Energy Efficiency and Renewable Energy Utilization in Desalination Systems

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Abstract

Desalination technologies and industry have advanced significantly in the past two decades to meet the growing freshwater demands stimulated by the compounding issues of both water quality and quantity in many regions of the world. As desalination processes are energy demanding, there have been many efforts dedicated to improve energy-efficiency of the process units, enhance energy conservation and recovery, and increase renewable energy integration in desalination plants. This perspective article highlights recent key advances and discusses possible venues for further development in desalination energy portfolio to reduce specific energy consumption and, via integration with solar energy, to minimize the environmental footprint associated with freshwater production. First, an overview of current desalination technologies and their energy requirements are presented followed by a discussion on opportunities for improving energy efficiency and energy recovery in both membrane and thermal desalination technologies. Then, various combinations of renewable energy driven desalination plants are discussed with some recent highlights in solar energy driven membrane, thermal and hybrid desalination processes. Technological readiness levels for novel desalination processes, their perceived impact and expected near-future developments in renewable energy integrated desalination technologies are presented. Finally, the potential for solar driven desalination as a cost-competitive freshwater supply alternative is discussed.

Keywords: desalination, energy efficiency, energy storage, renewable energy, solar energy, zero liquid discharge

1. Introduction to Desalination

Increasing populations as well as pressing concerns over both quality and quantity of surface and groundwater sources have led to the use of desalination technologies for freshwater production in many inland and coastal communities across the world (Gude, 2017; 2018). Once considered energy-intensive and cost-prohibitive, desalination technologies are now being embraced and are considered as important elements of water portfolio for many communities (Gude, 2016). Desalination can be performed through thermal or mechanical (pressure) means by evaporation/ condensation and membrane filtration techniques. Electrical energy can be directly applied to cause ion separation in processes called electrodialysis. All these separations require significant quantities of energy in the form of heat and/or electricity (Gude, 2015). Thermal technologies

depend both on heat and electricity for separation of freshwater from saline water while membrane technologies require electrical energy, which is converted to mechanical energy, for separating the dissolved solids from the saline water. A generic desalination scheme is shown in **Figure 1**. Saline water (mainly brackish or seawater) is subjected to pre-treatment prior to the main desalination operation, followed by post-treatment of distillate or permeate to meet the drinking water standards and consumer requirements. Pre-treatment may include disinfection and addition of chemicals to prevent scaling, biofouling, and corrosion. It may also include filtration in a reverse osmosis process (Gude, 2011). Post-treatment is necessary to increase the pH and hardness. Brine or concentrate produced from the process is managed and disposed through appropriate means. Energy requirements for desalination process are typically supplied by burning fossil fuels, the most common configuration involving combined water and power production collocated at the same site. In an effort to make the desalination application more sustainable, renewable energy sources, especially solar and wind are increasingly adopted for providing the energy needs (Gude et al., 2010; Fthenakis et al., 2016; Fthenakis, 2017).

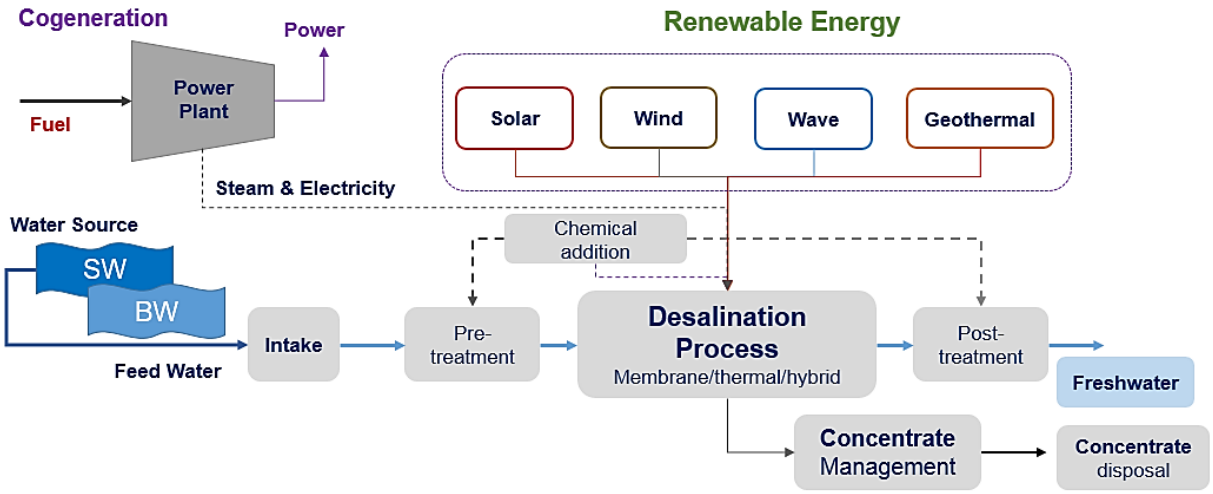


Figure 1*. Generic diagram for desalination processes powered by renewable energy sources including pre-treatment and post-treatment (source water refers to SW: seawater; BW: brackish water or ground water). Water and power production is achieved simultaneously in a cogeneration scheme. Renewable energy sources can be used to match the desalination energy needs.*

1.1. Desalination – Principles and Processes

Desalination processes, in principle, can be classified as phase change, non-phase change and hybrid processes (Gude et al., 2010). Phase change processes involve heating of the feed water to produce salt free product. Freshwater from the feed water is evaporated on a heating surface (evaporating surface) leaving the salts behind. The freshwater vapor is then condensed in cooling tubes (evaporating surface in the next stage) producing a high quality salt-free product. Technologies based on phase change processes are called thermal technologies, examples of which are solar stills (SS), multi-effect distillation (MED), multi-stage flash distillation (MSF), mechanical vapor compression (MVC), and thermal vapor compression (TVC). MED process can be designed to operate at either high temperature (e.g., ~>90°C) or low temperature (e.g., ~50-70 °C) ranges.

Non-phase change processes involve separation of dissolved salts from the feed water by applying mechanical pressure or voltage gradients. In pressure-driven systems (e.g. reverse osmosis –RO), a semi-permeable membrane barrier is used to separate the dissolved solids to allow water to permeate through the membrane. In voltage driven processes (e.g., electrodialysis –ED), voltage is applied across two electrodes to create an electric field and electrical charges that allow for ionic separation from the feed water. Positively charged ions will migrate towards the cathode while negatively charged ions migrate towards the anode. Hybrid processes integrate the operating principles of phase change and non-phase change separation techniques in a single unit or in the form of novel materials or in sequential steps to produce freshwater. Some of these processes are membrane distillation (MD); and reverse osmosis combined with forward osmosis (FO), MSF or MED processes.

1.2. Energy requirements for desalination

The energy required for unit freshwater product is expressed as "Specific Energy Consumption" (SEC) with units of kWh/m^3 (Gude 2011, Rao et al., 2018). SEC includes both heat and electricity requirements for thermal processes and only electrical energy for membrane processes. Energy costs are around 40-60% of the total freshwater costs through desalination (Zaozo and Prats, 2018). MED and MSF processes require about 45-320 kWh_t/m^3 of thermal energy and 1.5-3 kWh_e/m^3 electricity for pumping serving water intake and brine and distillate disposal (Gude et al., 2010; Shahzad et al., 2014). The MED-TVC and MED-MVC configurations require 45-128 kWh_t/m^3 (corresponding to a Gain to Output Ratio, GOR, of 14 and 5) and 8-15 kWh_e /m^3respectively. Seawater reverse osmosis process (SWRO) requires about 3 kWh_e/m^3 for the Mediterranean Sea, Atlantic and Pacific oceans, and 4 kWh_e/m^3 for the Arabian Gulf) including pre- and post-treatment. Brackish water desalination processes require 1.5-2.5 kWh_e/m^3 (for salinity in the range of 5,000-20,000 ppm) (Hanshik et al., 2016). The specific thermal energy consumption values for MSF, MED and MED-TVC processes vary between 250 and 300 MJ/m^3, 150 and 220 MJ/m^3, and 160 and 240 MJ/m^3, respectively (Gude et al., 2010). The ability of waste heat utilization by thermal desalination plants allows for combined water and power production schemes known as "cogeneration".

The thermodynamic limit for separating the dissolved salts from the saline water to produce freshwater using a semi-permeable membrane at a 50% separation efficiency is 1 kWh_e/m^3 or 3.6 MJ/m^3 (Gude 2011). However, current practical energy consumption is about 2-4 kWh_e/m^3 or 7-14 MJ/m^3 for membrane processes. These values translate to 12-18 kJ/kg of freshwater and 260 MJ/m^3 as thermodynamic and practical limits for thermal distillation processes. Current zero liquid discharge (ZLD) technologies, such as crystallization or vaporization are additional to initial desalination, adding 20 kWh_t/m^3 (72 kJ/kg) energy consumption (Bond and Veerapaneni, 2007).

Several approaches have been taken to improve the energy footprint of the desalination technologies. These include energy recycling and recovery, process hybridization, process modifications, integration with renewable and process waste heat sources to be discussed in later sections. Several emerging technologies have been evaluated to reduce the energy intensity of the desalination process. Some of the low-energy configurations include forward osmosis, membrane distillation, low temperature thermal processes, adsorption desalination, low temperature distillation, and capacitive deionization (CDI) (**Table 1)**.

1.3. Desalination industry with respect to other water sectors

There are more than 20,000 desalination plants operating worldwide with a total operating capacity of 97.4 million m^3/d and a total contracted capacity of 104.7 million m^3/d (IDA 2019). Seawater desalination continues to represent the largest percentage of online global capacity at 59%, followed by brackish water applications at 22%, river water projects at 9%, and wastewater recovery and purification water systems at 5% each (Gude, 2016). As the desalination industry maintains steady market due to continuing demand, the water reuse sector is also advancing steadily around the world due to the need to conserve freshwater sources. The global water reuse capacity has almost doubled in the past eight years. It increased from 59.7 million m^3/d in 2009 to 118 million m^3/d in 2017 (IDA 2019). A commonality between desalination and water reuse sectors is that both utilize advanced membrane separation processes for producing high quality water for freshwater supplies or direct non-potable uses. For example, in Singapore, five such projects supply up to 40% of the nation's water demands (for nearly 5 million people) for non-potable uses. This water is produced through microfiltration, RO and UV disinfection processes with an energy intensity of about 0.7 kWh/m^3. Singapore aims to increase this capacity to 55% by 2060 (Pub.gov.sg).

The US desalination capacity is around 350,685 m^3 per day (or 128,000,000 m^3 per year). California is more advanced in water reuse sector than any other state in the country. Current freshwater extraction from conventional water sources such as surface water and ground water sources demands about 0.29 kWh/m^3. The state-of-the art membrane based desalination processes equipped with energy recovery devices require about 3-4 kWh/m^3 to produce freshwater from seawater feed. Although this energy intensity is 10-14 times higher than the conventional water supply systems, this alternative is usually considered in locations where conventional methods of freshwater supplies are challenging or not possible. For example, the city of San Diego imports more than 80% of its freshwater supplies, of which, 54% is transported from Colorado River at an energy intensity of 1.6 kWh/m^3, 28% is transported through State Water project at an energy intensity of 2.5 kWh/m^3 and 18% is supplied through local sources at an energy intensity of 2.6 kWh/m^3 (Plappallly and Lienhard, 2012).

Desalinated water costs have also become comparable to conventional water supplies. Some recent projects in the Middle East are proposing desalinated water costs of \$0.5/m^3 (Molinos-Senante and González 2019). The water reuse technologies provide potable water at around \$0.30 - \$0.40/m^3 (IDA 2019); capital and specific water production costs decrease as the plant capacity increases (AWWA 2019).

2. Energy efficiency in desalination processes

The energy demands for desalination have declined drastically over the past two decades due to significant process improvements, energy recovery devices, and new membrane developments that led to enhanced recovery of freshwater from saline water sources.

2.1. Thermal desalination processes

Thermal desalination processes offer the possibility to recover and recycle thermal energy in a number of stages and this has been the focus of the process developments during the last few decades. MSF, and MED processes are based on this principle. This makes the process energy reusable over 10 times in successive stages. Thermal technologies are preferred in regions where the seawater quality in inconsistent due to algal blooms and elevated seasonal temperatures. Some

of the important considerations for thermal desalination processes are keeping higher top brine temperatures as the performance is affected by the top and bottom brine temperatures. Heat recovery during vapor condensation is essential to good performance. This entails small temperature differences during heat transfer staging and high heat transfer coefficients. Source water composition matters as insoluble salts cause scaling at high top brine temperatures. Thermal energy, especially when obtained by solar and waste heat sources, should be considered as an important component in reducing water desalination costs.

2.1.1. Process Modifications

As the desalination product in thermal processes is dependent on the total temperature difference (i.e., seawater temperature and the top brine temperature), increasing the top brine temperatures (TBT) (from 90°C to 120°C) and modifying the process operating conditions can enhance energy efficiency and productivity. It should be noted that high quality heat source will be required to operate at elevated TBT, and this could be a major limitation in using a solar energy source. For example, such operation makes it more difficult to use solar heat from Parabolic Trough Concentrated Solar Power (PT-CSP) plants unless they are solely dedicated to desalination operations. Cogeneration from CSP is penalized by the high operating temperature but the solar thermal source does not need to be CSP, as it can be a non-concentrating solar thermal only generator as vacuum static collectors. Recirculating brines and rearranging the process flow schemes allow for enhanced energy efficiency and distillate output, which is a feasible option for MSF process, although the benefits are not quite substantial. However, this can be achieved with minimum retrofitting in existing thermal desalination plants. For example, by utilizing the brine in different stages (transferring from earlier stages to later stages to take advantage of the temperature differential for enhanced evaporation) to increase the evaporation potential will result in up to 2.1% of freshwater production and the corresponding specific energy consumption is reduced by 3.4% (Choi, 2016).

Top brine temperatures (TBT) in MSF process are usually maintained at 110°C to avoid scale formation. However, Hanshik et al., (2016) reported that increasing the top brine temperature from 110°C to 120°C has increased the freshwater production rate by 15.8% along with a 6.4% reduction in specific energy consumption. On the other hand, it was shown that increasing the TBP by 30°C did not indicate a significant improvement in specific energy consumption (Hanshik et al., 2016). In addition, corrosion and fouling potentials are higher at higher operating temperatures, and careful consideration should be given to heat transfer materials in retrofitting the process components.

MED is more energy-efficient than MSF and further energy reduction was made possible by combining the process with a thermal vapor compressor (TVC) or mechanical vapor compressor (MVC) (Hanshik et al., 2016). In these technologies, the Gain Output Ratio (GOR), which is defined as the quantity of tons of water produced per ton of initial steam can reach 15, significantly higher than the maximum value of 11 for MSF (Ophir & Weinberg, 1997).

Also, in MED processes, using oval shaped corrugated tubes have increased the heat transfer coefficients by 70% compare to flat surface round tubes (Desportes, 2010). MED processes are often combined with TVC units for better operating flexibility and higher energy efficiency. A portion of the vapor generated in an intermediate or the last effect of the MED unit is recompressed in the thermo-compressor (steam ejector) to reduce the heat loss and to be reused as energy source for the first effect. This way energy efficiency is increased through the reduction of the amount of steam required to drive the distillation process and the specific power

consumption is also reduced by decreasing the cooling requirements of the condenser at the end of the process circuit.

Other developments in thermal desalination processes include integration of MED-AD to enable enhanced energy recovery and product output. The MED-AD process integrates the conventional MED process with an adsorption cycle to extend the operable temperature range of the conventional MED unit (Shahzad et al., 2014). Typical top brine temperature for MED is around 65°C with low brine temperatures of around 40°C. With this integration, the low brine temperature can be reduced to 5°C while keeping the top brine temperature the same, allowing for more stages for enhanced energy utilization and water recovery. Higher recovery of freshwater enabled by this configuration will generate more concentrated brine in the latter stages but likely with less fouling or scaling issues due to lower operating temperatures. Shahzad et al., 2015, report that this configuration could increase freshwater production rates by a three-fold. In another study, it was shown that MVC-AD combination has the potential to improve the desalinated water production by up to 45% (Askalany, 2016). Silica and Zeolite are used as adsorption materials in these systems.

2.1.2. Cogeneration

Cogeneration scheme has enabled low-cost energy input to desalination processes and the overall economics are significantly favorable compared to stand-alone desalination and power generation units. Hybridization of different thermal and membrane processes has also been considered for energy utilization. These include MSF-RO combination and MSF-MED-RO configuration among others. The premise for these hybridizations is to exploit the benefits and constraints of the individual processes. For example, higher feed water temperatures allow for higher water recovery in addition to utilizing the less concentrated brine water from thermal desalination process. In a cogeneration scheme, hybridization of thermal and membrane desalination processes in colocation with power plants, allows for better management of capital investments and environmental permitting while maximizing the process outputs with optimum energy consumption. The reduction in energy consumption can be attributed to the common or one-time requirement for pre-treatment, feed water intake, conveyance and transport in the combined processes.

2.2. Commercial Membrane desalination processes

The energy consumption in membrane desalination processes has been significantly reduced over the past three decades (see **Figure 2**). This was possible mainly due to the improvements in high performance membranes with higher flux and salt rejection capabilities, which also reduce the high pressure requirements for membrane separation. Fouling resistance of membranes has also been improved in recent years by modifying membrane characteristics such as hydrophilicity, surface roughness and concentration polarization at the membrane surface. In addition, incorporation of energy recovery devices and improvements in performance of high pressure pumps and booster pumps have contributed towards lower energy consumption. Further, innovative process configurations like closed circuit desalination, batch or semi-batch, and integration with other membrane processes such as forward osmosis have become important strategies to minimize the energy consumption in plant operations.

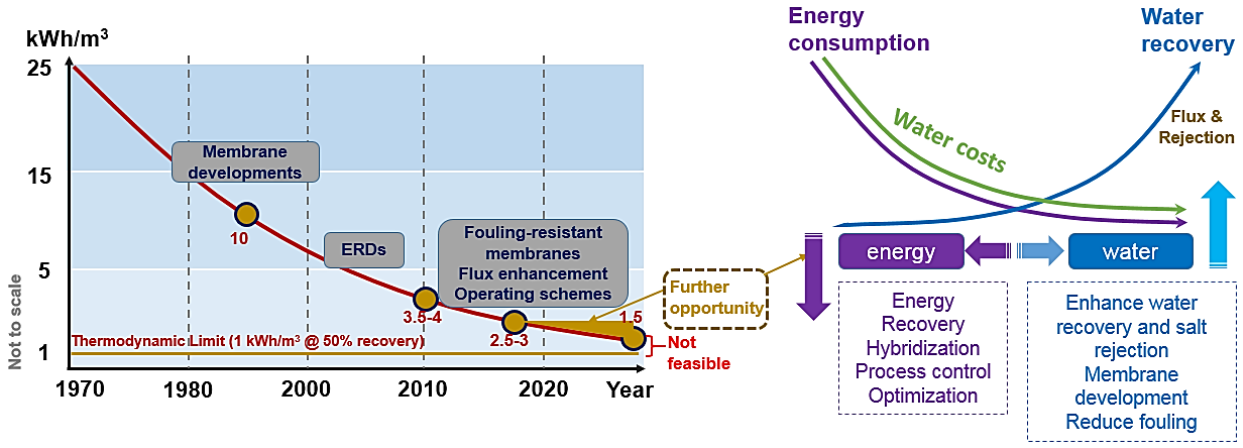


Figure 2*. Specific energy consumption trends in membrane desalination and further opportunities and strategies for improving water desalination costs.*

2.2.1. New membrane development

The performance of the pressure-driven membrane desalination systems is highly dependent on the membrane material (Goh and Ismail, 2014); several novel materials have been developed in recent years. Thin film nanotechnology in nanocomposite membranes has advanced to industrial applications. The application of zeolite and other interfacial polymerization techniques help increase the water permeability while enhancing the salt rejection or increase the hydrophilic nature of the membrane surface to minimize fouling (Subramani et al., 2015). These membranes have also decreased the specific energy consumption, due to the increased water flux, to 1.73-2.49 kWh/m^3. Other interesting developments include aquaporin membranes, nanotube membranes and graphene based membranes. Aquaporin membranes possess high permeability with nearly 100% rejection of dissolved molecules at osmotic pressures (Kumar et al., 2007). However, these membranes are still at bench-scale and more advancements are needed to improve their chemical resistance and mechanical strength. Nanotube membranes provide high permeability and high salt rejection rates (Das et al., 2014), but similar to aquaporin membranes, these membranes require further developments to study their practical feasibility. Graphene-based membranes are currently studied widely due to the possibility of developing more robust and high efficiency membrane materials (Surwade et al., 2015). These materials offer high surface area, high mechanical durability, atomic level thickness, nano-size pores and reactivity toward polar and non-polar water pollutants. Such characteristics impart high selectivity and water permeability providing enhanced separation efficiency (Homaeigohar & Elbahri, 2017).

2.2.2. Energy recovery devices

Seawater RO desalination systems are equipped with energy recovery devices to reduce energy requirements and to improve desalination water costs (Gude, 2011). After passing through the membrane, permeate (product) pressure is reduced to near atmospheric pressure while the concentrate retains most of the pressure energy from the feed water pump. An energy recovery device captures the energy embedded in this stream and reduces by one half the overall process energy requirements (Mohamed et al., 2008; Dimitriou et al., 2015).

Commonly used energy recovery devices are either centrifugal turbochargers or isobaric devices, which include pressure exchangers, also called work exchangers. Centrifugal turbochargers

convert the hydraulic energy embedded in the concentrate stream into mechanical energy to assist the high-pressure pump motor. The first energy recovery devices were of Francis-type turbines which were replaced by higher efficiency Pelton turbines. Pelton turbines are widely accepted in SWRO plants due to proven reliability. These devices have energy recovery efficiencies of between 60% and 85% (Gude, 2011). A pressure exchanger transfers hydraulic energy directly from the concentrate stream to the incoming seawater across a piston, using positive displacement technology. These devices can have energy recovery efficiencies of up to 96%. While the natural inclination is to use the most efficient device possible (i.e., a pressure exchanger rather than a Pelton wheel), it is necessary to evaluate the system as a whole for each specific application. Each device has its own merits: Some offer a greater degree of operating flexibility, while others offer a lower capital cost or higher efficiency (Drak and Adato, 2014).

Other process control and improvements include semi-batch or closed-circuit RO operation which has the potential to operate at near 100% recovery of freshwater by recirculating the concentrate in a number of cycles flushing out the concentrate and restarting the semi-batch or closed-circuit operation. This operation mode could reduce the specific energy consumption by 15-20%, down to 2.5 kWh/m^3 for seawater reverse osmosis (Amy et al., 2017).

2.3. Emerging Technologies and Hybridizations

Desalination process hybridizations can be motivated by various objectives: (i) Increasing water recovery; (ii) reducing energy consumption or enhancing energy recovery; iii) maximizing the use of renewable energy, and (iv) minimizing concentrate volumes. Utilizing osmotic processes such as forward osmosis (FO) for pretreatment is an attractive alternative as several combinations of FO process with membrane distillation (MD) and RO processes can be envisioned. Some of the configurations include FO-RO; FO-MD; and RO-MD. A recent study estimated the energy and exergy of various hybridizations in power-water cogeneration schemes and determined that hybridization of multiple desalination systems can help in reducing energy requirements (Altmann et al., 2019).

Membrane Distillation (MD) is driven by a vapor pressure difference at two sides of a microporous hydrophobic membrane (Yarlagadda et al., 2009). The difference in vapor pressure is typically achieved by the temperature difference between the hot feed water and cooler condensate sides. It has been well studied at laboratory- and pilot-scales, and technology developments have been reported recently. However, commercial implementation of MD has not been achieved yet, primarily due to the high energy consumption and membrane development challenges. Most of the energy needed is in the form of thermal energy, which makes it a suitable candidate for solar collector and CSP thermal applications. Even more, MD has the potential to be integrated with RO, which is currently the most economic desalination method, to utilize the brine from RO and condense it further towards achieving ZLD. Commercial MD systems with increased thermal efficiency could utilize either multi-effects or modules with spiral membranes and heat recovery. The challenge is in minimizing heat transfer/heat losses while maximizing mass transfer along the membranes.

Existing MD pilot plants use mostly flat sheet membranes in plate and frame and spiral-wound modules. Modules based on hollow fibre membranes are also considered, as well as the concept of multi-effect vacuum membrane distillation for improved heat recovery. MD possesses unique potential for providing a low-cost alternative for small-scale applications especially since it can use waste heat available at low cost (Yarlagadda et al., 2011). Initial designs were energy-prohibitive, however, recent investigations at the Plataforma Solar de Almeria show that vacuum-

assisted air gap MD technology could reduce SEC to levels that the technology becomes cost competitive (Zaragoza et al., 2018; Andrés-Mañas et al., 2018). Also, a recent investigation on multi-stage (4 stage) vacuum membrane distillation process has shown potential for significant energy reduction and increased freshwater production rates through an internal heat recovery configuration (Burhan et al., 2019).

FO is evolving as a promising technology for desalinating/cleaning high concentration waters produced from oil and gas extraction. Such waters have TDS values >100,000 ppm and cannot be treated with RO. In this case, the water is typically disposed of, at high cost, by transportation away from the site when disposal wells are unavailable. These systems may be of smaller scale and mobile. The characteristics of this market (high salinity water, typically isolated, off-grid, with high brine disposal costs) justify a higher cost. In this context, particular interest is given to technologies that can achieve zero-liquid discharge driven by solar thermal energy (US-DOE, 2017).

3. Renewable energy utilization

Water supply through renewable energy driven desalination is considered costly and to address the issues related to demand-supply and intermittence in availability, several novel concepts to increase energy efficiency have been proposed and studied. These include configurations beyond cogeneration allowing for maximum utilization of renewable energy sources. Among the renewables, solar energy resource is unarguably a distinguished candidate. About 40 minutes of sunlight could supply the global energy needs for a year (Zweibel et al., 2008). This represents a great potential for solar-powered desalination in arid and high-solar insolation regions with abundant brackish or saline water reserves. Wind and geothermal sources are also promising candidates for energy sources due to their high capacity factor (Gude, 2016), although these sources are not as geographically abundant as solar energy. Integrating different types of renewable energy sources can be a cost-effective and reliable option in some applications.

3.1. Desalination technology – renewable energy combinations

Potential renewable energy-desalination technology combinations are shown in **Fig. 3**. Renewable energy sources, in general, should be integrated with the most relevant desalination technology that has the capability to utilize the available energy in the most effective manner. Thermal desalination-renewable energy combinations require co-location whereas membrane-based ones do not, as electricity can be produced elsewhere and efficiently transmitted to the desalination plant (Gude, 2015).

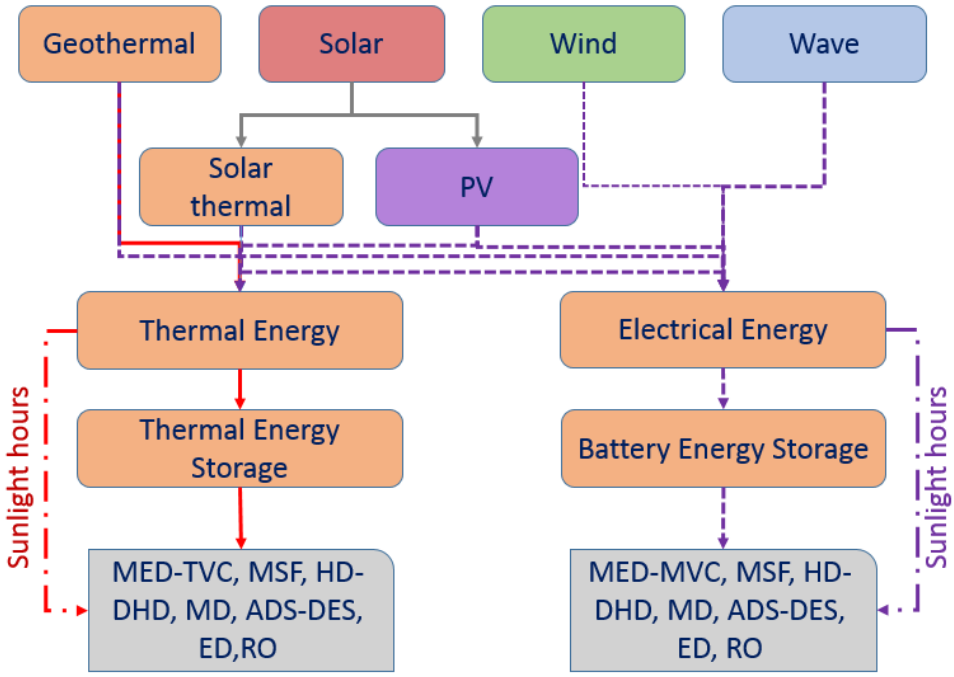


Figure 3. *Desalination technologies coupled with renewable energy and storage systems (PV-photovoltaic; MED, multi-effect distillation; MSF, multi-stage flash distillation; HD–DHD, humidification-dehumidification; MD, membrane distillation; ADS-DES, adsorption desalination; TVC-MED, thermal vapor compression MED; MVC, Mechanical vapor compression; ED, electrodialysis; RO, reverse osmosis (adapted from Gude, 2015).*

Among the renewable energy driven desalination systems, PV-RO's share is about 31% followed by wind-RO (12%), solar MD (11%), solar MED (9%), solar MEHD-DHD (multi-effect humidification and dehumidification) (9%) solar MSF (7%), and other combinations (Papapetrou et al. 2010). Solar powered water desalination has the potential to dramatically increase availability of fresh water in arid locations, which by virtue of their topography and climate have large solar resources.

3.2 Low-Cost Solar Still Thermal Desalination

Solar still is the oldest technology for desalination of saline water; a system constructed in Las Salinas, Chile in 1872 served the needs of a mining community there for 40 years till the mining site was decommissioned (Frick and Hirschmann, 1973; Abdenacer and Nafila 2007). This plant used about 4700 m^2 solar still area to produce 20 m^3 of distilled water per day in a single stage still configuration (Frick and Hirschmann, 1973). Stills use solar energy directly to evaporate freshwater from the saline water source, which in turn condenses on the ceiling of an enclosure and collected at the bottom. Although this process may provide low-cost and low carbon-footprint option for desalination, it is limited by large evaporation area requirements, low energy efficiency, and low product yield and. The solar still's efficiency is about 30-45% (Gude 2015). Due to its simplicity and ease of operation, this technology can play a significant role in addressing global water scarcity especially in low-income, near-coastal and high-solar insolation regions. Thermal insulation, energy absorption and storage in low-cost storage medium (for non-sunlight hour

operation) and concentrators (reflectors) are essential for improve the performance of the solar still (Gude, 2015). However, the productivity is still affected by the inability to recover and recycle the evaporative energy in a large number of stages. Three-chamber solar still is the most commonly studied configuration. Solar energy harvesting can be enhanced in still desalination by (i) concentrating solar energy; (ii) confining the energy to water at the evaporation surface; and (iii) by storing excess or unused energy in a storage medium for use during non-sunlight hours.

Many materials have been investigated for their potential to enhance solar energy utilization in solar still processes. Alumina, gold and other nanoparticles, graphene, wood, black titania and hydrogels were used (Li et al., 2016, Zhou et al., 2016, Liu et al., 2017, Yang et al., 2018). These materials have shown solar to heat efficiencies of 92%, 83%, and 71%, respectively (Ahmed et al., 2019). Recent studies aimed at addressing the low energy-efficiency in solar stills have focused on novel 2-dimensional structures for enhancing energy capture and vapor production to increase both energy efficiency and water production. For example, Li and co-workers (2016) have developed a 2-dimensional foldable graphene oxide film, which enables efficient solar energy absorption (>80%) to be directly used for water vapor formation increasing the yield of the process. The high efficiency is mainly due to broadband and efficient solar absorption (AM 1.5 G weighted absorbance of ~94% for 200 nm to 2,500 nm) along with suppression of conduction heat loss from absorber to bulk saline water. Graphene based 3-dimensional cross linked honeycomb foam material developed by Yang and Coworkers (2018) has resulted in evaporation rates of 2.6 kg/h-m^2-per g of material, with nearly 87% energy efficiency. A single sheet of graphene foam can act as efficient solar thermal energy capture and conversion device. A bilayer structure composed of wood and graphene oxide material has shown a thermal efficiency of nearly 83% (Liu et al., 2017). Wood is an abundant, naturally occurring, biocompatible material that allows for water transport from the bulk to photo-thermally active layer at the evaporative surface. The broad optical absorption spectrum of wood overlaps with the solar spectrum causing temperature rise under solar insolation. This material is highly scalable and cost-efficient with promising applications in solar stills and other solar thermal processes. The evaporative enthalpy of water is reduced by hydrogel network. A hydrogel based solar evaporator can produce nearly 2.5 kg/m^2-h at a solar irradiation of 1 kW/m^2 (Zhou et al., 2018). The hydrogel consisted of hydrophilic polymers such as polyvinyl alcohol, PVA and solar absorber material reduced graphene oxide. A salt-rejecting evaporation structure floating on the saline water bodies can produce freshwater at a rate of 2.5 kg/m^2-d at a material cost significantly lower than the conventional solar stills (Ni et al., 2018). As reported by Mashaly et al., 2016, solar stills can also be used for treating hypersaline waters in zero-liquid desalination schemes.

There have been modification and integration efforts to improve the solar still performance (efficiency) and productivity (Gaur and Tiwari, 2010). Various types of design (double and triple effect and various geometrical dimensions including shape and slope of the condensing surface) were also considered (Prakash and Velmurugan, 2015). Storage materials such as water, oil and sand (sensible storage material) and phase change materials (PCMs, e.g., paraffin and wax) were also used to enhance energy capture and store excess energy for use in non-sunlight hours (Gude, 2015). When sand was used as sensible heat storage material, the product yield was improved by 24% (El-Sebaii et al., 2009). Lauric acid and myristic acid as PCMs have improved the yield by 36% (Al-Hamadani and Shukla, 2014). With stearic acid, the efficiency was improved by 85% (El-Sebaii et al., 2009). Conventional solar still when operated under forced and natural circulation modes has improved the yields by 24% and 33%, respectively. When integrated with a flat plate solar collector, the yield of a conventional solar still was increased by 36% to 52%. When a solar

still was connected with a hybrid PV/Thermal collector, a 3.5-fold increase in product yield was reported (Kumar and Tiwari, 2008). In these systems, not only the yield of solar still has increased, but the thermal and electrical efficiencies of the PV/T collectors were also improved (Gaur and Tiwari, 2010; Satyamurthy et al., 2017; Singh 2018; Manokar et al., 2018). Overall, the findings from these studies suggest that the solar still product yields can be improved in general, but the cost-effectiveness and the environmental burden of the integrated configuration should be evaluated in detail.

3.3 Solar-Powered Multi-Effect Distillation

Multi-effect distillation (MED) is currently the most thermodynamically efficient among the commercialized thermal desalination technologies. Its coupling with solar thermal energy has been intensely investigated, both experimentally and analytically, at the Solar Desalination Unit of the Plataforma Solar de Almeria (PSA) and other facilities. The PSA pilots include flat-plate solar collectors, concentrating solar power (CSP) parabolic trough units, and thermal storage units connected with a 14-effect MED pilot plant (Chorak et al., 2017).

Flat-pate static solar collectors can drive a LT-MED process of relatively small size. However, large MED plants would require a large field of solar collector and many interconnections that would create unfavorable economics affected by capital and operating expenditures (Alhaj and Al-Ghamdi 2019). CSP on the other hand, requires a much smaller footprint for desalination. CSP supported desalination configurations have been proposed for various capacities and for various processes. These include CSP-MED (700-1,400 m^3/d), CSP-MED-TVC (4,545-9,000 m^3/d), CSP-MED-MVC (4,545 m^3/d), CSP-MSF (5,000 m^3/d), CSP-RO (28.8 m^3/d), CSP-Hybrid RO-MED (MED -1224 m^3/d and RO-19,372 m^3/d), and CSP-Hybrid RO-MED/TVC (7,600 m^3/d) (Mohammadi et al., 2019). CSP powered membrane distillation (Soomro and Kim, 2018) and low temperature distillation (Wellmann et al., 2018) processes have also been considered. We also note that the economics for cogeneration are more favorable for large capacities. CSP systems can be designed to support either thermal desalination, or electricity driven membrane desalination or a combination of the two processes.

3.4 PV-RO Desalination

The PV industry has accomplished phenomenal cost reductions through improving efficiency in the stages of manufacturing and deployment. The prices of photovoltaic electricity have been reduced to levels in parity with unsubsidized electricity rates in arid areas of high solar irradiation that need to expand the capacity of water desalination. Ten years ago utility scale PV systems were sold for $4,000 per kW, but now they are producing electricity with $1,000 per kW capital investment (Fthenakis, 2009, Green 2019). Solar energy integration and implementation costs become even more attractive with increasing scales of deployment. Scaling up of solar energy applications include electrification of transportation and production of hydrogen. To make this a reality, several infrastructure and policy/regulation related challenges need to be addressed. A Solar Grand plan for the year 2050 calls for $400-billion-dollar investment over the next three decades to meet up to 69% electricity needs in the U.S. by solar energy, while reducing greenhouse gas emissions by 62% (Zweibel et al., 2008; Fthenakis et al., 2009). The plan's projections of PV cost reductions by 2020 were accomplished two years early and more cost reductions are expected by 2030. In addition to low PV electricity costs, PV-RO has been the most commonly used technology due to its inherent simplicity, ease of operation and elegant nature. Photovoltaic energy

can be used to power electrodialysis and hybrid combinations including membrane and thermal processes. Most of the installations are in capacities less than 100 m^3/d (Gude et al., 2010, Gude 2015, Younos and Lee 2019); designs include autonomous systems with and without batteries operating in small island grids (Karavas et al., 2019). Also, recent studies pointed out to the feasibility of flexible systems that can handle some of the variability of solar energy resources (Atia and Fthenakis, 2019; Dimitriou et al., 2017; Kyriakarakos et al., 2017).

Another study examined cost reductions in small, stand-alone systems via smart combination of water and solar electricity storage (Fthenakis et al., 2016b). The study identified pathways for reducing the levelized cost of water (LCOW) production from seawater, via integration of PV into existing desalination plants, integration of PV and solar thermal technologies, and combinations of solar RO with conventional thermal desalination technologies. Such combinations could significantly decrease operating and maintenance (O&M), land, and grid integration costs.

Figure 4 shows the development stage and capacity range for various renewable energy driven desalination technologies. Some of the renewable energy desalination schemes have not yet been well-studied. It can be noted that small and novel applications for geothermal and wave energy technologies are in the basic research phase while the solar energy based desalination schemes have advanced to wide applications. Wind and geothermal energy sources are suitable for large scale applications. Desalination processes such as MD may find wide applications for solar and geothermal energy utilization for desalination. However, at this point, the large cost of the solar thermal energy hinders the commercial viability of solar MD when PV-RO is feasible, so the niche for solar MD in desalination is mostly brine concentration (Zaragoza et al., 2018).

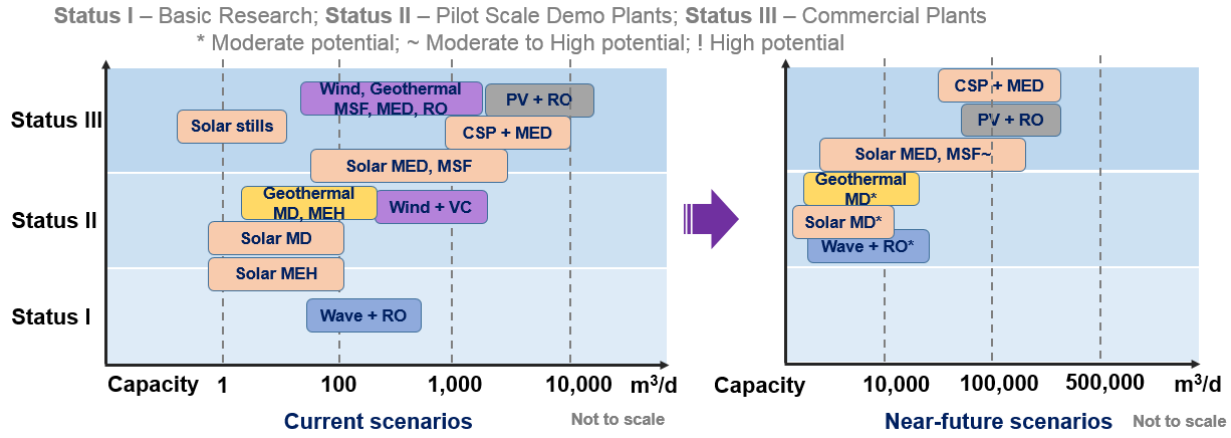


***Figure 4**. Comparison of technical advancement levels of different renewable-energy-driven desalination technologies.*

Currently, the largest operating renewable energy driven desalination plant is a cogeneration (CSP + MED) plant in Australia (Sundrop Farms, 2016), with 1,200 m^3/d, and the biggest proposed are a 30,000 m^3/d –expandable to 60,000 m^3/d PV-RO plant in Saudi Arabia (Metito, 2018) and a 227,232 m^3/d PV-RO in Chile (Molina, 2018). Powering RO desalination

plants via PV results in significant cost savings when both the direct costs and those of the fuel subsidies are considered. On a non-subsidy basis, the cost of electricity from photovoltaics has become comparable to that of electricity in the GCC countries (Ferroukhi et al., 2016); this is exemplified by a new contract to provide PV electricity for 5 US¢/kWh or less in the UAE. For comparison, the residential electricity rates in Abu Dhabi are 6 US¢/kWh and they do not reflect full cost recovery. With current subsidized rates, adding 10% of PV electricity into an existing RO plant would influence the cost per cubic meter of water produced by 2.5%, while reducing the carbon emissions of the plant by 10%. The value of integrating the simple solar output of PV power plants is also based on the fact that with little output profile adjustments, there is a direct complementarity between the output of thermal power plants and solar PV plants based on the reduction in ISO efficiency of the engines/turbines in these power plants during midday temperatures especially in areas like the GCC (**Figure 5**).

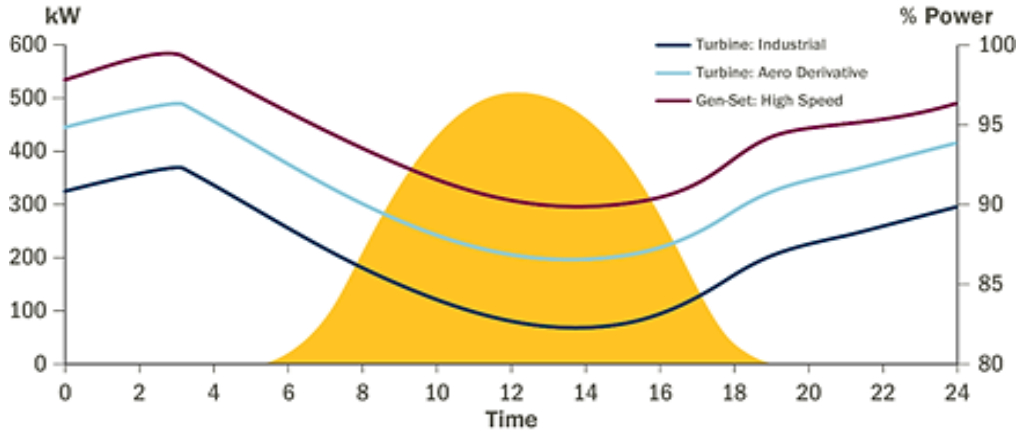


Figure 5*. Thermal and solar PV power plant outputs illustrate a complementary relationship due to mid-day thermal power efficiency reductions*

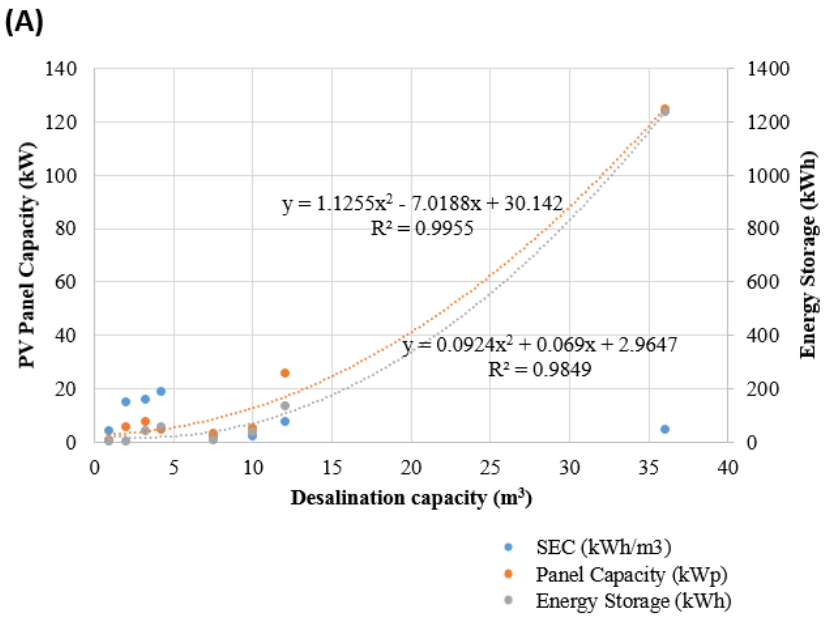
The potential also exists for grid-connected PV to provide up a fraction of the electricity used in RO plants enabling significant CO_2 emission reductions in the Gulf countries. Fthenakis et al (2016a) estimated that if the RO desalination industry in Saudi Arabia starts using solar electricity, up to 44% of the annual load of RO plants can be supplied. This would displace nearly 120 million barrels of diesel fuel per year resulting in 51.5 million tons per year reductions in CO_2 emissions. Another study indicates a potential for PV and grid-connected desalination creating a flexible supply and demand system that could provide ancillary services to the California electricity grid and generate additional revenue.

3.5 Energy storage

Due to the relative ease of storing thermal energy (i.e., by storing hot fluids or other materials) solar thermal energy is a unique complement to other forms of renewable energy that rely on intermittent sources (e.g. photovoltaics and wind). While daily thermal energy storage allows desalination plants to operate continually, seasonal variations still need to be considered when assessing the economic advantages of solar thermal desalination. Desalination technologies that utilize thermal energy and thus require thermal energy storage (TES) for uninterrupted process operation are MED, MSF, low temperature MED (LT-MED), humidification-dehumidification

(HD) and membrane distillation (MD). Thermal energy storage technology requires a suitable medium for storage and circulation for heat transfer while the photovoltaic/wind generated electricity can be stored in batteries. Thermal energy storage enables operation round the clock and higher reliability. Phase change and non-phase change storage materials can be utilized to capture extra energy for storage and its later usage. Application of storage materials depends on the temperature needs. Water is the most commonly used non-phase change material and is suitable for low temperature applications. Mineral salts (e.g., $NaNO_3$, $MgCl_2$ and Na_2CO_3), oils and paraffin can be used with both low temperature and high temperature desalination. Another category of storage materials is thermochemical materials which are CaO, MgO, $MgSO_4$, silica gel, and zeolite. In cogeneration (water-power) schemes, molten salts, water and high temperature oils are used (Gude, 2015).

Battery energy storage (BES) is essential to store electrical energy for electrodialysis (ED), reverse osmosis (RO) and mechanical vapor compression (MVC) technologies. **Figure 6** (A) shows relationships between PV panel capacities (kW), energy storage (battery size, kWh) and the seawater RO process capacity. Similarly, **Figure 6** (B) shows relationships for brackish water RO process capacity. The PV panel capacity and battery energy storage exhibit similar profiles for both scenarios. However, there are significant differences in the panel area and energy storage requirements as the specific energy consumption for desalination depend on the source water quality. Panel area and energy storage quantities also depend on local climate, solar insolation and panel and battery capacities and design materials. Data shown in Figure 6(A) and 6(B) are gathered from different studies with varying design bases.



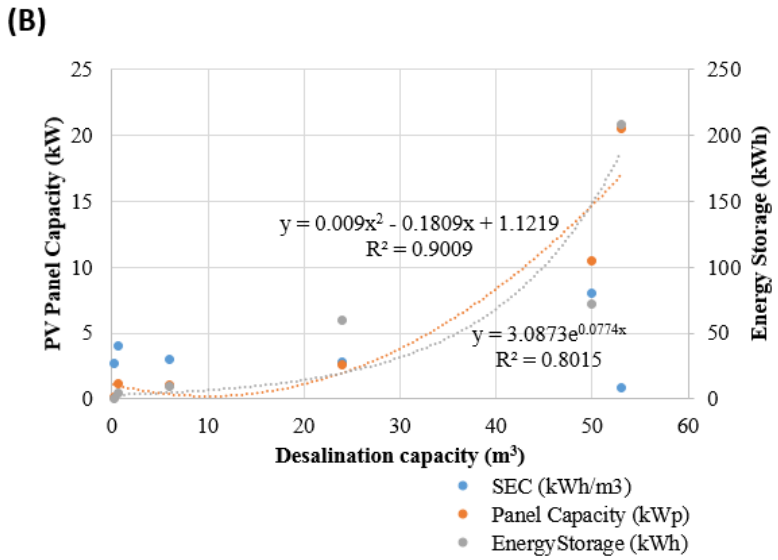


Figure 6*. Relationships between the RO desalination capacity, PV-panel capacity, and battery storage capacity: (A) seawater RO; and (B) brackish water RO. Note that specific energy consumption varies with the feed water composition and the pre- and post-treatment schemes (Data source: Gude 2010 and 2015).*

Other concepts for sustainable and energy-affordable desalination include pumped hydro energy and water storage in lieu of battery storage. Desalination can be made more affordable in situations where a low cost electrical energy can be used during non-peak hours, and in integrated energy-desalination designs where the plant can supply ancillary services to the grid (Atia and Fthenakis, 2019). In some cases, water storage can provide a solution for mitigating the variability of renewable energy supply-demand (Tafech et al., 2016).

4. Current Challenges

4.1. Concentrate management and energy consumption issues

One of the key issues related to desalination is the management of the effluent concentrate stream (brine). Current options for concentrate management in inland desalination plants include surface water disposal (41%), evaporation ponds (2%), sewer disposal (31%), deep well injection (17%), landfill disposal (2%), and other evaporation or irrigation systems (7%). Zero liquid discharge systems are being developed extensively to reduce the discharge volumes. Innovation, research and development activities in this area are motivated by the new USEPA effluent limitation guidelines (ELG), for power and produced oil and gas sectors in the US, new regulations on FGD streams and brine disposal in EU (European Union), new policies adopted in China to support the growth of heavy industries, and new discharge mandates developed by the Indian government to protect surface water pollution from inland thermal power plants, just to name a few. Consequently, the global cumulative installation capacity of ZLD systems is expected to be around 800,000,000 m^3/year in 2030 (Basu, 2017). Depending on the concentrate composition and desired end product use, the ZLD systems may employ ion exchange, membrane processes, evaporator or brine concentrator and crystallizer processes. Osmotically-assisted RO, semi-batch or closed-circuit RO, FO, MD, and RO-FO hybrids are suitable for ZLD applications. Specific energy consumption of thermal processes such as evaporator and crystallizer are expectedly high, about 43 kWh_t/m^3 for evaporator and 90 kWh_t/m^3 for crystallizer. However, combining FO with thermal

draw solution could reduce the specific energy consumption to 33 kWh_t/m^3, and FO with RO may achieve a SEC of 10 kWh_e/m^3 (Basu, 2017). Although membrane based systems provide low SECs, thermal based separations can be most cost-effective where waste heat sources are available.

4.2. Produced oil and gas water desalination energy requirements

The management of highly saline waters generated by conventional and unconventional oil and gas (O&G) recovery activities presents environmental challenges. For example, the saline water generation rate at O&G well sites can reach 1000 m^3/day, with as high as 300,000 mg/L total dissolved solids (TDS), and these effluents will be difficult to be treated by current water treatment processes.

Use of FO technology is proposed for such applications as well as for brine concentration either by itself, or in combination with RO and MD. MD is considered in similar applications coupled with forward osmosis (FO-MD), reverse osmosis (MD-RO), and reverse electrodialysis (MD-RED (Amy et al., 2017).

4.3. Other Environmental concerns

SWRO process emits ~1.4 kg CO_2 per cubic meter of produced water (Heihsel et al., 2019); this is a global average accounting for the use of fossil energy in regional electricity grids. The CO2 emissions in thermal desalination are much higher as they are 100% powered by fossil fuel combustion. Thus energy utilization in desalination contributes to significant environmental impacts in the forms of climate change, fossil depletion, marine eutrophication and ozone depletion (Mannan et al., 2019). Renewable energy integration allows for decarbonation of the process and this is the aim of the Global Clean Water Desalination Alliance (GCDWA, 2015), a multi-stakeholder platform launched at the 21st Conference of the Parties (COP21) of the United Nations Climate Change Conference in Paris. For example, solar photovoltaic systems have payback periods of less than a year in regions of high irradiation (Fthenakis and Alsema, 2006, Leccisi et al., 2016). In addition, a significant level of pretreatment of feed water is required (Yang et al., 2018). Brines generated from brackish water via an RO process (with 60-85% recovery) would have a concentration that is 2.5-7 times higher than the salinity of the treated water; the concentration factor of brines produced in seawater RO (with 30-50% recovery) would be between 1.25 and 2.0 (National Water Commission, 2008). Thermal desalination technologies have a wide range of recovery ratios between 15 and 50% with a concentration factor of 1.15 (due to cooling water mixing). MSF thermal desalination plants draw the source water equivalent to 8 or 10 times of the freshwater quantities produced in the plant, MED plants around 5-8 times, MED-TVC around 3.2-5, while RO plants draw a quantity of feed water that is about 3 times the produced fresh water (Morton et al.,1996; Sommariva, 2010). In addition to a higher water withdrawal, thermal desalination plants discharge brines at slightly higher temperatures, but their salinity is lower than membrane desalination plants. On the other hand, membrane desalination plants use more chemicals for pretreatment, control of membrane scaling and biofouling, and these end in the brine

5. Near-future developments in desalination

Fthenakis participated in an industry-academia workshop which complied expert opinions about the technology readiness of various desalination technologies and technology hybridizations that can be powered by renewable energy in order to minimize the carbon profile of the industry (Lienhard et al., 2016); a summary of these opinions is shown in **Figure 7.** On average, process

improvements for energy efficiency, hybrid desalination technologies, and advanced pretreatment technologies were rated as high impact and of high technology readiness. Salinity gradient energy recovery, forward osmosis, and membrane distillation were rated as relatively low technology readiness. These technologies have the potential to make an impact but they need more technological advancements. Next generation graphene-based membranes are also expected to make significant impact but they are still at the laboratory scale development. Regarding renewable energy and desalination technology combinations, PV-RO, and CSP-MED-RO technologies have matured technologically and have an excellent near-future potential. Some other combinations involving geothermal and wave energy sources have also a good potential. Among current desalination technologies, membrane based desalination plants are set to be the fastest growing in the near future. This is stemming from multiple factors, which include highly efficient energy (pressure) recovery devices, and implementation of new, larger and fouling-resistant membranes.

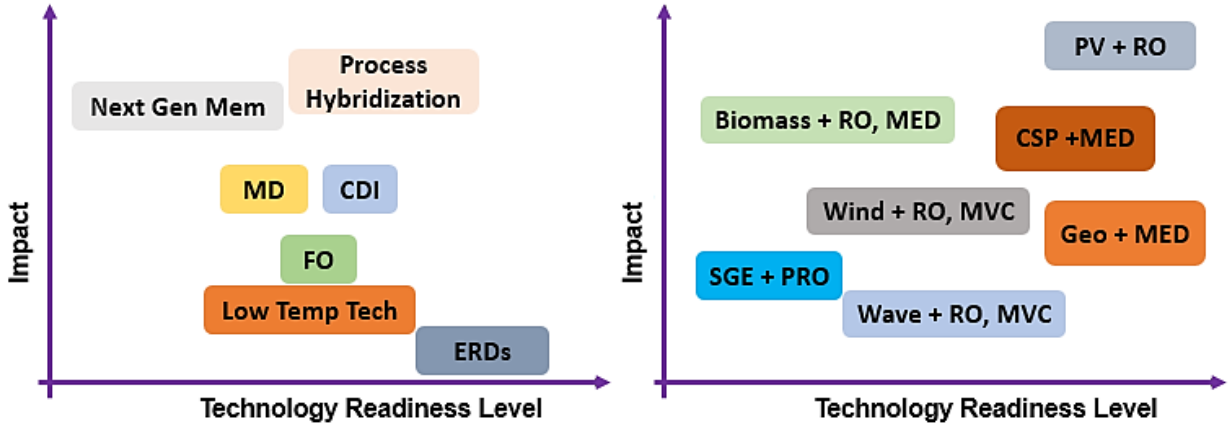


***Figure 7**. Technology readiness level and potential near-future impacts of research and development in desalination technologies and their integration with various renewable energy sources (based on Lienhard et al., 2016).*

Regarding thermal desalination plants, significant reduction in heat exchange material costs, increased use of waste heat, and brine reuse have resulted in improved water costs. In the Middle East region, integrated hybrid desalination plants that combine both thermal and membrane technologies are expected to evolve. These hybrid and integrated configurations will provide optimum solutions for combined water and power production. The most promising combinations for this application are by using MED, nanofiltration and RO systems. In addition, the GOR (Gain-Output Ratio) values for large MED plants have been improved and are expected to improve further. Similarly, larger diameter (16") membranes allow for reduced footprint and improved efficiencies and recoveries. Further, development of temperature resistant and fouling resistant membranes would increase flux and recovery from feed waters with elevated temperatures. Newer emerging desalination technologies take advantage of various processes including forward osmosis, osmotic power, membrane distillation, membrane nanotechnology and more futuristic ideas of desalination like bio-engineered bacteria able to consume specific ions and salt.

Currently available commercial thermal technologies, like MSF and MED, have matured a couple of decades ago and their growth curves have advanced well reaching saturation in market growth (Mayor 2019). This trend is mainly due to higher energy requirements and water production costs than RO. However, there are new market opportunities for MED due to the availability of low-cost thermal energy from solar and other renewable resources. Thermal desalination plants are also attractive from the design life which with retrofits can be about 40-50 years (Sommariva, 2001). As a comparison, the advancement of membrane technologies has been fairly recent and the longevity of these plants is not equally tested (Ziolkowska, 2015).

Membrane distillation is an attractive technology for solar-powered decentralized desalination that has not yet reached commercial scales (Zaragoza et al., 2014; Ruiz-Aguire et al, 2019). The main barriers are energy consumption and cost and increasing thermal energy efficiency is a pathway towards commercialization. Spiral wound air-gap membrane distillation (AGMD) process allows for internal heat recovery through multiple channels and stands out in terms of specific energy consumption when compared with plate and frame type flat sheet membrane distillation process. A pilot scale (10 m^3/d capacity) AGMD study has reported a GOR of 3.54 (or specific thermal energy (STEC) consumption of 183 kWh_t/m^3) indicating further need for improving energy efficiency (Lee et al., 2020). Recent research at PSA, Spain on vacuum assisted AGMD shows promise for STEC being reduced to about 50 kWh_t/m^3; new MD markets could be enabled if this target is accomplished.

Forward osmosis is also very promising, especially for high-salinity water desalination and ZLD applications. However, there is a need to develop efficient membranes for both MD and FO. An ongoing US-DOE R&D program (US-DOE, 2017) highlights the potential of solar thermal and solar hybrid desalination pathways projecting the feasibility of seawater desalination costs below \$0.50/m^3 (**Figure 8**) and it includes several projects on advancing MD and FO. The program supports R&D towards low-cost solar thermal energy desalination that could compete with RO in various markets. For example, agriculture has high water demands with runoff that is typically saline due to salts in the soil and groundwater occurring naturally or from fertilizer use. Produced water at oil and gas well sites can have particularly high salt content and is often generated away from grid infrastructure. This may be a particularly attractive market for solar thermal desalination that can operate off-grid in modular configurations. Thermal desalination, in general, has particular application for water with high total dissolved salt (TDS) content or for applications that require zero liquid discharge (ZLD), which RO cannot typically address.

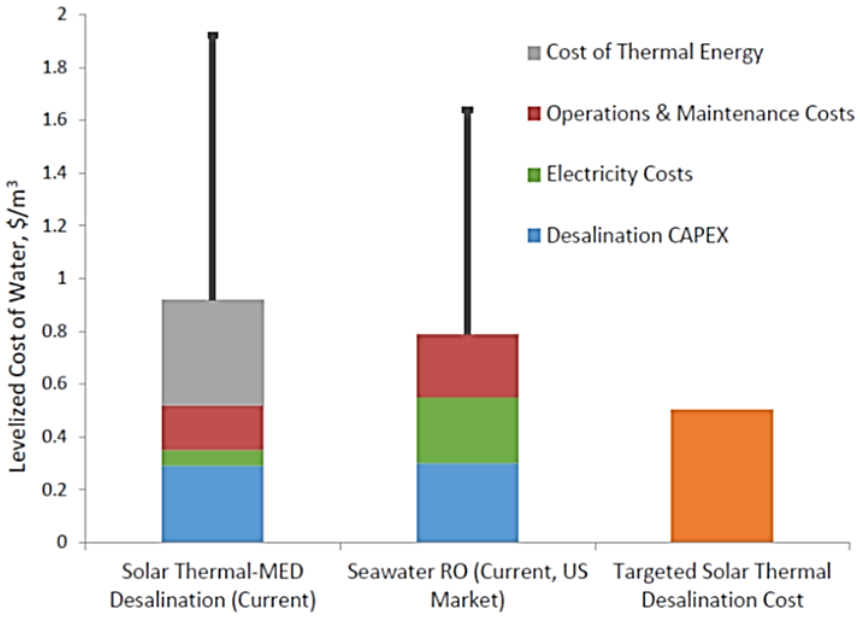


Figure 8. Comparison of targeted cost of \$0.50 /m^3 using solar thermal desalination with current plant costs. Error bras reflect variation of costs due to siting, permitting, irradiation and other regional variabilities. (US-DOE, 2017).

6. Concluding Remarks

Fresh water production from saline water desalination requires large quantities of energy and it generates greenhouse gas emissions, as it is currently powered by fossil fuels. Solar energy generation, which is abundant in arid regions, has become cost competitive with fossil-fuel power generation, and it creates great prospects for affordable and sustainable water production through desalination of sea- and other saline waters. PV can cost-competitively provide a part of RO desalination loads and solar thermal desalination, like LT-MED, has applications for water with high salt content or in ZLD applications which cannot typically be handled with RO. Membrane distillation is an attractive technology for solar-powered decentralized desalination but it has not yet reached commercial scales. The main barriers are energy consumption and cost; increasing thermal energy efficiency and using low cost solar or waste heat is a gate towards commercialization. Forward osmosis is also very promising, especially for high-salinity water desalination and ZLD applications. Solar thermal desalination, in general, has particular advantage when dealing with unendurable source water quality that is challenging for membrane processes.. While solar driven desalination plants can be attractive in most of the water-scarce regions, other renewable energy (wind, geothermal and wave) sources should be considered where these are cost-competitive and practically feasible. Regarding energy efficiency, innovative process schemes should be developed to enhance both water and energy recovery. This also requires development of more-efficient and robust membrane materials and processes. Finally, waste heat driven processes should be considered as much as possible in both desalination and ZLD applications for concentrate management.

Table 1. Comparison of desalination technologies based on operating principles and future prospects (NWC 2008, Gude et al., 2010; Gude 2015)

Process	Operating principle	Remarks	Future Prospects for major opportunities
Phase Change	Salt-free phase as product		
Thermal (MSF, MED, and solar stills)	Salt-free freshwater vapor is condensed to form pure water. Energy reuse in a number of effects or stages	Major application Well established High thermal energy demand	Strong in 'hybrid' systems such as in cogeneration, thermal-membrane combination and integration with crystallization for ZLD Better scale control, materials, hybrid optimization. Potential for solar thermal LT-MED
Freeze-thaw	Ice is salt-free, thaws to pure water.	Limited application and capacity Energy demand	Unlikely.
Voltage Driven	Salt ion transport		
Electrodialysis (ED)	Ions move through anion & cation membranes.	Significant for low salt feeds Well established Possibly high salts High electrical energy requirements	Strong, but only for low-salinity waters
Electro deionization	ED combined with ion exchange resin.	Possibly growing Enhances ED Possibly high salts Primary power	Strong, but seawater desalination is unlikely
Capacitive deionization (CDI)	Ions adsorb and/or desorb on electrode due to DC voltage.	Developmental Removes minor ions Possible application with high TDS water Energy recovery possible	Possible Practical modules and scale-up. Novel nano-structured (non-carbon) electrodes with high energy recovery.
Pressure Driven (non-phase change)	Water transport through membrane		
Reverse Osmosis (RO)	Pressure higher than osmotic pressure, water through polymer film, salts retained.	Major application Established Lower energy demand relative to thermal process Energetic efficiency is low	Strong, with novel membranes Better membranes and module design. High performance membranes via nanotechnology (mixed matrix, C nanotubes). High flux needs improved concentration polarization control.

			Osmotic pressure is unavoidable.
Forward Osmosis (FO)	Water passes to draw solute of high osmotic pressure. Draw solute regenerated to separate water.	Developmental Lower energy Ambient pressure Membrane type Possibly draw solute	Potentially strong Improved membranes. Effective draw solute + efficient heat transfer and regeneration.
Thermal - Membrane	Water vapor transport		
Membrane Distillation (MD)	Hot feed water evaporates through hydrophobic microporous membrane.	Small pilot plants Ambient pressure Low grade heat Availability of low grade heat	Potentially strong Improved membranes and modules. Some opportunities for breakthrough.
Bio-enabled	Cellular ion transport		
Biomimetic membranes	Cell wall transports/sorbs ions	Research phase, early stage Biological Process Development of industrial analogue to biological process	Possible, long-term (No established process to optimize as yet). Proof of concept stage, scale-up necessary

Acknowledgments

VF acknowledges support by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office (SETO) Award Number DE00008401. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the DOE. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

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