].

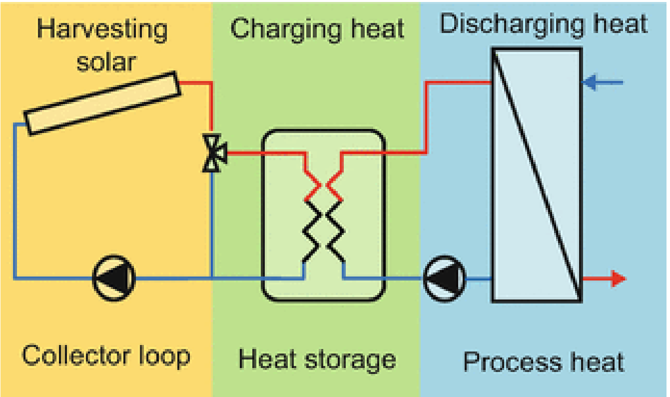

Figure 10: schematic of solar thermal system for process heat applications [52]

Solar thermal systems were previously considered costly as they first require energy conversion from solar thermal to electricity [28]. Thus the optimization of power cycle units which convert solar thermal energy to electricity is a crucial component of solar thermal powered desalination. The organic Rankine cycle (ORCs) is an example of a power cycle commonly used with solar thermal powered desalination processes which require electrical energy derived from solar thermal collectors. An ORC is similar to a conventional steam power plant, except that the working fluid is an organic compound of low boiling point and thus the evaporation temperature is lower [58]. Due to their ability to use low-temperature heat as well as technical maturity of its components, ORCs have seen an increase in medium to large scale (200 – 2000 kW_e) commercial applications [58]. Due to their modularity, the ORCs can be used with several heat sources, including solar energy. Solar organic Rankine cycles (sORCs) are primarily made of solar collectors and thermal energy storage systems. Currently, ORC research involves optimization of fluid and ORC design as well as their compatibility with solar thermal collectors.

As compared to other ORCs, sORCs offer the advantage of reducing carbon footprint while making use of low-temperature heat [59]. The efficiency of an sORC is determined by both the ORC efficiency and the solar collector efficiency. However, with increasing temperature, the collector is subject to higher ambient heat losses and therefore lower collector efficiency, but a higher conversion efficiency in the ORC (Figure 11). Hence, a trade-off between the two efficiencies must be made while choosing the temperature in the collector [60].

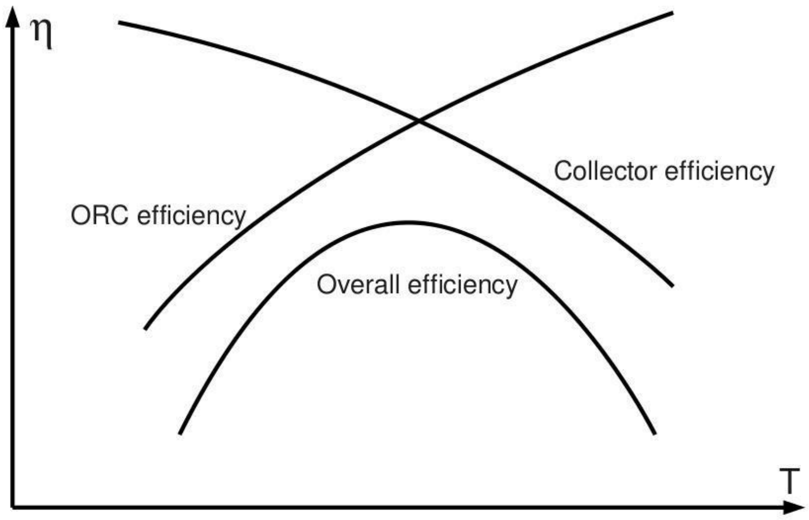

Figure 11: Trade-off between collector and ORC efficiency [60]

Additionally although solar thermal technologies are currently offered by various manufacturers and are technologically mature, the potential of meeting energy demands with solar thermal systems especially in regions with high solar irradiation remains unexploited [15]. Pouyfaucon and García-Rodriguez reviewed solar thermal desalination technologies, and compared distillation and reverse osmosis [28].

2.4 Factors affecting compatibility of desalination processes with solar energy systems

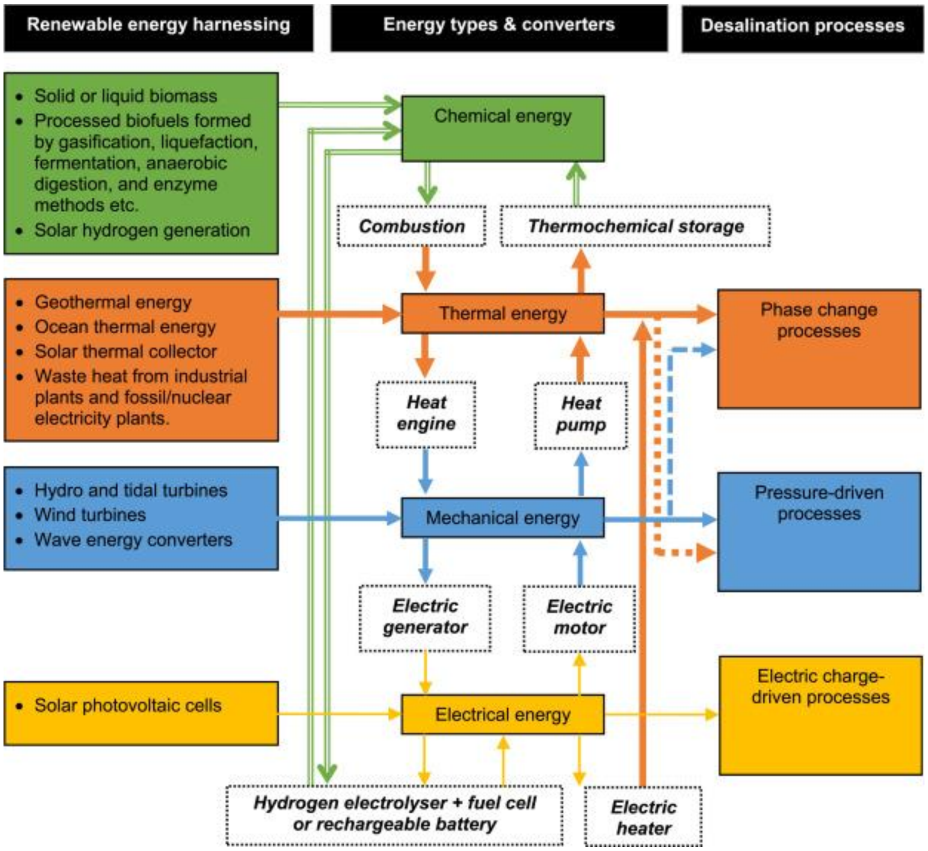

Figure 12: Coupling of RE sources and desalination processes [24]

Factors affecting compatibility of desalination processes with solar energy systems depends on the type of energy required – electrical or thermal. Due to the variable nature of solar irradiation, the performance of the process under intermittent and continuous conditions also plays a part in determining whether energy storage is to be used. This in turn depends on the size of the system as for small systems, energy storage may not be economically advantageous.

In the case of solar thermal technologies integrated with thermal desalination processes, the collector type and power cycle unit are determined by the range of operating temperature required for the process, as well as the power output of the system [46, 61]. **Figure 12** shows the coupling of RE sources and traditional desalination processes [62].

3. Solar desalination by technology

3.1 Direct solar desalination

Solar stills are one of the oldest and simplest forms of solar desalination. In a solar still, saline water is evaporated directly by solar energy and then condenses as distilled water [63]. There are several review articles available in literature focusing on advances in solar still productivity including operating conditions and design configurations [29-31, 33], as well as solar stills with latent heat storage for use in the absence of sunlight [32]. Current solar still designs are still not suited to large systems [64]. Although solar stills are low maintenance and affordable, they suffer from low efficiency and large amounts of heat loss, even for small systems and their productivity is limited [63].

In the last two years however, new materials have facilitated higher solar-to-heat efficiency, once again rendering direct solar desalination a promising technology. We refer to these as new generation direct solar desalination devices, and review developments in this section with respect to solar-to-heat conversion efficiency of advanced materials.

Kim *et al.* deposited a three-dimensional graphene network (3DGN) on wood and found that it provided a solar-to-vapor conversion efficiency of 91.8% and a 5 order decrease in salinity [65]. Adding the graphene network significantly enhanced the temperature at the top surface, which increased solar-to-vapor conversion efficiency, under simulated solar illumination at a power density of 1 kW/m^2. **Figure 13** shows the enhancement in top surface temperature as a result of graphene deposition, which in turn resulted significant efficiency for removal of salt ions.

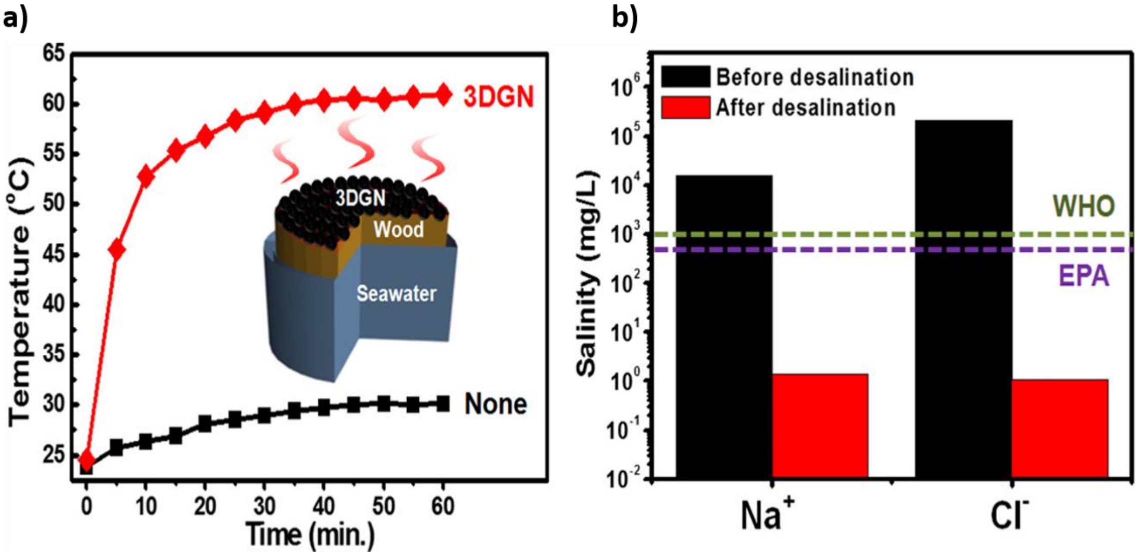

Figure 5: a) temperature of top surface with and without 3DGN-wood on seawater; b) desalination efficiency represented in change in Na+ and Cl- concentrations [65]

At the same time, Jun Yang’s group in Canada also developed a double-network hydrogel from poly(ethylene glycol) diacrylate (PEGDA) and PANi and deposited it on cellulose-wrapped polyethylene (EPE) insulating layer, for a steam generation device. The top layer served as the light-absorbing layer, while the cellulose-wrapped layer provided both thermal insulation and water supply. Their device had an efficiency of 91.5% as a solar steam generator under 1 kW/m^2. **Figure 14** shows a schematic of both devices and operating principle. In short, the top network provides the upper surface made up of photothermal network converts absorbed light to localized heat and evaporation at the surface will make room for more water to pass through via the pores, which is transported to the top before evaporating [66].

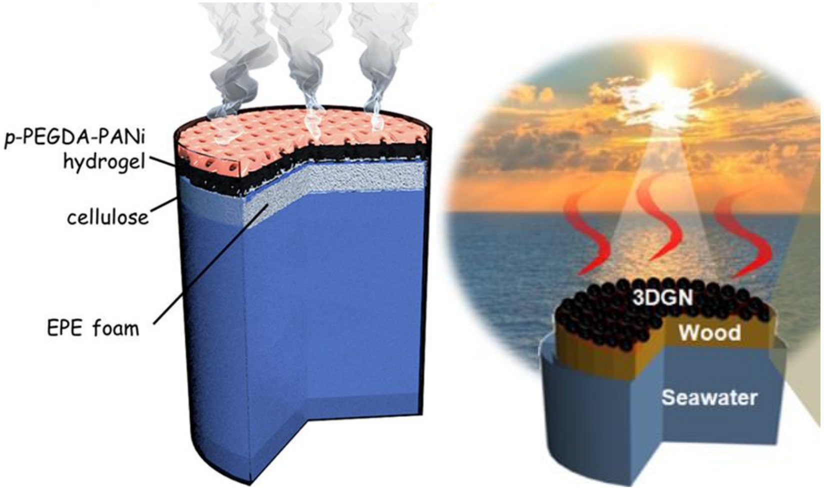

Figure 6: Schematic of Yin group's steam generation device (left), and Jang group's solar desalination/steam generation device (right) [65, 66]

Prior to both studies mentioned above, Liu *et al.* developed a solar desalination device based on graphene oxide-coated wood [67]. The device had a solar efficiency of 83% under an illumination of 12 kW/m^2.

Yu *et al.* fabricated gold nanoparticle (AuNP) films on a nanoporous anodized aluminum oxide (AA) supporting layer and studied the effect of the wettability of each layer on evaporation performance [68]. Interestingly, they found that the surface chemistry of the bottom layer played a more important role in evaporation performance than the light-to-heat conversion layer. A hydrophobic bottom layer was not desirable as the bubbles that formed between this layer and the water limited mass transport and also caused heat accumulation. Bilayer structures made of a photothermal top layer and a thermally insulating bottom layer are able to attain higher energy efficiencies than nanofluid systems due to localized heating effects [69]. Liu *et al.* also developed such a bilayer system with a plasmonic-active filter paper (PP) as the photothermal top layer, and a tripolycyanamide sponge as the insulating bottom layer [69]. However, they were not satisfied with the 70% evaporation efficiency as the bulk temperature rose by 10 C in 900 s, indicating heat loss. In order to reduce heat loss to bulk water, they isolated the PP layer from the bulk water with a polydimethylsiloxane (PDMS) block and air as an insulating material, with a controlled water supply and were able to achieve a faster evaporation rate of 11.97 kg m^{-2} h^{-1}e under 10 kW/m^2, with an evaporation efficiency of 89%. The temperature of the bulk water in the enhanced system only rose by 2 °C in 900s. The enhanced system mimics water transmission and evaporation mechanism in plants (**Figure 15**) and reduces heat loss by reducing the contact area between the photothermal layer and bulk water.

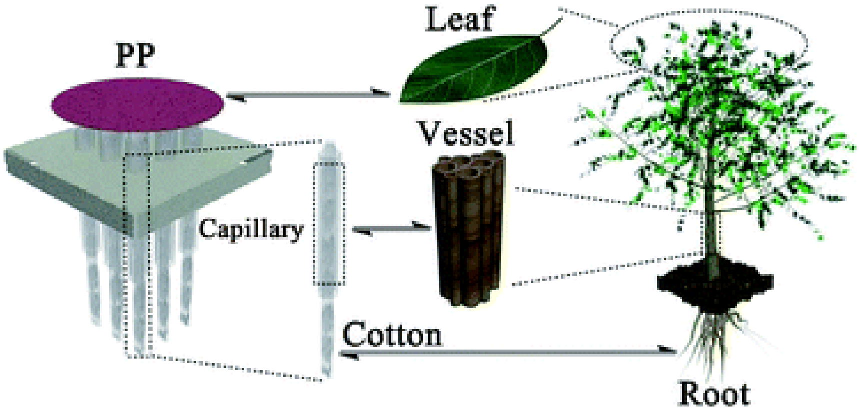

Figure 7: Schematic corresponding bionic system to water transmission and evaporation mechanism in plants [69]

Finnerty *et al.* developed a similar system inspired by the water transpiration of a natural tree [70]. They used to synthetic leaf made out of graphene oxide (GO) which was placed in contact with a water-absorbing sheet. Capillary action caused the water to be transported from the bulk to the leaf using a water-absorbing sheet. When the GO leaf was floating on water, the light-to-heat conversion efficiency was 54%, but when the leaf was lifted above water mimicking a plant, the efficiency increased to 78%. The leaf generated steam at a rate of 2 LMH under an illumination of 0.82 W/m^2. However, when they carried out an experiment with 15 wt. % NaCl, they found severe salt accumulation on the leaf, which could simply be rinsed off. Their study could be built on for potential zero liquid discharge solar desalination.

Shang *et al.* applied porous CuS/polyethylene (PE) hybrid membranes for solar distillation, achieving a 63.9% conversion efficiency from sunlight to heat for evaporation [71]. Apart from effective absorption across the full sunlight spectrum, the membrane had high solar-to-heat conversion efficiency and low thermal conductivity, and could be recycled 20 times. In addition to providing a pathway for cooler seawater to pass through, the microscale porosity also lowers the thermal conductivity, which in turn prevents heat loss.

Zhu *et al.* synthesized black titania nanocages for solar desalination, through a molten-salt-assisted method (**Figure 16**) [72]. The molten salt used was NaCl-$AlCl_3$.

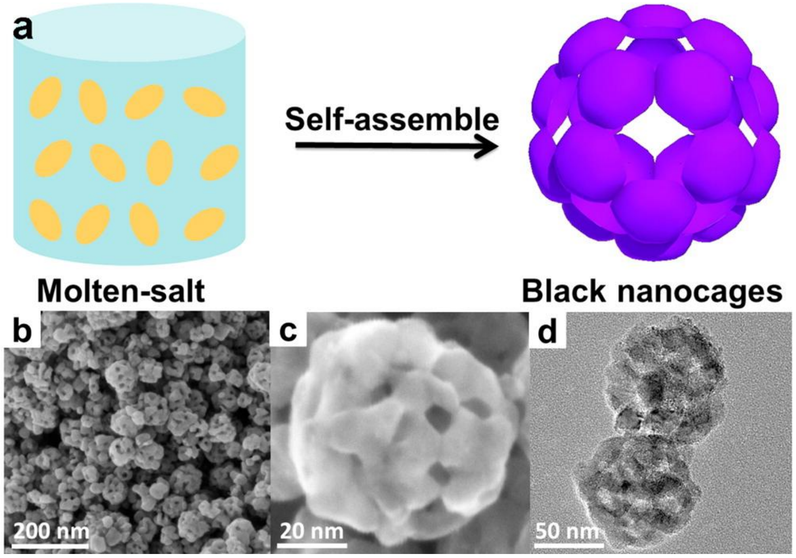

Figure 8: (a) schematic of formation of black titania nanocages; (b, c) SEM images and (d) TEM image of nanocages [72]

They found that the self-floating black titania nanocages had a solar-thermal conversion efficiency of up to 70.9% under 1 kW/m^2. The nanocage structure was made of interconnected nanograins that enhanced heat transfer from titania to water while the small pores (4 – 10 nm) allowed water vapor to permeate. **Figure 17** shows that the black titania was able to remove monovalent, divalent as well as trivalent salts from the water, and retained its solar efficiency for at least 10 cycles. Building on this study, Liu's group applied black titania/graphene oxide nanocomposite films for steam generation and achieved a solar-to-heat conversion efficiency of 69.1 % under 1 kW/m^2.

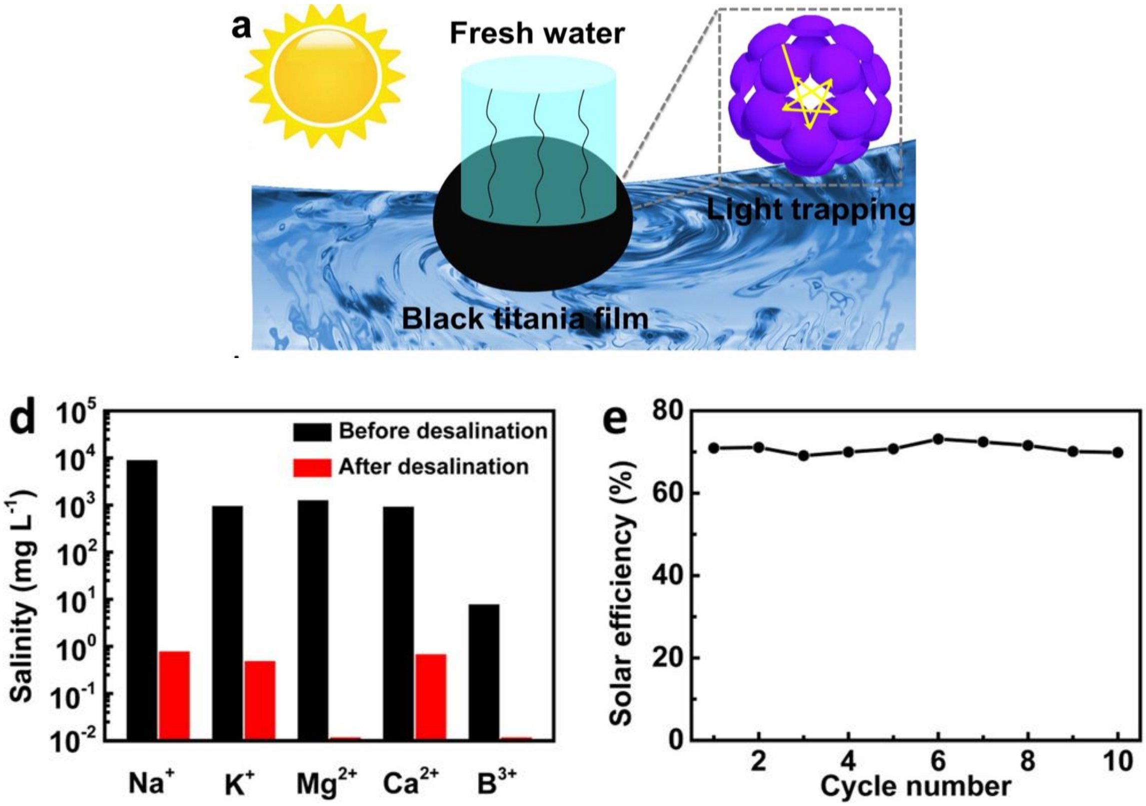

Figure 9: Solar desalination with black titania nanocages; top: principle of operation; bottom: content of salt ions before and after desalination (left), solar conversion efficiency with number of cycles (right) [72]

Zhou *et al.* also demonstrated a plasmon-enhanced direct solar desalination device through self-assembly of aluminum nanoparticles into a 3D porous membrane [73]. Also able to float naturally on water, this device is able to reduce salinity by 4 orders of magnitude and retains its performance over 25 cycles. They used low cost abundant materials, which makes this a feasible option for scaling up.

Table 1 shows selected solar-to-heat conversion efficiencies for materials from recent studies for direct solar distillation.

Table 1: Solar-to-heat conversion efficiencies for selected recent materials and configurations for use in direct solar desalination

Material	**Solar-to-heat efficiency**	**Irradiation**	**Reference**
CuS/PE	63.9 %	1 kW/m^2	[71]
3D graphene network	91.8 %	1 kW/m^2	[65]
p-PEGDA-PANi hydrogel double network	91.5 %	1 kW/m^2	[66]
black titania/graphene	69.1 %	1 kW/m^2	[74]
GO-wood	83 %	1 kW/m^2	[67]
Plasmonic-active filter paper (PP)	70 %	10 kW/m^2	[69]
PP-PDMS leaf lifted above water	89 %	10 kW/m^2	[69]
GO leaf lifted above water	78 %	0.82 W/m^2	[70]
black titania	70.9 %	1 kW/m^2	[72]

It is evident that direct solar desalination is going through a research revival phase, and long term progress in terms of increased productivity and efficiency is expected with the potential of closing the gap between this technology and its large-scale application.

3.2 Indirect solar desalination

Indirect solar desalination is generally divided into thermal and non-thermal processes. Our focus is on reverse osmosis (RO), which is the most dominant non-thermal desalination process.

3.2.1 Reverse osmosis

Reverse osmosis (RO) is currently the fastest growing desalination technology in the world [6], expected to reach a market size of US $9.227 billion by 2022 [75]. Reverse osmosis is a pressure-driven process in which separation occurs through a semi-permeable membrane by the solution-diffusion mechanism. Typical operating pressure for RO varies between 55 to 70 bars for seawater RO (SWRO), and is lower (15 – 30 bars) for brackish water RO (BWRO) [76]. An understanding of the energy consumption in RO plants is crucial in dictating how solar energy is used to power RO. Although the specific energy consumption (SEC) of an RO plant includes contributions from feed-intake facility, pre- and post-treatment as well as brine disposal, it is the membrane desalination section that contributes to 60 – 80% of the SEC [77, 78]. This includes the use of high-pressure pumps, ERDs and membrane trains.

SEC for seawater RO (SWRO) has dropped from 20 kWh/m^3 in 1980 to less than 3 kWh/m^3 [79, 80]. The rise in RO installations is largely due to reduction in energy consumption led by innovations in membrane materials, energy recovery devices (ERDs) and more efficient pumps [77]. Commercial membranes are now able to achieve salt rejections of 99.8% with flux evolving from as low as 0.16 m^3 / m^2 day to over 1.2 m^3/m^2 day over a span of 30 years [81, 82]. Furthermore, research in new chemical compositions for the active layer, modification of membranes with nanostructures as well as improvement in membrane configuration and fabrication techniques can further decrease energy costs [83]. Energy recovery devices (ERDs) make use of the residual energy of the brine to pressurize the feed therefore recovering energy and lowering water production costs [41, 84]. Another important area where reduction of energy costs has been possible is the efficiency of pumps used. Even a slight increase of 2% in pump efficiency can lead to a significant reduction of SEC, especially in the case of high salinity feed [77]. Feed salinity, permeate quality, recovery rate and feed temperature are operating parameters that affect pressure requirements, and in turn energy consumption [85]. Despite improvements, a significant portion of RO costs remains in the electrical energy required to pressurize the feed [86]. The applied pressure can be provided either by electricity, or by using mechanical pumps. Thus, PV and solar thermal technologies are both suitable for supplying energy to RO plants, although in the case of the latter, a power conversion unit or thermal energy driven water pump are needed to pressurize the feed. **Table 2** lists solar powered RO plants along with capacity and solar technology employed. Interestingly, the oldest of these plants only went online in 2011 and the majority only began operating in the last 5 years, indicating recent industrial focus on solar powered RO. Water production capacities vary between 16 m^3/day and 60,000 m^3/day in Al Khafji. Al Khafji is the world's first large-scale solar powered desalination plant, and relies on PV-RO. Although operation was to start in 2017, the plant is behind schedule and still under construction. Both forms of solar energy powered RO, PV and solar thermal (ST), are discussed in the sections below, with an emphasis on energy considerations and current technological status.

Table 2: Selected specifications of currently installed or under construction solar powered RO plants [8]

Plant	**Country**	**Capacity (m^3/d)**	**Online year**	**Feedwater**	**PV or solar thermal**	**Type of collector**
Genesis Solar	USA	3,168	2013	Brackish water (3000-20000 ppm)	CSP	Parabolic trough
Ben Guerdene solar powered BWRO	Tunisia	1800	2013	Brackish water	PV	-
Al Khafji solar-powered SWRO	Saudi Arabia	60,000	-	Seawater (20000 – 50000 ppm)	PV	-
Centro Morelos Solar Power Plant	Mexico	840	2014	Brackish water	PV	-
Baja California Sur IV Solar Power Plant	Mexico	48	2014	Brackish water	PV	-
Beheloke Brackish solar	Madagascar	16	2012	Brackish water	Information not available	-

Arenales Solar Power Plant	Spain	480	2013	Brackish water	Solar thermal (CSP)	Parabolic trough
Olivenza Solar Power Plant	Spain	720	2013	Brackish water	Solar thermal (CSP)	Parabolic trough
Solar, Fortaleza	Brazil	3600	2014	Brackish water	PV	-
Hassi R'mel solar thermal plant	Algeria	1577	2011	Wastewater	Solar thermal	Parabolic trough
California Valley Solar Ranch Water System (CVSR-WS)	USA	75	2012	Brackish water	PV	-
Qatar Solar Technologies Polysilicon Project, Ras Laffan	Qatar	12,000	2013	Seawater	PV	-
Solar-powered SWRO plant, Aniwa Island	Vanuatu	96	2013	Seawater	PV	-
Solar-powered	Vanuatu	96	2013	Seawater	PV	-

SWRO plant, Ambae Island						

3.2.1.1 PV-RO

PV powered reverse osmosis (PV-RO) has emerged as a mature and commercially available technology, with the very first projects combining the two technologies having come into existence in the 1980s [41]. A schematic of a PV-powered RO system is shown in **Figure 18**.

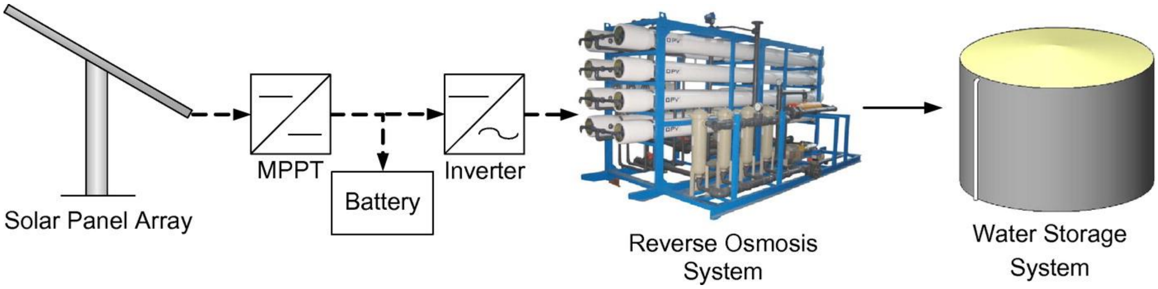

Figure 18: A schematic of PV operated RO system which includes an RO system, a water storage system and a solar panel array equipped with a maximum power point tracker, a battery and an inverter to convert the variable DC output from PV to AC [87]

The feasibility of PV-RO systems depends not only on variation in solar insolation, but also on type of source water being used, size of system, as well as government policies [88]. However, wider applicability of PV-RO on both large-scale and small-scale still remains limited by high energy costs, which needs to be addressed by improving the energy efficiency of PVRO systems. According to a review by Shalaby, SEC for experimental PV-RO desalination systems vary between 1.1 and 16.3 kWh/m^3, depending on system size, use of batteries, feed source (seawater or brackish water), pretreatment and type of ERD, if any [89].

To address energy efficiency, researchers have considered each of the two components separately [61] while very few studies focus on improving the coupling of PV and RO. For PV, the issue of solar energy being a variable energy source still needs to be tackled through the development of more affordable energy storage devices, or batteries. In RO systems, the energy efficiency of RO is further improved through the better performing membranes, more efficient ERDs and pumps. Improved process design also plays an important role in increasing the efficiency of RO systems, and has been addressed by many researchers recently [90-92].

Raval and Maiti introduced a simple yet innovative concept to improve the efficiency of both PV and RO by capturing thermal energy from the PV panel and using it to heat flowing feed water, simultaneously lowering the temperature of the PV module and increasing the temperature of the RO feed [93, 94]. They found that the energy consumption can be reduced by up to 28% as a result of the effect of temperature on PV modules and on RO productivity. The temperature of the feed water increases membrane flux at a rate of 3% per degree [95]. On the other hand, the electrical efficiency of PV has an inverse relationship with temperature, whereby a higher temperature is less desirable [96]. For crystalline silicon PV cells, the drop in efficiency is 0.2-0.5% for degree rise in temperature [97]. They were able to increase water output by 20% in the modified system [93]. Soon after, they also tuned membrane morphology to increase permeate flux and found that the combination of heat transfer from PV to RO feed and improved hydrophilicity reduced energy costs by about 40% [94]. While applying such techniques to plant design, consideration should be taken on the possible adverse effects of warmer feed water. Warmer water often aggravates biofouling as it promotes the growth of bacteria on the membrane surface. Additionally, along with water permeability, warmer feed temperature also increases salt permeability resulting in lower quality permeate [98].

3.2.1.1.1 Novel membranes and configurations for PV-RO

There have not been any studies in the last 4 years catered specifically to novel membrane materials and modification for PV-RO systems, although there have been several advances in RO materials in general [99-105], especially materials for anti-fouling [106, 107] that could be extended to PV-RO as well as solar thermal powered RO systems. Alghoul *et al.* optimized a small-scale 2kW PV-RO system for BWRO and reduced the SEC to 1.1 kWh/m^3 for a PV-RO unit operating under a load of 600 W using a commercial membrane in a two-stage configuration, with battery [108].

To lower RO energy costs, Chaabene *et al.* designed a PV-HEMRO system in which they incorporated a hydro electromagnetic (HEM) process reduce salt concentration by a factor of 30% prior to RO [109]. HEM was essentially applied as a pretreatment process in which the electromagnetic strength allowed separation of cations and anions, reducing salt concentration and lowering the pressure requirement for RO.

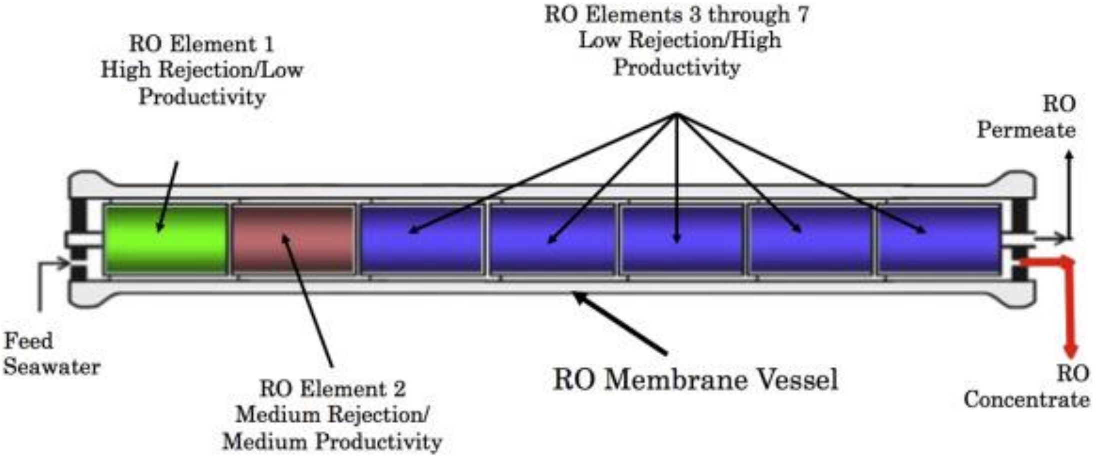

Figure 19: Hybrid membrane configuration [110]

The potential use of hybrid membrane configuration i.e. membrane elements of varying productivity and rejection in a single vessel has also been described by Voutchkov in detail as an alternative for reducing RO energy costs [110]. In conventional SWRO systems in which the same membrane elements are used, the first membrane produces 25% of the permeate and also uses 25% of the energy available, making energy distribution in the vessel uneven. This also results in the first element being most affected by fouling, while the remainder are more prone to concentration polarization as the feed salinity increases progressively. **Figure 19** presents a hybrid membrane configuration, known as a Hybrid membrane Inter-stage Design, in which a more even flux distribution can be attained using a combination of membranes varying between high permeability/low salt rejection, medium permeability/medium salt rejection and low permeability/high salt rejection [110-114]. This lowers the productivity and energy consumption of the first element allowing a more even flux distribution through the vessel. Such a hybrid membrane configuration has yet to be used in conjunction with solar energy. Other possible approaches in terms of plant design that can lead to reduced RO energy consumption for PV-RO as well as ST-RO systems include the use of three-center RO system design, low-recovery plant design and a split-partial two-pass RO system design, and are described in [110, 115, 116]. The choice as well as placement of the high pressure pumps are critical in predicting the energy efficiency of RO systems [83, 110, 117], although a survey of literature will show that PV-RO studies have focused more on investigating types of ERDs than high pressure pumps required for RO.

3.2.1.1.2 Energy recovery devices

The largest contributor to energy consumption and operating cost in RO systems is the high-pressure pumps. Until ERDs were first introduced in the 80s [118, 119], much of the energy used to pressurize the feed would leave the system with the brine. Recovering this pressure energy carried by the brine flow using ERDs could lead to significantly lower energy demands of a PV-RO system, especially for SWRO where large amounts of pressure are applied. The first ERDs used for SWRO had an efficiency of 77%, but introduction of newer designs led to efficiency improvements whereby newer pumps can reach efficiencies of up to 97%, resulting in energy savings of up to 40% [120]. ERDs are generally of two types: centrifugal and isobaric. Francis turbines, Pelton wheels and turbochargers constitute the first generation or centrifugal ERDs. These are limited in capacity and lower efficiencies than isobaric devices. On the other hand, isobaric ERDs which include piston-type work exchangers and rotary pressure exchangers (PX) are capable of unlimited capacity and efficiencies of about 97-98% [121-123]. The four most commonly available commercial ERD technologies are: Pelton turbine (PT), pressure exchanger (PX), axial piston motor (APM) and the Clark pump, also known as pressure intensifier (PI), each suitable for a different minimum brine flow rate as indicated by Rheinländer and Geyer [41]. Among these, the PT is of the centrifugal type while the remaining are isobaric devices. Dimitrou *et al.* found that both Clark pump and axial piston motor pump resulted in significant energy reduction for small-scale SWRO in part-load conditions, which are suitable for use with PV systems [124].

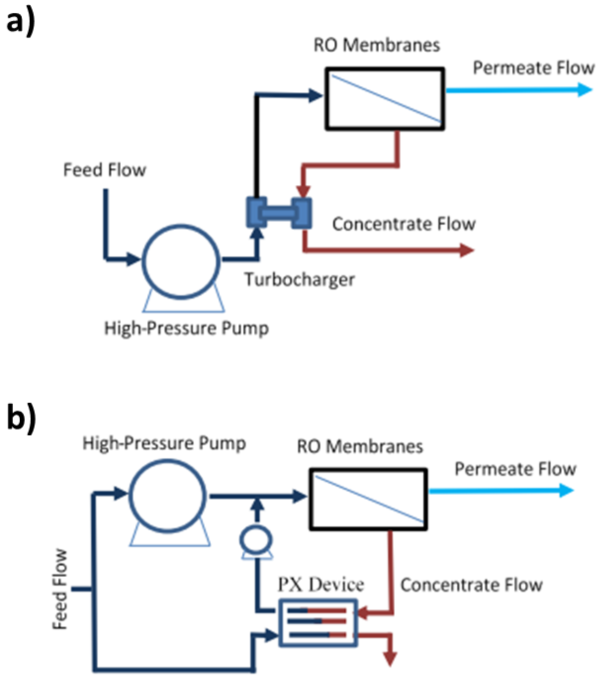

Figure 10: Flow diagram for an RO system with a) pressure exchanger, and b) turbocharger type ERDs [125]

Among commercially available isobaric technologies, pressure exchanger devices are said to offer several advantages including modularity, scalability, low maintenance, reduction of high pressure pump requirements and lower payback time [120, 121, 126-128] are available from various manufacturers. PX recovery devices allow the pressurized brine to come into contact with low-pressure feed such that the energy of the brine is transferred at high efficiency (**Figure 20a**) [125, 129].

Jones *et al.* modelled a PV-RO system for brackish water desalination in Jordan to evaluate the economic feasibility for agricultural purposes, without batteries [129]. Using solar irradiation data from Jordan, they found that the addition of a pressure exchanger type ERD lowered the water unit cost of a single stage PV-RO system, although a two-stage system without recovery resulted in the lowest cost (**Figure 21**).

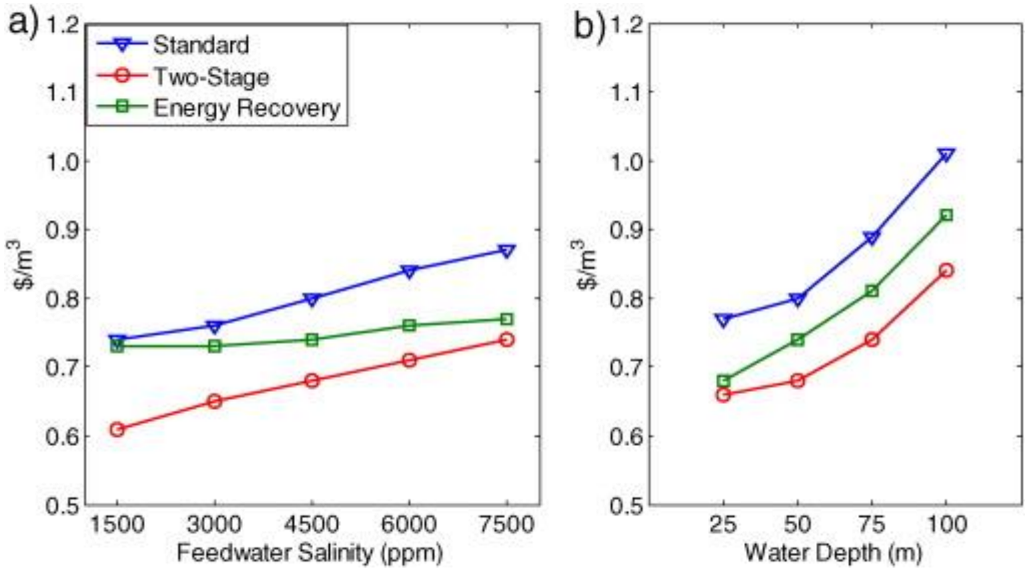

Figure 11: Water unit cost of modelled PV-RO system in Jordan [129]

Romero studied a PV powered BWRO desalination facility in Indonesia and found that small systems with ERDs are not economically feasible as ERDs significantly add to the cost of water produced [130].

The world's first large-scale PV-RO plant, Al Khafji solar powered SWRO, is also to use PX technology supplied by Energy Recovery Inc. (ERI) [8], as part of a $1.4 million contract [131]. ERI has supplied their PX ERDs to over 600 RO plants currently online or under construction, with capacities ranging from 100 to 140,000 m^3/day [8], resulting in significant cost savings [132]. The only PV-RO plant currently online for which an ERD supplier is available in literature is the Qatar Solar Technologies Polysilicon Project in Qatar, with a capacity of 12,000 m^3/d. This plant went online in 2013 and uses turbochargers provided by Fluid Equipment Development Company (FEDCO) for energy recovery [8]. The turbocharger is a type of centrifugal ERD [133], which although not as efficient as isobaric devices [121], are inexpensive and easy to implement. Turbochargers consist of a hydraulic turbine that transfers the energy of the brine to feed stream through a rotor (**Figure 20b**) [125, 129]. Even from the two examples of currently existing PV-RO plants with ERDs, there has been a shift from traditional centrifugal devices to high-efficiency PX devices. The use of ERDs in PV-RO systems is still far from its potential, and it is proposed that incorporation of high-efficiency ERDs will be an important factor in reducing system costs and, as a result, increasing installation of more medium and large-scale PV-RO plants.

3.2.1.1.2.1 PRO as an energy recovery process for RO

Pressure retarded osmosis (PRO) has also been considered for energy recovery in RO systems [134], sometimes in addition to other ERDs [135], and can be exploited for PV-RO. PRO is a process in which water passes through a membrane from a low-salinity solution into a high-salinity solution and power is generated by using a hydroturbine to claim the energy of the pressurized permeate [136, 137]. Although the Norwegian state-owned company Statkraft opened the world's first PRO prototype installation in 2009, their efforts in expanding the technology was discontinued largely due to unavailability of affordable and high-performing PRO membranes [138]. Energy Recovery is working with a Seoul-based global company on a pilot facility for furthering PRO using their pressure exchanger technology, making PRO development a particularly interesting area to monitor [139]. Additionally, the development of novel membranes for PRO has been a subject of interest for researchers in recent years [140-145]. More research into PRO and particularly the development of efficient membranes is needed before it can be considered as a viable source of energy recovery for PVRO systems. Only one known group has attempted to apply PRO to PV-RO system to date, in which [146]. In their study, Wu *et al.* used mathematical models to compare stand-alone PV-RO system with and without PRO and found that PRO increased annual production by more than nine times compared to PV-RO alone. However, they also cited concentration polarization and reverse solute permeation as factors reducing the performance of PRO power generation [146].

3.2.1.1.3 Are batteries a viable solution to PV-RO?

Despite its abundance, availability of solar energy is season and location dependent. Its intermittent and unreliable nature had traditionally deterred it from competing with more conventional energy sources, but solutions are now widely available in the form of energy storage systems [147]. In order to deal with the variation in solar radiation, the system needs to be adjusted in order to maintain maximum water production [148].

However, what impact do such systems have on overall cost of solar powered RO? How do different energy storage devices?

Freire-Gormaly and Bilton recently investigated the effect of intermittent operation on membrane permeability and scaling for PV-RO of brackish water [149, 150] in an attempt to better understand the effect of the variability of solar energy on PV-RO operation. They found that intermittent operation increases the rate of membrane fouling, which was observed through membrane permeability and membrane autopsy. In their work, they used Dow Filmtec BW30 membranes for brackish water RO (BWRO) and studied the effect of using an anti-scalant and of rinsing prior to shut-down on membrane permeability.

Figure 22 shows the performance of the membrane through six days of operation for the different experimental operating conditions. The membrane that was used in intermittent operation with anti-scalant and rinsing showed superior performance with permeability reduced to 87%, whereas in the case of continuous operation with anti-scalant, permeability declined to 30%. On the other hand, for all remaining operating conditions, permeability severely declined to almost zero due to membrane fouling [149]. This experimental study provides motivation for the use of batteries in PV-driven systems to ensure continuous operation, as well as optimization of operating conditions and implementation of procedures such as rinsing to improve membrane life.

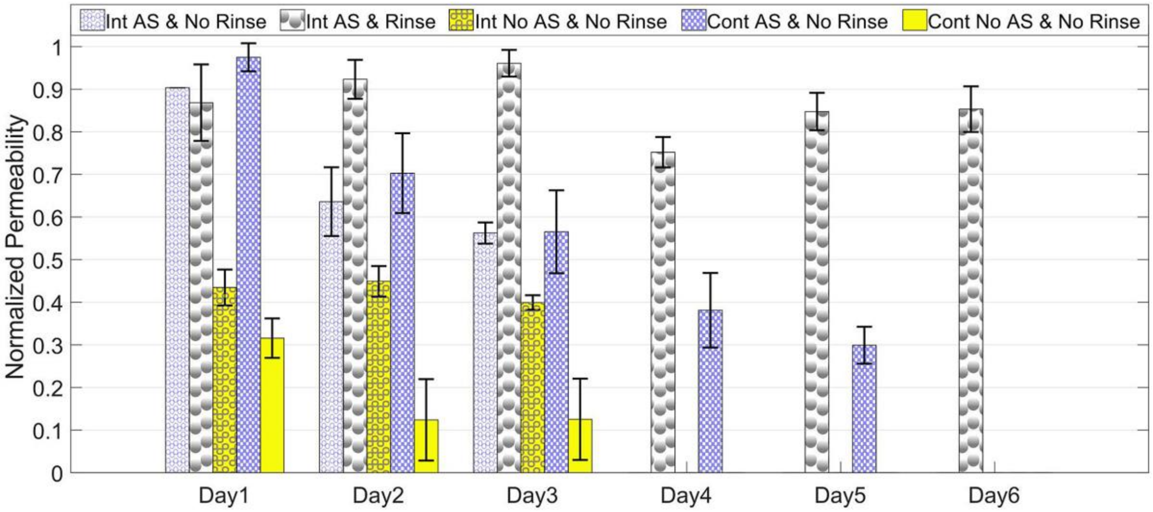

Figure 12: Comparison of permeability for five different operating conditions. Graph shows that permeability retained high after six days of operation only in the case of intermittent use with anti-scalant and rinse [149].

Bilton *et al.* modelled PV-RO for small communities (10 m^3/day) with batteries to make up for the intermittent energy supply, and found that PV-RO with lead acid batteries was far more cost effective than a similar sized RO system run by either a diesel generator or on a combination of wind and diesel [87]. Wu *et al.* recently optimized the design of stand-alone RO system driven by PV and diesel generator hybrid system and found that a system consisting of PV/diesel/battery/reverse osmosis is more economically and environmentally beneficial than a system driven solely by diesel or by PV [151]. Similar findings were concluded by Ghermandi's review on solar-driven desalination with reverse osmosis, when they compared the cost effectiveness of several plant designs that used PV or solar thermal along with diesel [117].

Elshafei *et al.* compared directly driven battery-less PV-RO to a conventional system with PV, charge controller and battery. They found that the battery-less system had greater water productivity per day [152]. In another study, Kim *et al.* compared the unit cost of water produced for PV-RO of high salinity seawater with and without battery storage for a production capacity of 150 m^3/day [153]. Interestingly, they found that the unit cost of water was 30% less for the battery-backed system, owing mainly to initial investment costs. Monnot *et al.* developed a high-recovery design for small-scale PV-RO system with a capacity of 5 m^3/day and considered the effect of using a battery [154]. The optimized design used a battery and had a 65% recovery rate, which was made possible using a dual stage RO plant. They noted that the extra cost of using the battery was compensated by reducing the number of RO modules in the battery-backed system. Additionally, further reductions were obtained through the use of PX as an ERD, bringing SEC down to less than 3 kWh/m3, which is significant for such a small-scale system [154]. Karavas et al. experimentally investigated a PV-driven SWRO system based on a DC microgrid [155]. The system employs hydraulic energy recovery and short-term electric energy storage using hybrid capacitors. They found that energy storage increased water productivity and also allowed continuous operation regardless of insufficient solar irradiation [155].

Although it is possible to address insufficient solar radiation by using batteries, they can significantly increase operation cost [148] However, sizing the battery charging system requires consideration of several factors such as battery storage capacity, desalination load, required PV rating, daily power output as well as estimated PV array size [156].

3.2.1.2 Solar thermal RO systems

In solar thermal RO (ST-RO), thermal energy is first collected by solar collectors and is transferred to a power conversion unit (PCU) and/or thermal energy storage system. The PCU, usually made of a power cycle, produces mechanical or electrical power which is used by the RO plant [46]. Much of the focus in solar thermal powered RO recently has been diverted to improving overall system efficiency with the aim of increasing the contribution of solar thermal technology to global RO installations.

Similar to PV, the commercialization and large-scale installation of ST-RO depends on the SEC of the system, which in turn is a function of the SEC of each system alone – the solar thermal collector and power cycle, and the RO system. Since factors affecting RO have been discussed in the section above, this section focuses on the solar thermal system.

The most common types of solar collectors used in ST-RO are power towers and parabolic trough. Giwa designed a model for thermosiphon-powered RO which could be used with solar collectors [157]. Thermosiphoning is a heat exchange approach that makes use of the natural density differences between fluids of different temperature [157]. They found that the water produced through this system would only be economically feasible if other RO costs were significantly reduced [157].

Among power cycles, ORCs have gained attention among researchers for ST-RO systems. This is because when coupled with RO, ORCs can use the colder feed water as a heat sink, which also causes heating of the feed and improves membrane flux [158]. As described in Section 2.3.2, a solar ORC consists of a solar collector and a Rankine cycle. Other potential power cycles that can be used in solar thermal systems include steam Rankine cycle, Stirling engines and Brayton cycle. However, the simplicity of the Rankine cycle makes it an appropriate choice for ST-RO systems and it is the most highlighted power cycle for ST systems in recent years. Although ORCs are widely applied for waste heat recovery and geothermal power, their use in solar applications has only recently augmented [159].

Recent studies on the optimization of solar organic Rankine cycles to increase their efficiency [160, 161] are likely to play a huge role in opening up prospects for scaling up of ST-RO systems. In fact, Garcìa-Rodrìguez and Delgado-Torres have found that ST-RO systems powered with sORCs consume less energy per cubic meter of water produced when compared with solar distillation and PV-RO [162].

Advances in solar thermal power cycle design and efficiency [163] will prove to be crucial in opening up prospects for scaling up ST-RO. The efficiency of the sORC is also dependent on its individual components, namely the efficiency of the solar collector and the efficiency of the ORC, which in turn depends on variables such as choice of working fluid, operating temperature, etc.

Some studies have also focused on comparing PV-RO to solar thermal RO. When Manalokas compared PV and sORC integrated with RO, they found that the cost of the sORC system was more than twice that of the PV-RO system [164]. However, more recently when Patil *et al.* compared the levelized cost of electricity (LCOE) from PV and sORC with energy storage for a production capacity of 50 kW, they found that LCOE for the sORC is actually 27% less than that with PV. In both cases, parabolic trough collectors were used for the sORC. The conflicting results could be due to the presence of energy storage as well as different production capacity in each study. This highlights the need for further research in assessing the techno-economical competitiveness of solar thermal technologies in comparison to PV, especially for powering RO plants.

3.2.2 Membrane distillation

Membrane distillation is a thermally driven separation process in which a temperature difference is applied across a porous hydrophobic membrane. The resulting vapor pressure difference drives vapor molecules to pass through the membrane and condense on the permeate side (**Figure 23**). Apart from desalination, MD is applied to separation of pharmaceutical compounds, juices, dairy compounds, as well as treatment of oily wastewater [165]. In areas where solar energy is available all year round, membrane distillation could prove to be an economically competitive desalination technology [166].

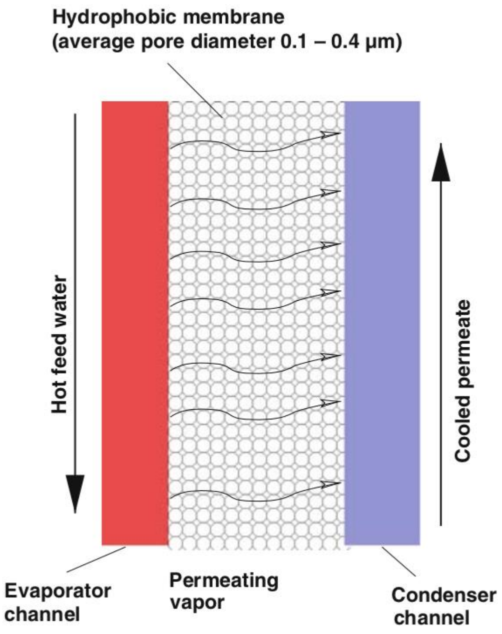

Figure 13: Principle of operation of DCMD [167]

Based on the growth rate of publications in MD, Thomas *et al.* identified three phases in the development of MD systems, namely initiation 1970 – 1990), emergence (1991 – 2010) and growth (2010-2016) and found that significant funding went into solar-powered MD, which accounted for close to 7% of publications in the emergence phase [168]. Hogan *et al.* published one of the first studies discussing the feasibility of a solar powered membrane distillation plant in rural areas [169], hence garnering interest for future studies. As Thomas *et al.* have highlighted in their review, many research projects on solar powered MD were funded by the European Commission during the ‘emergence’ phase, resulting in pilot plants in several countries including USA, Saudi Arabia, Singapore, Australia, Mexico, Spain and China [168, 170]. Some of these projects are listed below:

- SMADES: SMAll-scale, stand-alone DEsalination system (2003)
- MEMDIS: Development of stand-alone, solar thermally driven and photovoltaic-supplied desalination system based on innovative membrane distillation (2003)
- MEDESOL: Seawater Desalination by Innovative Solar-Powered Mem- brane Distillation System (2006)
- MEDIRAS: MEmbrane DIstillation in Re- mote AreaS (2008)

For a more detailed description of these projects and how they fared, the reader is referred to [168, 171]. Although there are also several simulation studies evaluating the feasibility of different solar MD systems [172], slow development and the still high LCOW from SPMD has hindered technology maturity and prevented large-scale plants from being conceptualized. In their review, Zhang *et al.* also comment on the productivity of solar MD pilot plants [27]. This section provides a cost comparison between solar powered MD and other technologies, and then focuses on new developments in nanostructured photothermal materials for solar powered MD. A cost process model for solar powered MD is shown in **Figure 24**.

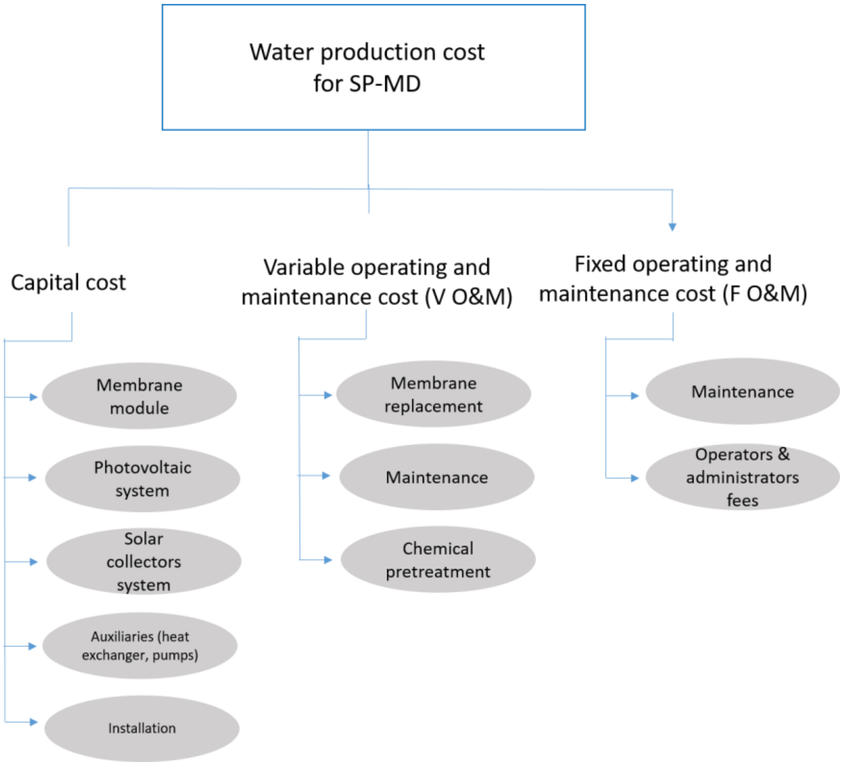

Figure 14: water production cost model for solar powered MD [173]

Moore *et al.* developed a process model to simulate a solar powered sweeping gas MD system powered by both solar thermal and PV [174]. They found the cost of water for an optimized system to be $85/m^3. However, other studies have shown the cost of air gap MD to be as low as $5.16/m^3 owing to increased energy efficiency.

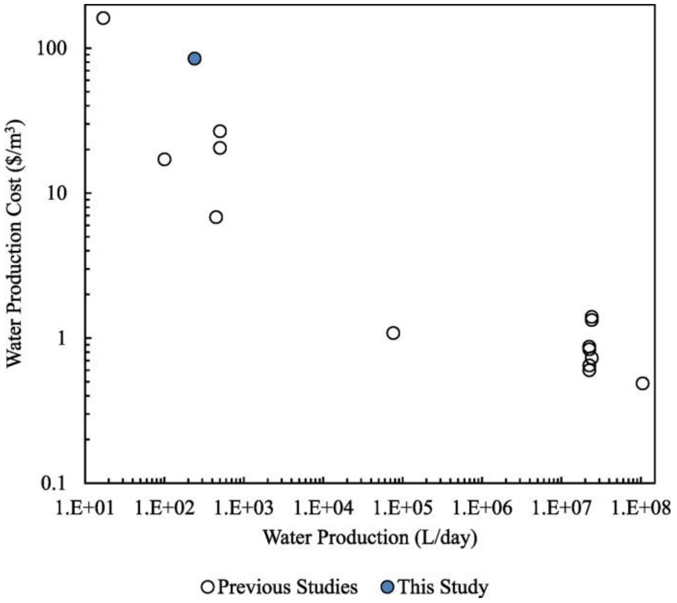

Figure 15: Comparison of reported MD water production costs as function of production volume per day (adjusted for inflation) [174, 175]

Figure 25 shows water production cost as a function of production volume for different MD studies, although these include systems with varying configuration, energy source and cost models. **Table 3** shows a comparison of levelized cost of water (LCOW) from conventional SWRO and solar powered MD. It can be seen that the LCOW from solar powered MD is still a long away from being economically competitive. However, breakthroughs in lowering thermal energy requirements through energy efficient membranes and MD systems are expected to lead to reduced LCOW in future. It should be noted that these values vary with plant size, geographical location, source of water, etc. LCOW for various MD technologies powered by solar energy is shown in **Table 3**.

Table 3: Comparison of LCOW from solar powered desalination technologies to conventional SWRO [11, 174]

Desalination technology	**LCOW ($/m^3)**	**Ref**
SWRO	1.25	

Solar powered MD	5 - 85	[168]
Hybrid energy systems - **PV-diesel RO**	1.59 - 2.39	[151]

Table 4: Estimated cost of water from different MD systems [168, 173]

MD technology	**LCOW (\$/m^3)**	**Year**
MD-solar	15-18	2008
AGMD-solar	18	2011
DCMD-solar	12	2011
VMD-solar	16	2011

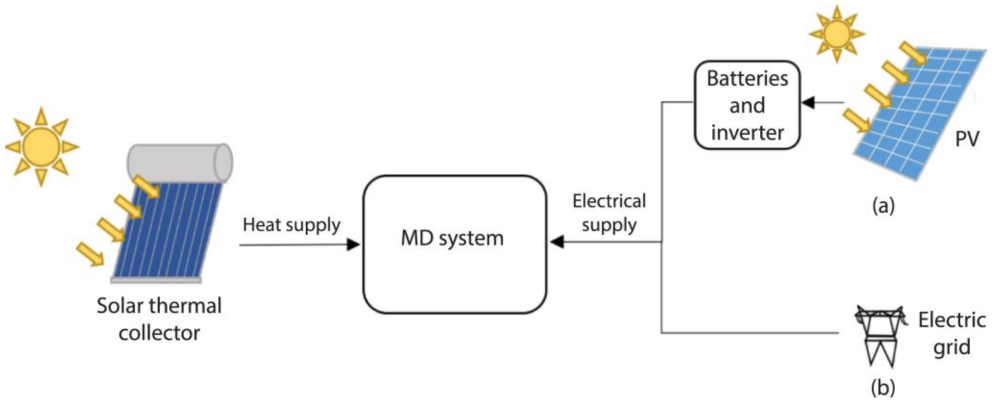

Figure 16: Schematic of a solar-powered MD system in (a) stand-alone, and (b) assisted ways [170]

Solar collectors typically used to provide thermal energy to MD processes are flat plate collectors, evacuated tube collectors, parabolic concentrators, or salinity-gradient solar ponds. Solar ponds have very low thermal efficiency (up to 20%), and are prone to challenges such as salt transport across zones [176]. Pumps and other electrical devices use energy either supplied by the grid, known as the assisted way, or from solar PV collectors, known as the stand-alone way [170]. A schematic of a solar-powered MD system in both ways is shown in **Figure 26**. Additionally, depending on whether the salty water is used directly in the solar thermal collector or heated via a heat exchanger, the system is single-looped or two-looped, respectively (**Figure 27**) [170]. The two-looped system increases the operation life of the system as direct circulation of salty water may cause corrosion [177].

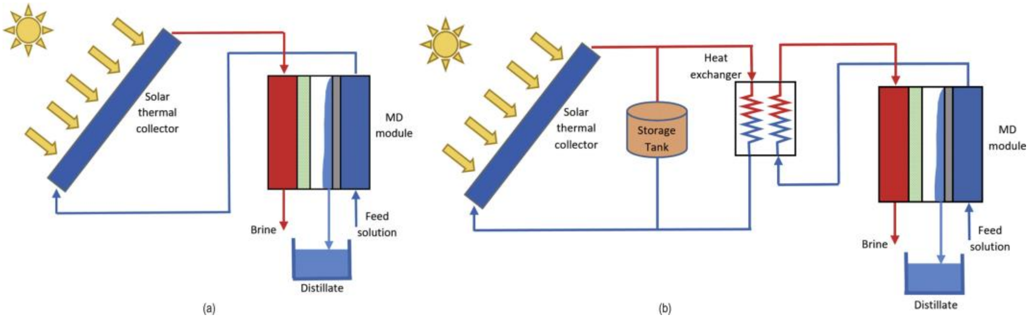

Figure 17: Solar-powered MD system: (a) single-loop, and (b) two-loop [170]

3.2.2.1 Photothermal materials for solar powered MD

The photothermal conversion efficiency in the collector is a crucial parameter in the performance of the resulting solar powered MD system. Photothermal materials convert light to heat (as shown in **Figure 28**). Materials used for photothermal solar conversion in particular are ‘absorber’ materials with high absorptance across the solar spectrum, i.e. wavelength of 250 – 2500 nm [178]. These typically include metals, semiconductors as well as combinations of organic-inorganic and metallic semiconductors [178].

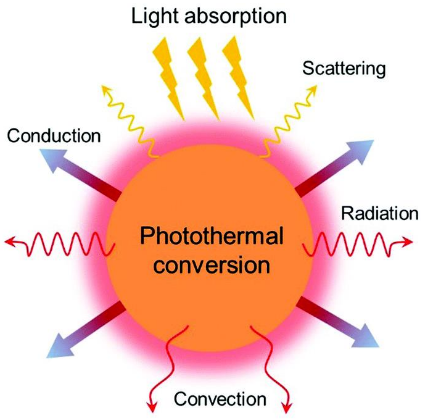

Figure 28: Photothermal conversion [178]

The most recent revival of solar driven desalination has been brought about by advances in nano-enabled photothermal materials, as reviewed by Peng Wang [179]. Membrane distillation is the focus of many recent and current studies using photothermal nanoparticles, with the aim of reducing thermal energy requirements that contribute to up to 70% of the total MD system cost [168].

Nanofluids, which are suspensions of nanoparticles, have lately attracted attention as heat transfer fluids for their high ability to absorb solar energy and thus increase solar absorption efficiency [180-183], and researchers are in the early stage of evaluating how nanofluids could enhance the efficiency of solar powered MD systems. Metals, carbon-related nanoparticles and metallic oxides/nitrides are common precursors for nanofluids.

Zhang *et al.* incorporated nanofluids to increase the solar energy utilization efficiency in solar powered MD [184]. They identified TiN as the optimal nanofluid based on optical transmittance data. They found that increasing the concentration of TiN from 0 to 100 mg/L in 35000 ppm NaCl feedwater increased the flux by a factor of 1.57 and enhanced the utilization efficiency from 32.1% to 50.5%. This is a result of the increase in feedwater temperature brought about by incorporating TiN nanoparticles, as can be seen in **Figure**

29. This increased feed temperature increases the temperature difference between the feed and permeate and thus increasing the driving force for MD. They also confirmed that the permeate did not contain any TiN nanoparticles, which could have been a cause for concern.

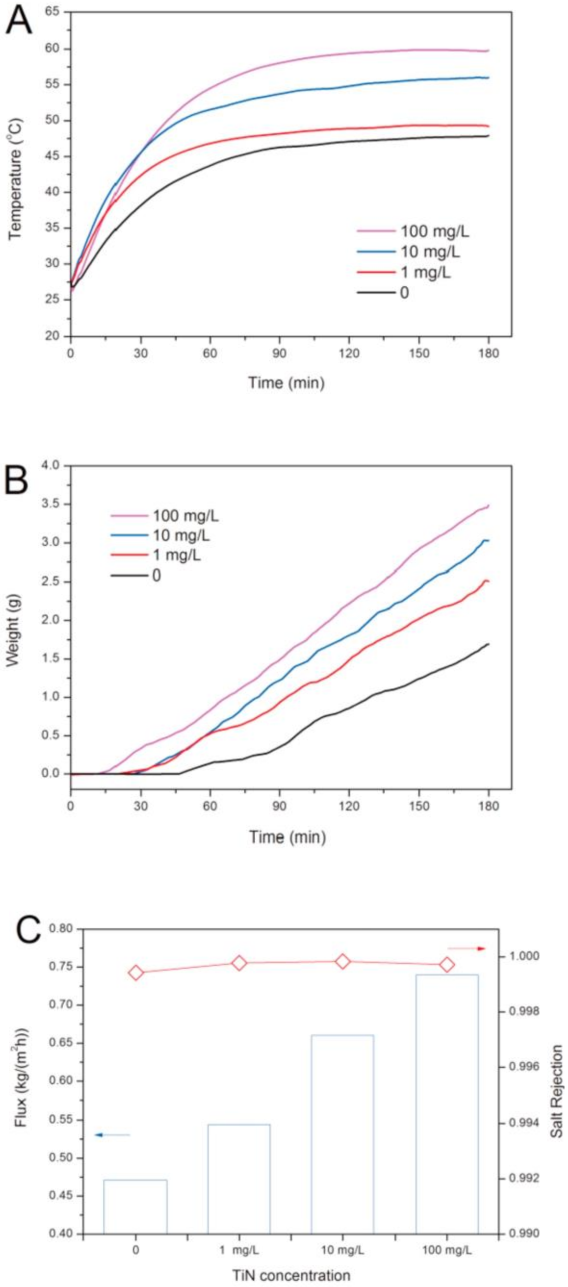

Figure 29: Effect of TiN nanoparticle concentration in 35000 ppm NaCl on (A) feed temperature, (B) permeate weight and (C) flux and salt rejection [184]

The effective driving force in membrane distillation is, however, the temperature difference between the two surfaces of the membrane, which is always less than the temperature difference between the bulk feed and permeate due to temperature gradient in the fluids. This phenomenon is known as temperature polarization [185]. In the case of using photothermal materials to improve MD performance, it then makes sense to induce such localized heating at the membrane surface, rather than in the bulk solution, as shown in the schematic in **Figure 30** [179].

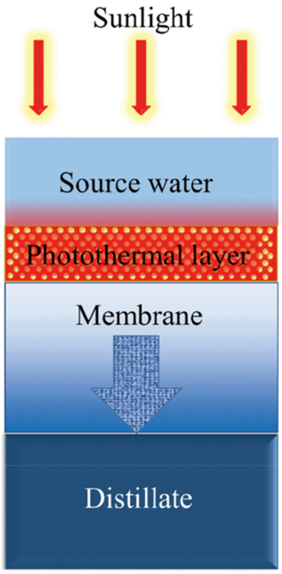

Figure 18: Design of MD integrated with photothermal layer [179]

This concept of nanoparticle-assisted solar vaporization has been explored by Qilin Li's group at Rice University. Their group's project on 'nanophotonics-enabled solar membrane distillation' is one of 14 solar thermal desalination projects to have received funding from the U.S. Department of Energy in June 2018 [186]. They first demonstrated the use of carbon black nanoparticles (NP) embedded in electrospun polyvinyl alcohol (PVA) and deposited on a conventional PVDF MD membrane (**Figure 31**) [187]. The localized heating increased membrane surface temperature on the feed side and reduced energy requirement. They obtained a flux of 5.38 kg/m^2 h and salt rejection of 99.5% for the enhanced MD module, which had a solar efficiency of 20%. They also found that the membrane active area, where the transmembrane temperature gradient is positive, remained high along the length of the MD module in the case of the NP-coated membrane, but dropped in the case of the uncoated membrane due to greater heat losses from feed to permeate (**Figure 32**).

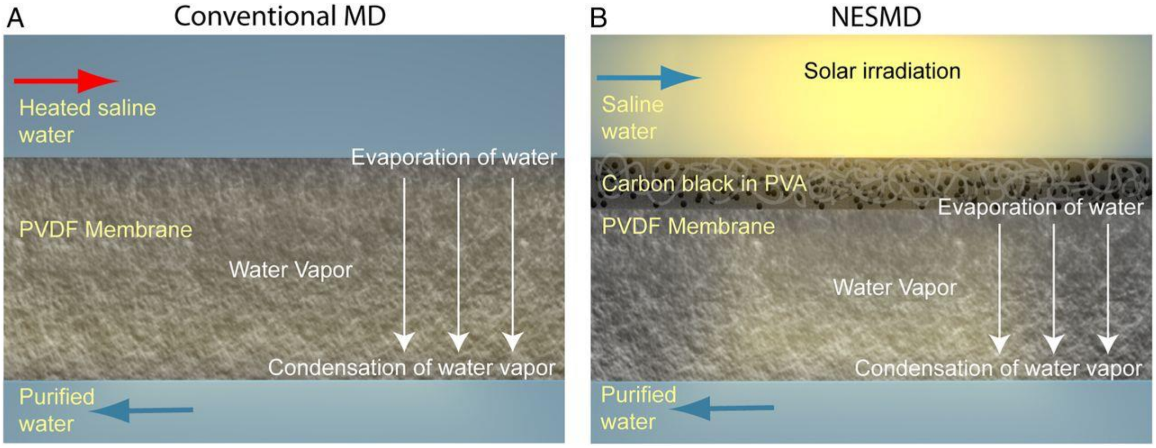

Figure 19: Comparison of MD with (A) conventional PVDF membrane and (B) PVDF membrane deposited with a layer of carbon black-embedded electrospun PVA [187].

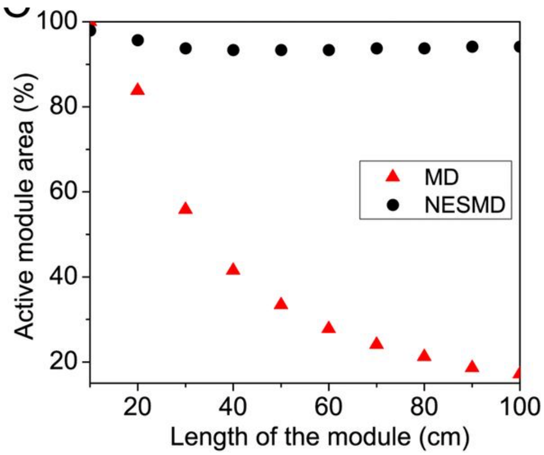

Figure 20: Active area, i.e. membrane area with positive transmembrane temperature gradient for both modules [187]

In another study, the same group coated hydrophobic PVDF membranes with either carbon black NPs or SiO_2/Au nanoshells and found an increase of 33% in permeate flux under simulated sunlight [188]. The membranes were tested on a bench-scale DCMD setup. In MD, a key membrane parameter is the liquid entry pressure, which indicates the pressure required for a liquid to penetrate inside the membrane. It depends on several factors including surface tension of the liquid, membrane hydrophobicity as well as pore shape and size [189]. In order to ensure stable MD performance, a high LEP is required to prevent wetting of the membrane by the feed. The LEP and salt rejection in this study remained unaffected by the NP coating.

In another study, Politano *et al.* demonstrated the improved energy efficiency and flux of vacuum membrane distillation (VMD) using PVDF membranes loaded with silver NPs under UV irradiation [190]. The membranes were prepared with nonsolvent-induced phase inversion. Due to the increased temperature at the membrane surface, the flux through the membrane that was loaded with 25% Ag NPs was 11 times more than the unloaded membrane. Although tested under UV irradiation, they suggested that the plasmonic response of the NPs could be evoked across the solar irradiation spectrum.

Tan *et al.* [191] modified PVDF membranes with MXene for DCMD. MXene is a group of early transition metal carbides, nitrides and carbonitrides with a layered morphology [192]. They tested the membranes for feeds of bovine serum albumin (BSA) and sodium chloride (NaCl) under 50W LED irradiation. They found that, per unit volume distillate, MXene-coated PVDF led to a 12% reduction in energy input and the flux decline also reduced by 56-64%, demonstrating the anti-fouling ability of MXene.

Another group at the Washington University in St. Louis coated PVDF membranes with polydopamine (PDA) by a self-polymerization process and tested the photothermal membrane for DCMD with simulated solar irradiation [193]. As both base and modified membranes were initially hydrophilic, a fluoro-silanization method was used prior to testing to increase their water contact angle. At a higher irradiation intensity of 7.0 kW/m^2, the flux through the coated membrane was 12.6 times that of the uncoated membranes. Flux and efficiency of the PDA-coated membrane for solar powered MD under different feed conditions and solar irradiation are shown in **Figure 33**.

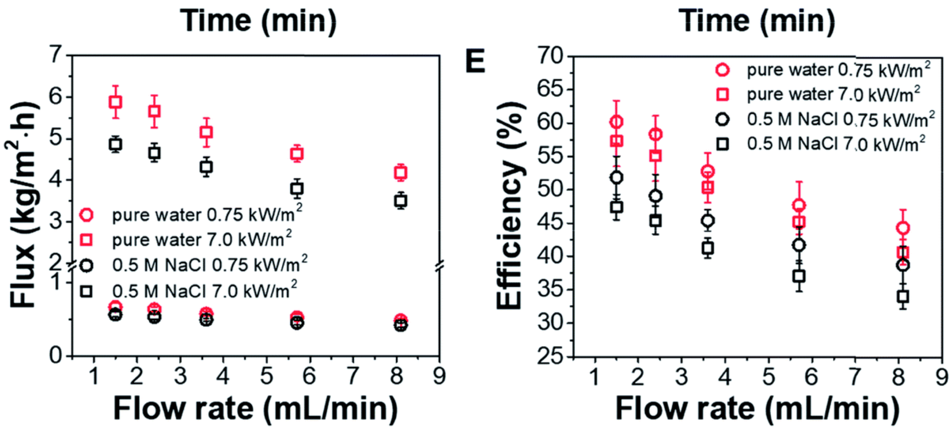

Figure 21: Flux (left) and solar conversion efficiency (right) of PDA-coated PVDF membrane for DCMD [193]

From the studies above, the rise in interest in new materials for enhancing energy conversion and MD performance in SPMD systems in just the last year and a half is evident. However, research in enhancing device design to fully benefit from these new materials is just as important and could help make solar MD competitive with other technologies. Although some of these studies have considered energy savings, an understanding of how these improvements along with new designs can aid in reducing the cost of water from solar powered MD.

4. Future outlook

4.1 Hybrid RE-driven desalination

The application of solar energy to desalination processes demonstrates potential for further growth, in terms of enhanced performance, energy savings and/or cost reduction. In particular, the use of hybrid RE systems to drive desalination has garnered significant interest among the research community [194].

4.1.1 PV-wind-RO

The advantage of a hybrid PV-wind system is that each source can compensate for lack of availability of the other [195]. This is relevant given the variable character of both and ensures more continuous energy availability [196, 197]. To date, there have been a few studies optimizing the hybrid solar PV-wind system of electricity generation, taking into account variables such as water availability, load, location of solar wind plant and its size [198-202].

In the only experimental study coupling PV-wind with desalination which was conducted in 2001, Weiner *et al.* experimentally designed and operated a small-scale stand-alone BWRO plant powered by a combination of solar PV and wind [203]. Mokheimer *et al.* modelled a small-scale hybrid wind/solar PV powered RO desalination system with a production capacity of 5 m^3/day [204]. They found that cost for the hybrid system can be reduced if multiple wind turbines are used. Although the efficiency of the overall system depends on feed salinity which also determines load demand [204]. Similarly, Rehman and El-Amin investigated a solar PV/wind/diesel hybrid for a remote area in Saudi Arabia. Interestingly, they found that the diesel-only system had the greatest cost efficiency despite the progress undergone in reducing the cost of PV in the last few decades [205]. This is an indication of the continuing untapped potential in RE-driven desalination, and particularly the need to further drive down energy costs to allow such systems to economically compete with fossil fuel-driven desalination.

4.2. Other desalination processes

4.2.1 Forward osmosis

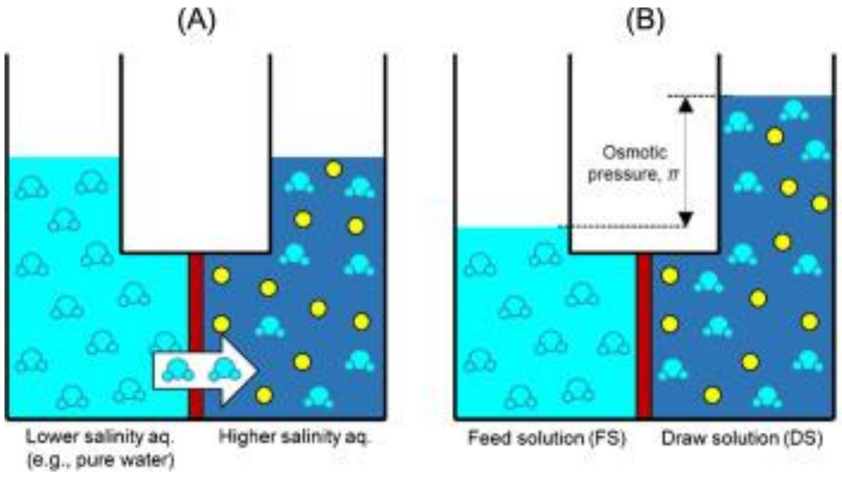

Figure 22: Schematic of FO process [206]

Forward osmosis is a type of salinity gradient-driven or osmotically driven desalination process in which a pressure difference across a semi-permeable membrane results in selective water transport (**Figure 34**) [206]. As it enables natural diffusion of water from the feed to a higher concentration solution, it does not require hydraulic pressure, making it a low-energy alternative to RO for desalination. It thus has the potential to significantly reduce energy costs associated with desalination. There have been a few FO installations recently with the majority in China, one of which has a capacity of 2800 m^3/day, the highest for an installed FO plant to date [8]. The technology is still limited by lack of high-performing membranes and has a long way to go in terms of large-scale commercial installations [206].

The concept of solar powered FO was introduced by Khaydarov in 2007 [207], using a system of solar batteries, solar thermal exchangers, a pretreatment unit and the various fluids of the FO device [207].

Razmjou *et al.* [208] investigated the feasibility of a bilayer polymer hydrogel as draw agent for FO using solar concentrated energy source. The hydrogel consisted of a water-absorptive layer which provided osmotic pressure, and a dewatering layer to release the water absorbed during FO [208]. Using a Fresnel lens collector, they found that increasing the energy of the concentrator from 0.5 to 2 Kw/m^2 in increased dewatering flux through by a factor of 2.5. Monjezi investigated a model to demonstrate the the use of solar thermal energy from salinity gradient solar ponds for FO. He found that a production capacity of 5,200 m3/day of potable water can be achieved with an SEC of 0.46 kWh/m^3 [209]. In a shift from typical FO, Shafer *et al.* suggested a hybrid FO system which uses a low-temperature distillation for thermolytic draw solute recovery. They proposed that this would reduce energy costs and allow FO to benefit from solar thermal energy [210]. With significantly lower energy cost compared to conventional desalination techniques, growth of solar powered FO is an extremely promising area for the decarbonization of desalination.

4.2.1 Dewvaporation

Future trends of solar desalination include shifting to other less explored desalination techniques. Dewvaporation is one such technique that holds the potential for solar powered desalination. In dewvaporation, a saturated steam is used as carrier gas to vaporize water from saline feed as distillate [211]. It offers the advantage of energy reuse, depending on the use of heat exchanger and improved process design [212]. Ranganathan recently proposed the development of a solar powered dewvaporation system for seawater desalination [211]. According to a technical report, they immobilized gold nanoparticles on the PMMA surface to achieve a water evaporation conversion efficiency of over 50% [211].

5. Conclusions

Solar energy-driven desalination is a rapidly growing area of research, with significant progress in the last few years. Increasing desalination capacity and the competing need for decarbonization and mitigation of the adverse effects of global warming has resulted in efforts to drive desalination with renewable energy sources. Solar energy in particular is an attractive source of energy to power desalination, especially since fresh water scarcity and solar irradiation coincide in many regions. Direct solar desalination has garnered interest in the past two years as novel photothermal materials, graphene-based and metal/ceramic nanostructures, have facilitated evaporation through localized heating.

Solar energy can be harnessed as electrical energy using solar PV technology, or as solar thermal energy using collectors which can also be converted to electricity. As the most dominant desalination technology, RO is well suited to be driven by solar energy systems. In this review, solar powered RO has been reviewed with a focus on reduction of energy consumption through membrane materials, design configuration, energy recovery devices and the use of energy storage systems.

Solar power coupled with emergent processes such as membrane distillation (MD) has also seen a revival recently, with the advent of photothermal materials that allow localized heating at the membrane surface, resulting in improved MD performance. Future outlook with regards to hybrid RE systems of solar PV-wind, as well as prospects of solar energy for driving newer processes such as forward osmosis and dewvaporation in terms of energy savings have also been considered.

A few gaps in literature regarding the aspects covered in this survey have been identified. Further research in the following areas is likely to boost solar driven desalination.

- In the case of solar powered MD, many studies are based on modelling and simulation. There is a pressing need to bridge the gap between theoretical and experimental work to advance solar MD towards commercialization.
- Similarly, studies on hybrid RE systems for desalination are largely theoretical. Experimental studies are needed to evaluate the feasibility of these systems for real operation.
- The use of energy recovery devices in real PV-RO plants is very limited. It is possible that this could be a factor in the slow large-scale development of PV-RO. Additionally, further improvements in ERDs should be sought to bring down the cost of solar powered RO. This could be particularly beneficial for solar thermal powered RO plants, which are still significantly behind PV-RO in terms of installation capacity.
- As continuation of the point above, available studies on the use of pressure retarded osmosis for energy recovery in RO is extremely scarce. This is partly driven by the lack of high-performing PRO membranes. Therefore, advances in PRO membrane materials and design optimization could potentially provide more options for energy recovery in PV-RO systems.

6. References

1. WWAP, *The United Nations World Water Development Report 2018: Nature-based Solutions.* 2018, UNESCO: Paris.
2. Luo, T., R. Young, and P. Reig, *Aqueduct projected water stress country rankings*. 2015, World Resources Institute: Washington, D.C.
3. Technavio, *Global Desalination Market 2018-2022*. 2018.
4. Buros, O., *The ABCs of desalting*. 2000: International Desalination Association Topsfield, MA.
5. Asaba, B., *Desalination And Water Reuse Markets Recover*, in *Middle East Utilities*. 2016: United Arab Emirates.
6. Research, O., *Global Water Desalination Market: 2018-2025 Key Industry Insights, Segments, Opportunities, and Forecasts*. 2018.
7. Voutchkov, N., *Desalination - Past, Present and Future*, in *International Water Association*. 2016.
8. *DesalData*.
9. Mahmoudi, H., *Renewable Energy Technologies for Water Desalination*. 2017: CRC Press/Balkema.
10. Ayoub, G.M. and L. Malaeb, *Developments in Solar Still Desalination Systems: A Critical Review.* Critical Reviews in Environmental Science and Technology, 2012. 42(19): p. 2078-2112.
11. Caldera, U. and C. Breyer, *Learning Curve for Seawater Reverse Osmosis Desalination Plants: Capital Cost Trend of the Past, Present, and Future.* Water Resources Research, 2017. 53(12): p. 10523-10538.
12. Fane, A.G., *A grand challenge for membrane desalination: More water, less carbon.* Desalination, 2018. 426: p. 155-163.
13. Al-Karaghouli, A. and L.L. Kazmerski, *Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes.* Renewable and Sustainable Energy Reviews, 2013. 24: p. 343-356.
14. Gökgöz, F. and M.T. Güvercin, *Energy security and renewable energy efficiency in EU.* Renewable and Sustainable Energy Reviews, 2018. 96: p. 226-239.
15. Kylili, A., et al., *Environmental assessment of solar thermal systems for the industrial sector.* Journal of Cleaner Production, 2018. 176: p. 99-109.
16. HERNANDEZ;, C.V., T. TELSNIG, and A.V. PRADAS, *JRC Wind Energy Status Report 2016 Edition*. 2016, Joint Research Center, European Commission.
17. Forinash, K., *Renewable energy*, in *Physics and the Environment*. 2017, Morgan & Claypool Publishers. p. 6-1-6-29.
18. *Energy Explained*. 8 September 2018]; Available from: https://www.eia.gov/energyexplained/index.php.
19. Shahzad, M.W., et al., *Energy-water-environment nexus underpinning future*

desalination sustainability. Desalination, 2017. 413: p. 52-64.

20. Thangavel, P. and G. Sridevi, *Environmental Sustainability: Role of Green Technologies*. 2014: Springer India.
21. Coddington, O., et al., *A Solar Irradiance Climate Data Record.* Bulletin of the American Meteorological Society, 2015. 97(7): p. 1265-1282.
22. Hart, M., *Hubris: The troubling science, economics, and politics of climate change*. 2015: Lulu. com.
23. Kabir, E., et al., *Solar energy: Potential and future prospects.* Renewable and Sustainable Energy Reviews, 2018. 82: p. 894-900.
24. Pugsley, A., et al., *Global applicability of solar desalination.* Renewable Energy, 2016. 88: p. 200-219.
25. M, C. and A. Yadav, *Water desalination system using solar heat: A review.* Renewable and Sustainable Energy Reviews, 2017. 67: p. 1308-1330.
26. Sharon, H. and K.S. Reddy, *A review of solar energy driven desalination technologies.* Renewable and Sustainable Energy Reviews, 2015. 41: p. 1080-1118.
27. Zhang, Y., et al., *Application of solar energy in water treatment processes: A review.* Desalination, 2018. 428: p. 116-145.
28. Pouyfaucon, A.B. and L. García-Rodríguez, *Solar thermal-powered desalination: A viable solution for a potential market.* Desalination, 2018. 435: p. 60-69.
29. El-Sebaii, A.A. and E. El-Bialy, *Advanced designs of solar desalination systems: A review.* Renewable and Sustainable Energy Reviews, 2015. 49: p. 1198-1212.
30. Prakash, P. and V. Velmurugan, *Parameters influencing the productivity of solar stills – A review.* Renewable and Sustainable Energy Reviews, 2015. 49: p. 585-609.
31. Sharshir, S.W., et al., *Factors affecting solar stills productivity and improvement techniques: A detailed review.* Applied Thermal Engineering, 2016. 100: p. 267-284.
32. Shukla, A., K. Kant, and A. Sharma, *Solar still with latent heat energy storage: A review.* Innovative Food Science & Emerging Technologies, 2017. 41: p. 34-46.
33. Srithar, K. and T. Rajaseenivasan, *Recent fresh water augmentation techniques in solar still and HDH desalination – A review.* Renewable and Sustainable Energy Reviews, 2018. 82: p. 629-644.
34. Reif, J.H. and W. Alhalabi, *Solar-thermal powered desalination: Its significant challenges and potential.* Renewable and Sustainable Energy Reviews, 2015. 48: p. 152-165.
35. Labouret, A., et al., *Solar Photovoltaics*. 2010, Stevenage, UNITED KINGDOM: Institution of Engineering & Technology.
36. Deambi, S., *Photovoltaic System Design : Procedures, Tools and Applications*. 2016, Milton, UNITED KINGDOM: Chapman and Hall/CRC.

37. Harry, *Photovoltaic Modules : Technology and Reliability*, ed. Wirth, et al. 2016, Berlin/Boston: De Gruyter.
38. Bauer, G.H., *Photovoltaic Solar Energy Conversion*. 2015: Springer Berlin Heidelberg.
39. Goetzberger, A., C. Hebling, and H.-W. Schock, *Photovoltaic materials, history, status and outlook.* Materials Science and Engineering: R: Reports, 2003. 40(1): p. 1-46.
40. Ogbomo, O.O., et al., *A review of photovoltaic module technologies for increased performance in tropical climate.* Renewable and Sustainable Energy Reviews, 2017. 75: p. 1225-1238.
41. Rheinländer, J. and D. Geyer, *Photovoltaic Reverse Osmosis and Electrodialysis*, in *Seawater Desalination: Conventional and Renewable Energy Processes*, G. Micale, L. Rizzuti, and A. Cipollina, Editors. 2009, Springer Berlin Heidelberg: Berlin, Heidelberg. p. 189-211.
42. Zhou, Z. and M. Carbajales-Dale, *Assessing the photovoltaic technology landscape: efficiency and energy return on investment (EROI).* Energy & Environmental Science, 2018. 11(3): p. 603-608.
43. Awerbuch, S., *Investing in photovoltaics: risk, accounting and the value of new technology.* Energy Policy, 2000. 28(14): p. 1023-1035.
44. Almosni, S., et al., *Material challenges for solar cells in the twenty-first century: directions in emerging technologies.* Science and Technology of Advanced Materials, 2018. 19(1): p. 336-369.
45. Benda, V., *9 - Crystalline Silicon Solar Cell and Module Technology*, in *A Comprehensive Guide to Solar Energy Systems*, T.M. Letcher and V.M. Fthenakis, Editors. 2018, Academic Press. p. 181-213.
46. Delgado-Torres, A.M., et al., *Chapter 3 - Water Desalination by Solar-Powered RO Systems*, in *Current Trends and Future Developments on (Bio-) Membranes*, A. Basile, A. Cassano, and A. Figoli, Editors. 2019, Elsevier. p. 45-84.
47. *Solar energy technologies - solutions for today's energy needs*, S.e.I. Association, Editor. 2018: Washington D.C.
48. Patil, V.R., et al., *Techno-economic comparison of solar organic Rankine cycle (ORC) and photovoltaic (PV) systems with energy storage.* Renewable Energy, 2017. 113: p. 1250-1260.
49. Kalogirou, S.A., *Solar Energy Engineering: Processes and Systems*. 2009: Elsevier Science.
50. Jebasingh, V.K. and G.M.J. Herbert, *A review of solar parabolic trough collector.* Renewable and Sustainable Energy Reviews, 2016. 54: p. 1085-1091.
51. Price, H., et al., *Advances in parabolic trough solar power technology.* Journal of solar energy engineering, 2002. 124(2): p. 109-125.
52. Wahed, A., et al., *Levelized Cost of Solar Thermal System for Process Heating Applications in the Tropics*, in *Transition Towards 100% Renewable Energy:*

Selected Papers from the World Renewable Energy Congress WREC 2017, A. Sayigh, Editor. 2018, Springer International Publishing: Cham. p. 441-450.

53. IRENA, *Renewable Capacity Statistics 2018*. 2018.
54. Letcher, T.M., *1 - Why Solar Energy?*, in *A Comprehensive Guide to Solar Energy Systems*, T.M. Letcher and V.M. Fthenakis, Editors. 2018, Academic Press. p. 3-16.
55. IRENA, *Solar PV Costs 2010-2015*. 2016.
56. IRENA, *The Power to Change: Solar and Wind Cost Reduction Potential to 2025*. 2016.
57. Jaeger-Waldau, A., *PV Status Report 2017*. 2017, Joint Research Center, European Commission.
58. Vélez, F., *Selecting working fluids in an organic Rankine cycle for power generation from low temperature heat sources.* Dyna, 2014. 81(188): p. 173-180.
59. Kim, K.H. and C.H. Han, *A review on solar collector and solar organic rankine cycle (ORC) systems.* Journal of Automation and Control Engineering, 2015. 3(1).
60. Quoilin, S. and V. Lemort, *Technological and economical survey of organic Rankine cycle systems.* 2009.
61. Garg, M.C., *Chapter 4 - Renewable Energy-Powered Membrane Technology: Cost Analysis and Energy Consumption*, in *Current Trends and Future Developments on (Bio-) Membranes*, A. Basile, A. Cassano, and A. Figoli, Editors. 2019, Elsevier. p. 85-110.
62. Pugsley, A., et al., *Chapter 2 - Solar Desalination Potential Around the World*, in *Renewable Energy Powered Desalination Handbook*, V.G. Gude, Editor. 2018, Butterworth-Heinemann. p. 47-90.
63. Dsilva Winfred Rufuss, D., et al., *Solar stills: A comprehensive review of designs, performance and material advances.* Renewable and Sustainable Energy Reviews, 2016. 63: p. 464-496.
64. Panchal, H., *Present Status of Solar Still: A Critical Review*. 2012.
65. Kim, K., et al., *Mesoporous Three-Dimensional Graphene Networks for Highly Efficient Solar Desalination under 1 sun Illumination.* ACS Applied Materials & Interfaces, 2018. 10(18): p. 15602-15608.
66. Yin, X., et al., *Macroporous Double-Network Hydrogel for High-Efficiency Solar Steam Generation Under 1 sun Illumination.* ACS Applied Materials & Interfaces, 2018. 10(13): p. 10998-11007.
67. Liu, K.-K., et al., *Wood–Graphene Oxide Composite for Highly Efficient Solar Steam Generation and Desalination.* ACS Applied Materials & Interfaces, 2017. 9(8): p. 7675-7681.
68. Yu, S., et al., *The impact of surface chemistry on the performance of localized solar-driven evaporation system.* Scientific Reports, 2015. 5: p. 13600.
69. Liu, Z., et al., *High-absorption recyclable photothermal membranes used in*

a bionic system for high-efficiency solar desalination via enhanced localized heating. Journal of Materials Chemistry A, 2017. 5(37): p. 20044-20052.

70. Finnerty, C., et al., *Synthetic Graphene Oxide Leaf for Solar Desalination with Zero Liquid Discharge.* Environmental Science & Technology, 2017. 51(20): p. 11701-11709.
71. Shang, M., et al., *Full-Spectrum Solar-to-Heat Conversion Membrane with Interfacial Plasmonic Heating Ability for High-Efficiency Desalination of Seawater.* ACS Applied Energy Materials, 2018. 1(1): p. 56-61.
72. Zhu, G., et al., *Constructing Black Titania with Unique Nanocage Structure for Solar Desalination.* ACS Applied Materials & Interfaces, 2016. 8(46): p. 31716-31721.
73. Zhou, L., et al., *3D self-assembly of aluminium nanoparticles for plasmon-enhanced solar desalination.* Nature Photonics, 2016. 10: p. 393.
74. Liu, X., et al., *Black titania/graphene oxide nanocomposite films with excellent photothermal property for solar steam generation.* Journal of Materials Research, 2018. 33(6): p. 674-684.
75. LLP, K.S.I., *Global Reverse Osmosis (RO) Systems Market - Forecasts from 2017 to 2022.* 2017, Knowledge Sourcing Intelligence LLP. p. 70.
76. Dashtpour, R. and S.N. Al-Zubaidy, *Energy efficient reverse osmosis desalination process.* International Journal of Environmental Science and Development, 2012. 3(4): p. 339.
77. Karabelas, A.J., et al., *Analysis of specific energy consumption in reverse osmosis desalination processes.* Desalination, 2018. 431: p. 15-21.
78. Greenlee, L.F., et al., *Reverse osmosis desalination: water sources, technology, and today's challenges.* Water research, 2009. 43(9): p. 2317-2348.
79. Elimelech, M. and W.A. Phillip, *The Future of Seawater Desalination: Energy, Technology, and the Environment.* Science, 2011. 333(6043): p. 712-717.
80. Stillwell, A.S. and M.E. Webber, *Predicting the specific energy consumption of reverse osmosis desalination.* Water, 2016. 8(12): p. 601.
81. Dow, *DOW FILMTEC™ SW30XHR–440i Element.* 2017, Dow Chemical Company.
82. Baker, R.W., *Membrane Technology and Applications.* 2012: Wiley.
83. Zarzo, D. and D. Prats, *Desalination and energy consumption. What can we expect in the near future?* Desalination, 2018. 427: p. 1-9.
84. Song, J., et al., *A review of the current status of small-scale seawater reverse osmosis desalination.* Water International, 2017. 42(5): p. 618-631.
85. Riedinger, A.B. and C.E. Hickman, *Considerations of energy consumption in desalination by reverse osmosis.* Desalination, 1982. 40(3): p. 259-270.
86. Association, W., *Seawater Desalination Power Consumption (White Paper).* 2011.
87. Bilton, A.M. and L.C. Kelley, *Design of power systems for reverse osmosis desalination in remote communities.* Desalination and Water Treatment,

2015. 55(10): p. 2868-2883.

88. Bilton, A.M., et al., *On the feasibility of community-scale photovoltaic-powered reverse osmosis desalination systems for remote locations.* Renewable Energy, 2011. 36(12): p. 3246-3256.

89. Shalaby, S.M., *Reverse osmosis desalination powered by photovoltaic and solar Rankine cycle power systems: A review.* Renewable and Sustainable Energy Reviews, 2017. 73: p. 789-797.

90. Chong, T.H., S.-L. Loo, and W.B. Krantz, *Energy-efficient reverse osmosis desalination process.* Journal of Membrane Science, 2015. 473: p. 177-188.

91. Kim, J. and S. Hong, *Optimizing seawater reverse osmosis with internally staged design to improve product water quality and energy efficiency.* Journal of Membrane Science, 2018. 568: p. 76-86.

92. Kim, J. and S. Hong, *A novel single-pass reverse osmosis configuration for high-purity water production and low energy consumption in seawater desalination.* Desalination, 2018. 429: p. 142-154.

93. Raval, H.D. and S. Maiti, *A Novel Photovoltaic Powered Reverse Osmosis with Improved Productivity of Reverse Osmosis and Photovoltaic Panel.* Journal of Membrane Science and Research, 2015. 1(3): p. 113-117.

94. Raval, H.D. and S. Maiti, *Ultra-low energy reverse osmosis with thermal energy recovery from photovoltaic panel cooling and TFC RO membrane modification.* Desalination and Water Treatment, 2016. 57(10): p. 4303-4312.

95. Singh, R., *Hybrid Membrane Systems for Water Purification: Technology, Systems Design and Operations.* 2006: Elsevier Science.

96. Skoplaki, E. and J.A. Palyvos, *On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations.* Solar Energy, 2009. 83(5): p. 614-624.

97. Shukla, A., et al., *Cooling methodologies of photovoltaic module for enhancing electrical efficiency: A review.* Solar Energy Materials and Solar Cells, 2017. 160: p. 275-286.

98. Voutchkov, N., *Pretreatment for Reverse Osmosis Desalination.* 2017: Elsevier Science.

99. Zheng, J., et al., *A non-MPD-type reverse osmosis membrane with enhanced permselectivity for brackish water desalination.* Journal of Membrane Science, 2018. 565: p. 104-111.

100. Yao, Y., et al., *A novel sulfonated reverse osmosis membrane for seawater desalination: Experimental and molecular dynamics studies.* Journal of Membrane Science, 2018. 550: p. 470-479.

101. Wang, J., et al., *Fast polydopamine coating on reverse osmosis membrane: Process investigation and membrane performance study.* Journal of Colloid and Interface Science, 2019. 535: p. 239-244.

102. Park, H.M., K.Y. Jee, and Y.T. Lee, *Preparation and characterization of a thin-film composite reverse osmosis membrane using a polysulfone*

membrane including metal-organic frameworks. Journal of Membrane Science, 2017. 541: p. 510-518.

103. Ahmad, A., et al., *Novel Polyurethane/Polyvinyl chloride-co-vinyl acetate crosslinked membrane for reverse osmosis (RO).* Desalination, 2017. 420: p. 136-144.
104. Rodríguez-Calvo, A., et al., *Novel membrane materials for reverse osmosis desalination.* Hydrology: Current Research, 2014. 5(2): p. 1.
105. Asempour, F., et al., *Synthesis and characterization of novel Cellulose Nanocrystals-based Thin Film Nanocomposite membranes for reverse osmosis applications.* Desalination, 2018. 439: p. 179-187.
106. Zhang, Y., et al., *Surface modification of polyamide reverse osmosis membrane with organic-inorganic hybrid material for antifouling.* Applied Surface Science, 2018. 433: p. 139-148.
107. Liu, L.-F., et al., *Modification of Polyamide-Urethane (PAUt) Thin Film Composite Membrane for Improving the Reverse Osmosis Performance.* Polymers, 2018. 10(4): p. 346.
108. Alghoul, M.A., et al., *Design and experimental performance of brackish water reverse osmosis desalination unit powered by 2 kW photovoltaic system.* Renewable Energy, 2016. 93: p. 101-114.
109. Chaabene, A.B., K. Ouelhazi, and A. Sellami, *Novel design and modeling of a photovoltaic hydro electromagnetic reverse osmosis (PV-HEMRO) desalination system.* Journal of Desalination and Water Treatment, 2017. 66: p. 36-41.
110. Voutchkov, N., *Energy use for membrane seawater desalination – current status and trends.* Desalination, 2018. 431: p. 2-14.
111. Peñate, B. and L. García-Rodríguez, *Reverse osmosis hybrid membrane inter-stage design: A comparative performance assessment.* Desalination, 2011. 281: p. 354-363.
112. Mokhtari, H., H. Ahmadisedigh, and I. Ebrahimi, *Comparative 4E analysis for solar desalinated water production by utilizing organic fluid and water.* Desalination, 2016. 377: p. 108-122.
113. Han, D., M. Hwang, and I.S. Kim, *Effect of boron rejection and recovery rate on a single-pass design of SWRO using hybrid membrane inter-stage design (HID) concept.* Desalination, 2017. 404: p. 215-223.
114. Mickols, W.E.B., M. Maeda, and J. Tonner, *A Novel Design Approach for Seawater Plants.* 2005.
115. Chong, T.H. and W.B. Krantz, *Process economics and operating strategy for the energy-efficient reverse osmosis (EERO) process.* Desalination, 2018. 443: p. 70-84.
116. Chen, X. and N.Y. Yip, *Unlocking High-Salinity Desalination with Cascading Osmotically Mediated Reverse Osmosis: Energy and Operating Pressure Analysis.* Environmental Science & Technology, 2018. 52(4): p. 2242-2250.
117. Ghermandi, A. and R. Messalem, *Solar-driven desalination with reverse*

osmosis: the state of the art. Desalination and Water Treatment, 2009. 7(1-3): p. 285-296.

118. Peñate, B. and L. García-Rodríguez, *Energy optimisation of existing SWRO (seawater reverse osmosis) plants with ERT (energy recovery turbines): Technical and thermoeconomic assessment.* Energy, 2011. 36(1): p. 613-626.
119. Stover, R.L., *Retrofits to improve desalination plants.* Desalination and Water Treatment, 2010. 13(1-3): p. 33-41.
120. Arenas Urrea, S., et al., *Technical review, evaluation and efficiency of energy recovery devices installed in the Canary Islands desalination plants.* Desalination, 2018.
121. Stover, R.L., *Seawater reverse osmosis with isobaric energy recovery devices.* Desalination, 2007. 203(1): p. 168-175.
122. School, W., *'New Water' Offers an Ocean of Hope.* Knowledge@Wharton, 2013.
123. MacHarg, J.P. and B. Sessions, *Modular pumps bring efficiencies.* IDA Journal of Desalination and Water Reuse, 2013. 5(2): p. 106-113.
124. Dimitriou, E., et al., *Experimental comparison of the performance of two reverse osmosis desalination units equipped with different energy recovery devices.* Desalination and Water Treatment, 2015. 55(11): p. 3019-3026.
125. Jones, M.A., *Systems Modeling and Economic Analysis of Photovoltaic (PV) Powered Water Pumping Brackish Water Desalination for Agriculture.* 2015.
126. ERIEnergy, *How the PX Pressure Exchanger® Works.* 2013.
127. Migliorini, G. and E. Luzzo, *Seawater reverse osmosis plant using the pressure exchanger for energy recovery: A calculation model.* Vol. 165. 2004. 289-298.
128. Harris, C., *Energy recovery for membrane desalination.* Desalination, 1999. 125(1-3): p. 173-180.
129. Jones, M.A., et al., *Economic analysis of photovoltaic (PV) powered water pumping and desalination without energy storage for agriculture.* Desalination, 2016. 387: p. 35-45.
130. Romero, R.G., *A PV Powered BWRO Desalination Installation with Energy Recovery and Hydro-Pneumatic Energy Storage.* 2013.
131. writers, S.S., *Energy Recovery Awarded $1.4 million For Deal in World's First Large-Scale Solar-Powered Desalination Plant*, in *Solar Thermal Magazine*. 2015.
132. Cameron, I.B. and R.B. Clemente, *SWRO with ERI's PX Pressure Exchanger device — a global survey.* Desalination, 2008. 221(1): p. 136-142.
133. Staff, A., *Reverse Osmosis and Nanofiltration, (M46).* 2011: American Water Works Association.
134. Wan, C.F. and T.-S. Chung, *Energy recovery by pressure retarded osmosis (PRO) in SWRO–PRO integrated processes.* Applied Energy, 2016. 162: p.

687-698.

135. Kurihara, M., et al., *Role of pressure-retarded osmosis (PRO) in the mega-ton water project.* Desalination and Water Treatment, 2016. 57(55): p. 26518-26528.

136. Achilli, A. and A.E. Childress, *Pressure retarded osmosis: From the vision of Sidney Loeb to the first prototype installation — Review.* Desalination, 2010. 261(3): p. 205-211.

137. Yang, Z. and C.Y. Tang, *Chapter 7 - Novel Membranes and Membrane Materials*, in *Membrane-Based Salinity Gradient Processes for Water Treatment and Power Generation*, S. Sarp and N. Hilal, Editors. 2018, Elsevier. p. 201-221.

138. ForwardOsmosisTech, *Statkraft discontinues investments in pressure retarded osmosis*, in *ForwardOsmosisTech*. 2014.

139. EnergyRecovery, *Osmotic Power Play: Energy Recovery Teams With GS Engineering & Construction Corp to Develop Highly Available Renewable Energy Source*. 2013.

140. Chen, Y., et al., *Enhancing pressure retarded osmosis performance with low-pressure nanofiltration pretreatment: Membrane fouling analysis and mitigation.* Journal of Membrane Science, 2017. 543: p. 114-122.

141. Holt, T., et al., *Pressure Dependency of the Membrane Structure Parameter and Implications in Pressure Retarded Osmosis (PRO)*, in *Osmotically Driven Membrane Processes-Approach, Development and Current Status*. 2018, InTech.

142. Han, G., et al., *Advanced Anti-Fouling Membranes for Osmotic Power Generation from Wastewater via Pressure Retarded Osmosis (PRO).* Environmental Science & Technology, 2018. 52(11): p. 6686-6694.

143. Wan, C.F., et al., *Thin-film composite hollow fiber membrane with inorganic salt additives for high mechanical strength and high power density for pressure-retarded osmosis.* Journal of Membrane Science, 2018. 555: p. 388-397.

144. Yaroshchuk, A., *"Breakthrough" osmosis and unusually high power densities in Pressure-Retarded Osmosis in non-ideally semi-permeable supported membranes.* Scientific Reports, 2017. 7: p. 45168.

145. Zhao, D.L., S. Das, and T.-S. Chung, *Carbon Quantum Dots Grafted Antifouling Membranes for Osmotic Power Generation via Pressure-Retarded Osmosis Process.* Environmental Science & Technology, 2017. 51(23): p. 14016-14023.

146. He, W., Y. Wang, and M.H. Shaheed, *Stand-alone seawater RO (reverse osmosis) desalination powered by PV (photovoltaic) and PRO (pressure retarded osmosis).* Energy, 2015. 86: p. 423-435.

147. Julian Blanco Gálvez, S.M.R.E.D.V.G.B.S.C.B.S.K., *SOLAR ENERGY CONVERSION AND PHOTOENERGY SYSTEMS: Thermal Systems and Desalination Plants-Volume III*. 2010.

148. Bilton, A.M., L.C. Kelley, and S. Dubowsky, *Photovoltaic reverse osmosis—Feasibility and a pathway to develop technology.* Desalination and water Treatment, 2011. 31(1-3): p. 24-34.
149. Freire-Gormaly, M. and A.M. Bilton, *Experimental quantification of the effect of intermittent operation on membrane performance of solar powered reverse osmosis desalination systems.* Desalination, 2018. 435: p. 188-197.
150. Freire-Gormaly, M. and A. Bilton, *An experimental system for characterization of membrane fouling of solar photovoltaic reverse osmosis systems under intermittent operation.* Desalin. Water Treat., 2017. 73: p. 54-63.
151. Wu, B., et al., *Optimal design of stand-alone reverse osmosis desalination driven by a photovoltaic and diesel generator hybrid system.* Solar Energy, 2018. 163: p. 91-103.
152. Elshafei, M., A.K. Sheikh, and N. Ahmad, *Directly Driven RO System by PV Solar Panel Arrays.* Open Journal of Applied Sciences, 2013. 3(02): p. 35.
153. Kim, J., et al., *Design Optimization of Batteryless Photovoltaic-Powered Reverse Osmosis Water Desalination in Remote Areas.* 2014(46514): p. V06AT07A053.
154. Monnot, M., et al., *Integrated approach in eco-design strategy for small RO desalination plants powered by photovoltaic energy.* Desalination, 2018. 435: p. 246-258.
155. Karavas, C.-S., et al., *A novel autonomous PV powered desalination system based on a DC microgrid concept incorporating short-term energy storage.* Solar Energy, 2018. 159: p. 947-961.
156. Gude, V.G., *Chapter 10 - Energy Storage for Desalination*, in *Renewable Energy Powered Desalination Handbook*, V.G. Gude, Editor. 2018, Butterworth-Heinemann. p. 377-414.
157. Giwa, A. and S.W. Hasan, *Novel thermosiphon-powered reverse osmosis: Techno-economic model for renewable energy and fresh water recovery.* Desalination, 2018. 435: p. 152-160.
158. Li, C., Y. Goswami, and E. Stefanakos, *Solar assisted sea water desalination: A review.* Renewable and Sustainable Energy Reviews, 2013. 19: p. 136-163.
159. Quoilin, S., et al., *Techno-economic survey of Organic Rankine Cycle (ORC) systems.* Renewable and Sustainable Energy Reviews, 2013. 22: p. 168-186.
160. Li, S. and W. Li, *Thermo-economic optimization of solar organic Rankine cycle based on typical solar radiation year.* Energy Conversion and Management, 2018. 169: p. 78-87.
161. Ramos, A., et al., *Optimisation of a high-efficiency solar-driven organic Rankine cycle for applications in the built environment.* Applied Energy, 2018. 228: p. 755-765.
162. García-Rodríguez, L. and A.M. Delgado-Torres, *Solar-powered Rankine cycles*

for fresh water production. Desalination, 2007. 212(1): p. 319-327.

163. Gençer, E. and R. Agrawal, *Synthesis of efficient solar thermal power cycles for baseload power supply.* Energy Conversion and Management, 2017. 133: p. 486-497.
164. Manolakos, D., et al., *Technical and economic comparison between PV-RO system and RO-Solar Rankine system. Case study: Thirasia island.* Desalination, 2008. 221(1): p. 37-46.
165. Drioli, E., A. Ali, and F. Macedonio, *Membrane distillation: Recent developments and perspectives.* Desalination, 2015. 356: p. 56-84.
166. Banat, F., R. Jumah, and M. Garaibeh, *Exploitation of solar energy collected by solar stills for desalination by membrane distillation.* Renewable Energy, 2002. 25(2): p. 293-305.
167. Micale, *Seawater desalination : conventional and renewable energy processes*, ed. Giorgio, et al. 2009, Heidelberg ; New York: Springer.
168. Thomas, N., et al., *Membrane distillation research & implementation: Lessons from the past five decades.* Separation and Purification Technology, 2017. 189: p. 108-127.
169. Hogan, P.A., et al., *Desalination by solar heated membrane distillation.* Desalination, 1991. 81(1): p. 81-90.
170. González, D., J. Amigo, and F. Suárez, *Membrane distillation: Perspectives for sustainable and improved desalination.* Renewable and Sustainable Energy Reviews, 2017. 80: p. 238-259.
171. Lee, J.-G., et al., *Dynamic solar-powered multi-stage direct contact membrane distillation system: Concept design, modeling and simulation.* Desalination, 2018. 435: p. 278-292.
172. Ravisankar, V.A., et al., *Solar-driven membrane distillation demonstration in Leupp, Arizona.* Reviews on environmental health, 2016. 31(1): p. 79-83.
173. Saffarini, R.B., et al., *Economic evaluation of stand-alone solar powered membrane distillation systems.* Desalination, 2012. 299: p. 55-62.
174. Moore, S.E., et al., *Process modeling for economic optimization of a solar driven sweeping gas membrane distillation desalination system.* Desalination, 2018. 437: p. 108-120.
175. Khayet, M., *Solar desalination by membrane distillation: Dispersion in energy consumption analysis and water production costs (a review).* Desalination, 2013. 308: p. 89-101.
176. Ullah, R., et al., *Energy efficiency of direct contact membrane distillation.* Desalination, 2018. 433: p. 56-67.
177. Porrazzo, R., et al., *A neural network-based optimizing control system for a seawater-desalination solar-powered membrane distillation unit.* Computers & Chemical Engineering, 2013. 54: p. 79-96.
178. Zhu, L., et al., *Solar-driven photothermal nanostructured materials designs and prerequisites for evaporation and catalysis applications.* Materials Horizons, 2018. 5(3): p. 323-343.

179. Wang, P., *Emerging investigator series: the rise of nano-enabled photothermal materials for water evaporation and clean water production by sunlight.* Environmental Science: Nano, 2018. 5(5): p. 1078-1089.
180. He, Q., et al., *Experimental investigation on photothermal properties of nanofluids for direct absorption solar thermal energy systems.* Energy Conversion and Management, 2013. 73: p. 150-157.
181. Lingbo, M., et al., *Photothermal properties of nanofluid-based solar collector.* Acta Energiae solaris sinica, 2009. 12: p. 014.
182. Meng, Z., et al., *Thermal Conductivities, Rheological Behaviors and Photothermal Properties of Ethylene Glycol-based Nanofluids Containing Carbon Black Nanoparticles.* Procedia Engineering, 2012. 36: p. 521-527.
183. Xuan, Y., H. Duan, and Q. Li, *Enhancement of solar energy absorption using a plasmonic nanofluid based on TiO 2/Ag composite nanoparticles.* RSC Advances, 2014. 4(31): p. 16206-16213.
184. Zhang, Y., et al., *Enhancement of energy utilization using nanofluid in solar powered membrane distillation.* Chemosphere, 2018. 212: p. 554-562.
185. Martínez ‐ Díez, L. and M.I. Vázquez ‐ Gonzàlez, *Temperature polarization in mass transport through hydrophobic porous membranes.* AIChE journal, 1996. 42(7): p. 1844-1852.
186. Energy, U.D.o., *Department of Energy Announces $21 Million to Advance Solar Desalination Technologies.* 2018: www.ene.
187. Dongare, P.D., et al., *Nanophotonics-enabled solar membrane distillation for off-grid water purification.* Proceedings of the National Academy of Sciences, 2017. 114(27): p. 6936.
188. Wu, J., et al., *Photothermal nanocomposite membranes for direct solar membrane distillation.* Journal of Materials Chemistry A, 2017. 5(45): p. 23712-23719.
189. Rezaei, M., et al., *Wetting phenomena in membrane distillation: Mechanisms, reversal, and prevention.* Water Research, 2018. 139: p. 329-352.
190. Politano, A., et al., *Photothermal Membrane Distillation for Seawater Desalination.* Advanced Materials, 2017. 29(2): p. 1603504.
191. Tan, Y.Z., et al., *Photothermal-enhanced and fouling-resistant membrane for solar-assisted membrane distillation.* Journal of Membrane Science, 2018. 565: p. 254-265.
192. Sinha, A., et al., *MXene: An emerging material for sensing and biosensing.* TrAC Trends in Analytical Chemistry, 2018. 105: p. 424-435.
193. Wu, X., et al., *Localized heating with a photothermal polydopamine coating facilitates a novel membrane distillation process.* Journal of Materials Chemistry A, 2018.
194. Khan, M.A.M., S. Rehman, and F.A. Al-Sulaiman, *A hybrid renewable energy system as a potential energy source for water desalination using reverse osmosis: A review.* Renewable and Sustainable Energy Reviews, 2018. 97: p.

456-477.

195. Lai, W., et al., *Effects of wind intermittence and fluctuation on reverse osmosis desalination process and solution strategies.* Desalination, 2016. 395: p. 17-27.

196. Cherif, H. and J. Belhadj, *Large-scale time evaluation for energy estimation of stand-alone hybrid photovoltaic–wind system feeding a reverse osmosis desalination unit.* Energy, 2011. 36(10): p. 6058-6067.

197. Nema, P., R.K. Nema, and S. Rangnekar, *A current and future state of art development of hybrid energy system using wind and PV-solar: A review.* Renewable and Sustainable Energy Reviews, 2009. 13(8): p. 2096-2103.

198. Nair, A., et al. *Modelling and Optimising the Value of a Hybrid Solar-Wind System*. in *IOP Conference Series: Materials Science and Engineering*. 2017. IOP Publishing.

199. Rehman, S. and A.Z. Sahin, *A wind-solar PV hybrid power system with battery backup for water pumping in remote localities.* International Journal of Green Energy, 2016. 13(11): p. 1075-1083.

200. Jones, L.E. and G. Olsson, *Solar Photovoltaic and Wind Energy Providing Water.* Global Challenges, 2017. 1(5): p. 1600022.

201. Yang, H., et al., *Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm.* Solar Energy, 2008. 82(4): p. 354-367.

202. Ma, T., H. Yang, and L. Lu, *A feasibility study of a stand-alone hybrid solar–wind–battery system for a remote island.* Applied Energy, 2014. 121: p. 149-158.

203. Weiner, D., et al., *Operation experience of a solar- and wind-powered desalination demonstration plant.* Desalination, 2001. 137(1): p. 7-13.

204. Mokheimer, E.M.A., et al., *Modeling and optimization of hybrid wind–solar-powered reverse osmosis water desalination system in Saudi Arabia.* Energy Conversion and Management, 2013. 75: p. 86-97.

205. Rehman, S. and I. El-Amin, *Study of a solar pv/wind/diesel hybrid power system for a remotely located population near Arar, Saudi Arabia.* Energy Exploration & Exploitation, 2015. 33(4): p. 591-620.

206. Yasukawa, M., T. Suzuki, and M. Higa, *Chapter 1 - Salinity Gradient Processes: Thermodynamics, Applications, and Future Prospects*, in *Membrane-Based Salinity Gradient Processes for Water Treatment and Power Generation*, S. Sarp and N. Hilal, Editors. 2018, Elsevier. p. 3-56.

207. Khaydarov, R.A. and R.R. Khaydarov, *Solar powered direct osmosis desalination.* Desalination, 2007. 217(1): p. 225-232.

208. Razmjou, A., et al., *Bifunctional Polymer Hydrogel Layers As Forward Osmosis Draw Agents for Continuous Production of Fresh Water Using Solar Energy.* Environmental Science & Technology, 2013. 47(22): p. 13160-13166.

209. Abbassi Monjezi, A., *Development of a comprehensive transient model of*

energy capture and storage in solar ponds for use in thermal regeneration of draw solutes in forward osmosis. 2017, University of Surrey.

210. Shaffer, D.L., et al., *Forward osmosis: Where are we now?* Desalination, 2015. 356: p. 271-284.
211. Ranganathan, S., *Final Scientific/Technical Report for Program Title: Solar Powered Dewvaporation Desalination System*. 2017, Polestar Technologies Inc., Needham Heights, MA (United States).
212. Hamieh, B.M. and J.R. Beckman, *Seawater desalination using Dewvaporation technique: experimental and enhancement work with economic analysis.* Desalination, 2006. 195(1): p. 14-25.