



Renewable energy powered membrane desalination — review of recent development

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Received: 15 March 2021 / Accepted: 23 April 2022 / Published online: 5 May 2022

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Abstract

Due to current water stress, there is a problem with hygiene and sanitation in many parts of the world. According to predictions from the United Nations, more than 2.7 billion people will be challenged by water scarcity by the middle of the century. The water industry is increasingly interested in desalination of the sea, ocean, and brackish water. Desalination processes are widely classified as thermal or membrane technologies. In the Middle East, thermal desalination remains the primary technology of choice, but membrane processes, for example reverse osmosis (RO), have evolved rapidly and in many other parts of the world are currently even surpassing thermal processes. The purpose of this paper is to review the renewable energy source, the technology, desalination systems, and their possible integration with renewable energy resources and their cost. This article suggests that the most practical renewable desalination techniques to be used are the solar photovoltaic integrated RO desalination process, the hybrid solar photovoltaic-wind integrated RO desalination process, the hybrid solar photovoltaic-thermal (PVT) integrated RO desalination process, and the hybrid solar photovoltaic-thermal effect distillation (PVT-MED) desalination process. However, intensive research is still required to minimize the cost, reduce the heat loss, enhance the performance, and increase the productivity.

Keywords Desalination · Freshwater · Renewable energy

Introduction

Since ancient times, the growth of civilisation has been centred around sources of freshwater (Sherbinin et al. 2009). However, due to the current high living standards and increased industrialisation, there is a large increase in water consumption. As a result, the shortage of freshwater is becoming a significant problem in several parts of the world. The more civilisation and industrialisation grow, the more the freshwater deficiency

increases. There are about 1.1 billion people who do not have access to freshwater sources, while 2.4 billion people lack access to sanitized water, and around 2.7 billion people face water scarcity for at least 2 month per year. As a result, many people have no choice but to consume stagnant water or otherwise be completely prohibited from water. This can have major health effects on these people who will become more exposed to diseases such as typhoid fever, cholera and other water-borne illnesses. Water is a major factor in disease prevention and control; in a recent study (Anim and Ofori-Asenso 2020), water is reported to have a critical part in the prevention and control of COVID-19 spread especially in Africa due to the importance of water in individuals' hygiene and sanitation. Unfortunately, around 300 million people in the sub-Saharan region suffer from water deficiency, which puts them in a very dangerous situation and makes them more vulnerable to COVID-19 (Anim and Ofori-Asenso 2020). Two million people, mostly children, die every year from diarrheal diseases alone. Poor sanitation is accepted widely as a major contributor to water-borne diseases, causing more than 1200 deaths per day among children under the age of 5.

It is estimated that for two-thirds of the world population clean water will be hardly accessible by 2025 (unwater.org).

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Although water covers 75% of the earth's surface, most of it is salty and brackish water. Freshwater in lakes, rivers and groundwater constitutes only 0.65% of global water, and its availability is not correlated with the population and the use of water in different parts of the world (Meissner 2001). It is argued that potable water can be extracted from sea, lakes or rivers accessible in water-stressed areas. Brackish water salinity is up to 10,000 parts per million (ppm), and seawater salinity ranges between 35,000 and 45,000 ppm as dissolved salts, resulting in that these waters are not suitable for human consumption. According to the World Health Organization (WHO), in some specific cases a salinity of 500 ppm and 1000 ppm is allowed (WHO 2011). One of the most promising solutions to overcome water shortcoming is desalination (Alkaisi et al. 2017). Desalination techniques must be utilized to bring salinity down to the allowed limit. This technology could potentially reduce water poverty in regions with scarce freshwater resources and help developing countries achieve their food security goals (Alhaj and Al-Ghamdi 2019). Nearly 400 million individuals used desalinated water in 2015, and it is projected that by 2025, about 14% of the world's population will have to use desalinated water (Chandrashekhara and Yadav 2017).

Seawater desalination consumes huge quantity of energy which is estimated to be tenfold the energy required for river and lake water treatment. This vast amount of energy needed for desalination has serious consequences on the environment and results in high cost of freshwater. A recent study (Hindiyeh et al. 2021) is expecting the fossil fuels that we use to provide our energy to run out in the current century. They anticipate oil to deplete by 2052, gas to deplete by 2060 and coal to deplete by 2090. Oil supplies approximately 40% of the world's energy, and 96% is used for transportation, while global oil demand is growing at a fast rate; the global oil demand increased by 1.8% in 2018. Gas totalled 23% of the total energy demand but grew at a 4.6% rate in 2018; gas had the second-highest share of total electricity generation at 23%, or 6091 terawatt-hours (TWh). Global coal demand accounted for 0.7% in 2018. Coal's share of total electricity generation totalled 10,116 TWh, as it commanded 38% of total generation around the world (Hindiyeh et al. 2021). The most effective way to mitigate the energy-associated impacts of desalination technologies is to supply the energy needs of the process (either in whole or partially) from clean renewable energy sources, for example solar energy (Alhaj et al. 2017). Thus, utilisation of alternative energy sources and implementation of improved desalination technique are important for widespread and sustainable desalination. Desalination technologies based on renewable energies will have no less of an impact on the environment and will be more sustainable, and the cost of producing freshwater is supposed to decrease due to the availability of free energy sources. Many renewable

energy-based desalination techniques have not been found in the market because of the occasional intermittent nature of renewable energy sources and also because of the high storage and capital costs.

The focus of the current review is to present recent developments in membrane-based desalination processes using renewable energy techniques and to meet the challenges.

Desalination using thermal and electrical energy

Desalination is growing fast to bridge the gap between the needed and the available freshwater; 67% of the desalinated water is seawater, 19% is brackish water, 8% is river water and 6% is wastewater (Al-karaghoulis et al. 2011). Thermal energy has been historically used for desalination. Thermal desalination is still in use even in current desalination processes as thermal vapor compression (TVC), multi-stage flash (MSF) technology with a 17.6% share and multiple-effect distillation (MED) with a share of 6.9% (Hindiyeh et al., 2021). It exists mainly in petroleum-enriched areas such as the Middle East.

In the TVC method (Farbod 2020), water vapor is fed to the evaporator and the steam goes to the compressor. The steam is compressed at this point, and its temperature rises to evaporate the sprayed feed water on the heat exchangers. Preheating the feedwater is used to start the process and reach the evaporation temperature. The required heat to evaporate water in this method is provided by thermal vapor compression (TVC) using high-pressure steam. In the TVC method, the required steam is supplied by lateral processes such as power cycles or industrial processes.

The multi-stage flash MSF (Farbod 2020) was invented in the early 1950s. Today, more than 80% of the freshwater produced by the thermal method which is produced at MSF sites. In this method, the water is heated in several stages, and at each stage, the pressure and temperature decrease compared to the previous stage. Typically, MSF includes 15 to 28 levels or stages. The latest MSF technology has reached 45 stages that can compete with RO in terms of capacity and energy consumption. Inlet brine is heated to 90–115 °C in the heater tank, and water vapor is produced. The pressure level in the first stage is slightly lower than the saturation pressure of water vapor (Voutchkov 2012). When a stream of saturated water passes through a pressure convertor, the pressure suddenly decreases, forming the so-called sudden evaporation (flashing) phenomenon. As the water enters each step, some of the water suddenly evaporates and enters the vapor phase as it passes through the pressure reducing nozzle. The vapours formed on the condenser tubes are distilled and then collected in special trays. As the steam phase changes to liquid, some

latent heat is released, which is used to preheat the saline water before entering the first stage. The MSF method is performed at each step by lowering the pressure and producing some amount of steam that will be distilled at the same stage. Fortunately, the amount of seawater recovered by this method is approximately 10–30% (Kim et al. 2016). The typical energy consumption of MSF units is 250–330 kJ/kg of freshwater, and the amount of electricity required for processing is in the range of 3–5 kWh/m³. Generally, the use of the MSF method for desalination due to low efficiency, high costs and high environmental impacts in the future can be ignored compared to MED and RO (Bennett 2014; Ghafour et al. 2014).

The multi-effect distillation MED (Farbod 2020) process has been used in various industries such as paper production, sugar, dairy industry and desalination. Small MED sites with a total capacity of less than 500 m³ per day were built in the 1960s. Subsequent improvements have expanded the recovery capacity of this method. In 2006, the capacity of MED sites increased to 36,000 m³/day (Al-Othman et al. 2018). This method also uses several steps or levels where each step takes place in a separate tank, and the pressure in each step is gradually reduced. For multi-stage distillation, 8–16 steps are typically used to minimize energy consumption. The water on the surfaces of the evaporator pipes is spread out as a thin film, which causes the water to evaporate rapidly. The steam produced is distilled on a cool external surface. Here, the latent heat from the distillation water is used to heat the saline water at lower temperatures and pressures, which means that after initial heat in the first stage, there is no need to heat the water in other stages. In summary, the latent heat from the condensation at each stage is used to evaporate the water at a later stage. This reduces the total energy consumption for water desalination. Therefore, the energy costs in the MED method are lower than in the MSF technique (Ortega-Delgado et al. 2017). The usual amount of freshwater in this method is about 20–35% of the water that entered into the system (Voutchkov 2012). Throughout the world, membrane techniques utilising electrical energy have recently substituted thermal energy (IRENA 2012; Gnanaswar et al. 2010; Do Thi et al. 2021). Membrane techniques are using less energy; they have the advantages of high productivity, light weightiness and compactness (Alawaji et al. 1995; Headley 1997; Kanzari et al. 2005; Harrison et al. 1996). In spite of improvements achieved, a lot of work is still needed to enhance the performance and lower the cost of membrane desalination.

In reverse osmosis (RO) desalination, seawater is pushed against semipermeable membranes that allow molecules of water to pass through and prevent salt molecules from passing. A high-pressure pump is needed to push seawater

against osmotic pressure and pressure loss through the system (Stover 2007).

When desalting seawater, a booster pump and energy recovery equipment are needed to reduce the area required for the high-pressure pump and restore the pressure from the concentrate (Stover 2007). This is not required in brackish water desalination due to low levels of total dissolved solids (TDS) (Drak and Adato 2014). The high cost remains the first drawback for sustainable desalination (Subramani et al. 2011); in RO desalination of seawater utilising electricity, energy accounts for 30% of the desalination cost. Consumption of high energy leads to more greenhouse gas emission (Raluy et al. 2005). Another problem facing the growth of the desalination industry is the issue of using oil fuel, which sparks environmental and sustainability concerns. The current installed desalination systems' capacity is more than 90 million m³/day, which demands over 850 million tons of oil each year (IRENA 2012). This amount is expected to increase with the development of the desalination sector throughout the world. In addition, sources of fossil fuel are anticipated to be depleted in a few decades. Current global desalination is estimated to consume 75.2 TWh of energy per year (Wakil et al. 2017). Recent global desalination plants are estimated to release 76 million tons of CO₂ every year, which is expected to reach 218 million tons by 2040 (GCWDA 2015). Additionally, changes in oil price and supply will affect water price.

The above information shows the importance of using renewable energy in desalination practices. There is increased dependence on desalination as a reliable source of freshwater in places which are suffering severe water scarcities.

In recent years, desalination has gained more markets and is anticipated to continue gaining more markets in the upcoming years especially in MENA countries (Middle East and North Africa) (GWI 2004; Gorjian and Ghobadian 2015; Quteishat and Abu-Arabi 2004).

In a study conducted by Joyner Eke et al. (2020) regarding the latest state of desalination plants around the world, they state that there are about 16,876 desalination plants in operation, 270 plants under construction. There are 14,360 operating RO plants, which means that 85.1% of the current operational plants are accounted for by RO. Additionally, 247 plants out of the 270 plants under construction are RO plants. In 2020, the global installed desalination capacity was 97.2 million m³/day of freshwater production from desalination plants.

The cost of energy is still responsible for the high cost of desalination in addition to the environmental impacts associated with using fossil fuels as the main energy source for desalination. Decreasing the cost of energy is essential to reduce the cost of desalination.

Different renewable energy types used for desalination

Different renewable energy sources are available around the world. The main renewable energy sources used for desalination are solar, wind, wave, geothermal and blue energy — otherwise known as osmotic power. Another form of renewable energy that is emission-free is nuclear energy, but it suffers limited applications in the desalination sector due to issues of safety and waste disposal.

The increase in utilising renewable energy in the desalination sector is depending on the progress in renewable energy technologies. The energy produced from renewable resources has increased about 5 times between 2005 and 2015, most of it through solar and wind resources. Solar energy is the most studied, particularly for the Middle East and North America. Among other sources of energy from renewable sources include geothermal, blue energy or salinity gradient power (SGP). Blue energy is extracted by controlled mixing of two saline solutions with different concentrations.

Utilisation of solar energy

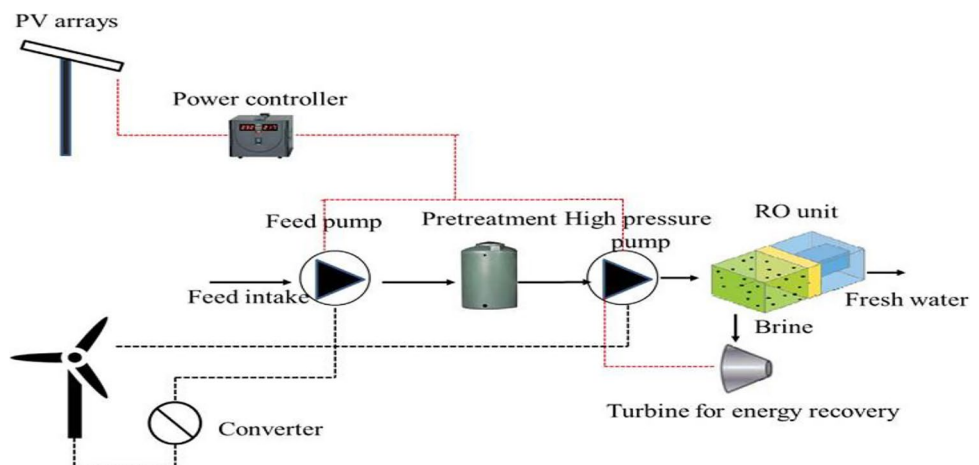
Among the renewable energies, solar energy is the most popular and widely used around the world. The main reason is that solar energy is available for free in the natural form of heat which can be used directly to desalinate and in even greater quantities. It is the most plentiful source available on the Earth, and also the cleanest. Arid areas often have a lot of potential for solar energy (Chauhan et al. 2021). Solar energy can be converted to thermal energy or to electricity to run the high-pressure pump (Fig. 1). One of the most reliable and widely used technologies used to harvest solar energy is photovoltaic (PV) systems. Photovoltaic technology has witnessed an increase in the number of photovoltaic systems being installed and

a decrease in the costs of installation. The cumulative global solar photovoltaic capacity has continuously grown since 2000. In 2019, global cumulative solar PV capacity reached 633.7 GW, with 116.9 GW of new PV capacity installed in that same year. One major advantage of photovoltaic systems is that they come in a vast variety of sizes and complexities, from small-scale household systems to solar parks that can generate enough energy to power large facilities or a populated residential area. Photovoltaic (PV) driven reverse osmosis (RO) and thermal solar units have been used in some parts of the world (Esfahani et al. 2016) with capacity ranging from 1 m³ per day up to several hundred cubic meters per day. These units have a specific energy consumption (SEC) ranging from 2.4 to 17.9 kWh/m³ and 0.9 to 29.1 kWh/m³ for sea and brackish water, respectively (GCWDA 2015).

In Dubai, a RO desalination project powered by solar energy has recently been launched. It produces about 30 m³ of desalinated clean water per day and consumes 2.8 kW h/m³ of the produced freshwater. Most RO units are coupled with photovoltaic modules for desalinating water (Herold and Neskakis 2001; Hrayshat 2008; Gocht et al. 1998; Al and Nair 2000). The high cost of producing energy from renewable resources (especially the cost of photovoltaic cells) compared to conventional sources, in addition to limited operational hours, makes RO desalination. The use of renewable energy is still expensive (Hamed 2005). However, with the rapid development of renewable energy technologies, the cost is expected to be reduced and the cost of water production will eventually become lower.

Batteries are needed in these units to store electricity and ensure that the power supply is continuous and regular. However, these batteries have the disadvantages of a short lifetime and require replacement; they lose power during charging and discharging, their efficiency declines with time, and their disposal causes environmental problems and, in turn, increases the cost of desalinated water.

Fig. 1 Reverse osmosis system powered with solar/wind-driven electrical energy (Greenlee et al. 2009)



To exclude the use of batteries, energy regulation and variable flow should be considered. The energy and water flow can be adjusted accordingly with changes in solar sources. A study by Thomson and Infield (2002; 2005) and Lee et al. (2016) showed the results of applying a change in flow rate to the RO unit.

The authors indicated that the studied system has the advantages of good performance and cost reduction. Another RO prototype system powered by solar energy without batteries and with low energy impact was developed by Soric et al. (2012); an important component is the energy regulator, which maintains enough energy to the RO system.

The Rankin cycle concept has been introduced (Delgado-Torres and García-Rodríguez 2007a; Manolakos et al. 2005; Peñate and Rodríguez 2012), to eliminate energy losses of energy due to conversion of thermal energy into electrical energy and to eliminate the use of storage batteries. The concept is to use solar collectors to evaporate the low-boiling liquid that drives the RO pump shaft. The system has been improved in terms of location, solar collectors and low boiling fluid used (Bruno et al. 2008; Nafey 2010).

Another alternative that has been suggested is the integration of renewable-renewable and renewable conventional energy sources to keep working hours as long as possible or to support the renewable with conventional energy to reach optimum utilisation of RO desalination (Ramin et al. 2021, Cherif and Belhadj 2011; Mohamed and Papadakis 2004). It should be said that the costs of the units of water are higher than those produced by RO driven by electrical energy. A recent study indicated that using hybrid photovoltaic batteries and power-to-gas power plants to power RO units will be able to meet the global needs of 2030 at water cost costs ranging from 0.59 to 2.81 €/m³ (Caldera et al. 2016).

A different technology is the integration of concentrated solar power with desalination (CSP-D). Solar irradiation is concentrated using mirrors onto a linear receiver, i.e. parabolic trough collectors (PTC), or a central receiver, i.e. solar tower (ST). In either case, the absorbed concentrated irradiation is then used to heat a heat transfer fluid (HTF) to drive a power block, usually a Rankine cycle. By design, this power block is relatively standard, so much of the same well-proven technology from fossil fuel power plants can be utilized (Amr et al. 2019). Because concentrated solar power (CSP) generates both heat and electricity, either or both can be used to control desalination processes. There is a great opportunity to better utilize the incident solar energy in a CSP plant since 80% of the solar energy harvested by the solar field is “labelled” as losses (Bishoyia and Sudhakara 2017; Gandrud 2017). The power block of a large-scale CSP plant will dump about 30% of its energy as waste heat into the environment through the steam condensers (Bishoyia and Sudhakara 2017; Gandrud 2017).

Using this energy flow, a thermal desalination plant can partially (or even fully) replace the condenser. Electricity generated from the CSP plant can be used to power a pressure-driven desalination process, such as RO. In that case, the desalination process is simply another electrical load supplied by the CSP plant. Nevertheless, the main advantage of this option is that the electricity generated on-site is typically much cheaper, i.e. lower than the wholesale price (and much lower than the retail price) since it does not require transmission (Palenzuela et al. 2011). Although most of the studies attempt to drive the desalination system using the CSP’s waste heat, RO systems driven by grid electricity represent a well-developed technology that could readily be integrated with CSP plants. Studies have recently shown that CSP-D plants, if deployed, can bring a significant benefit to the electricity and water demands of arid regions. According to the study by Trieb et al. (2002), a 200-MW CSP plant operating in Dubai was able to deliver 1.5 billion kWh/year of electricity, 60 million m³/year of freshwater, sufficient power for 250,000 people and a sufficient amount of freshwater for 50,000 people (Trieb et al. 2002). In comparison to a conventional fossil-fuelled desalination plant, it is about 1.5 million tonnes of oil equivalent energy less to generate an equal amount of water per year (Kalogirou 2005). Furthermore, with respect to The Paris Agreement, a CSP-D plant could reduce emissions by > 300,000 t of equivalent CO₂ annually, compared to the conventional fossil-fuelled desalination plant (DEFRA 2005). Even though the technology readiness level of CSP-driven desalination technologies is still quite low, PV-RO systems are highly commercially adopted (Lamei et al. 2008; Caldera et al. 2016; Bilton et al. 2011; Childs et al. 1999; Shalaby 2017; Ali et al. 2018; Salcedo et al. 2012).

In recent years, much attention has been paid to improving large-scale desalination plants, but small desalination plants that are capable of providing freshwater and freshwater in rural areas have been neglected. Monjezi et al. (Manikandan et al. 2020) presented a new way of combining solar photovoltaic thermal cells (PVT) for the reverse osmosis (RO), where seawater represents a cooling medium that improves the thermal effectiveness of solar energy production and increases the pace of freshwater generation. Adding the battery unit ensures a continual pace of freshwater supply, which leads to minimalisation of often occurring membrane fouling when using desalination units run by renewable energy. The integrative system was imitated in Alexandria, Egypt, for its possessions of seawater and climatic conditions. The results show that the proposed method leads to a depletion of 0.12 kWh/m³ in the specific electricity consumption rate of RO desalination and also increases the electricity generation capacity of PVT cells, leading to a 6% reduction in the solar panel surface area.

Another study focused on small-scale and portable solar-powered RO desalination plants was conducted by Manikanda et al. (2020). In this study, they have designed and modelled a portable desalination plant that uses solar energy for reverse osmosis (RO). Power is provided by a photovoltaic system that includes a storage battery. It is estimated that the entire need for energy anticipates the power supply, capacity of solar panels, storage systems and sizing of the charge controller.

According to the study by Liponi et al. (2020), fossil fuel usage prevails over solar energy at present, although solar energy utilisation plays a significant role in the desalination process in some dry areas where fuel transportation is more expensive. The practicality of the small-scale distillation plant also lies in the heat waste recovery system, which increases its value. The usage of the small capacity plant might decrease the expenses of the desalination and also increase its efficiency ratio in comparison with the large capacity plant.

Comparative analysis shows that the overall performance of photovoltaic thermal coupled desalination systems is better than that of desalination systems coupled with a separate photovoltaic panel and/or solar thermal collector to meet the energy needs. The additional electricity generated from photovoltaic thermal desalination paves the way for standalone desalination in remote locations even though the initial costs are a little higher (Anand et al. 2021).

The utilisation of wind energy for water desalination

Wind power has attracted the attention of researchers. The project SDAWES (Seawater Desalination by an Autonomous Wind Energy System) has tested and analysed RO units that operate with wind power (Carta et al. 2004). Desalination plants operated with wind power should be designed to respond to fast variation in the wind at different locations, which may cause regular shut-down and start-up operations.

The operational analysis of an RO desalination plant that uses wind energy directly without energy storage placed on Canary Islands was provided by Carta et al. (2003), which is a wind farm that provides energy requirements to eight module desalination plants. They indicated that the average output and the standard of the generated water were found to be independent of an interrupted operation.

It has been reported by Loutatidou et al. (2017) in the United Arab Emirates that wind-driven RO can compete with thermal desalination. The produced water quality, time spent within the safe operating window and the specific energy consumption (SEC) growth when an operational interruption is avoided when using a supercapacitor bank have also been described (Richards et al. 2014).

Several ideas have been suggested to avoid energy interruption in the wind-driven RO units to provide a continuous water supply. Another possibility is to produce as much water as possible during energy hours, and the excess water is then used when there is no production (Gold and Webber 2015).

The utilisation of wave energy for water desalination

Enough waves at coastal areas provide an opportunity to directly utilize wave energy to pressurize and pressurize seawater to produce freshwater. Some desalination units have been designed based on this principle, where the wave energy is absorbed by the converter, which directly transfers it to the RO arrangements. The effectiveness of converting wave energy is greater than the effectiveness of converting other types of renewable energy. The theoretical conversion efficiency for solar energy, as an example and based on best arrangements, does not exceed 87%, whereas for wave energy it is 100%, although the utilisation of wave energy is almost absent compared to solar and wind energies.

Wave energy-based desalination across different parts of the world has been evaluated by Davis (Davies 2005). His evaluation showed that 1-m-high waves have the ability to operate a desalination plant to satisfy the irrigation requirement of a 0.8-km-width strip along a dry and sunny coastline, and if the wave is 2 m high, then the width of the coastline strip jumps to 5 km. He also indicated that wave-based desalination could reduce water deficiency by 16% in Morocco, 64% in Oman and 100% in Somalia.

Much less attention has been devoted to wave energy compared to other renewable resources. A self-sustaining wave energy desalination plant has been reported by Sharmila et al. (2004). It is based on alternating pressurising and depressurising a column of air entrapped above a column of water by the action of waves. The pressurized air is then utilized to run a turbine and extract power. The power extracted is reported to run an RO plant that produces 10 m³/day of water.

Folley et al. (2008), in a different study, studied the possibility of wave-powered RO desalination plant utilising a pressure exchanger-intensifier to recover energy. The idea is to use wave energy directly to compress the seawater without converting the wave energy to electrical energy. They found that an SEC (specific energy consumption) of less than 2 kW h/m³ of desalinated water is feasible using their system with different seawaters, showing that it is economically and technically appropriate for desalination of seawater. If the recovery rate is kept at 25–35%, the specific energy consumption (SEC) comes down to 1.85 kW h/m³ since there will be no need for pretreatment requirements and scaling problems will be reduced to wave-powered. It

must be noted that the practical use of wave energy for the desalination process has so far been limited to laboratory cases. The mostly mentioned problem with the wave power is its fluctuation over time (like in the case of wind energy), which is a failure in the sustainability of these desalination units (Foteinis and Tsoutsos 2017; Burn et al. 2015; Corsini et al. 2015). Wave-powered desalination is expected to receive more attention soon. A desalination pilot plant (DPP) based on wave power is installed on Garden Island, Australia. The device utilized is called CETO. This innovative system uses numerous buoys to exploit wave power to pump seawater into a RO unit to produce freshwater, in which the production capacity is 150 m³/day (Viola et al. 2016). The first wave energy-powered desalination plant is currently being worked on in Perth, Australia.

The utilisation of geothermal energy for water desalination

Geothermal energy, considered renewable energy, occurs inside the earth in the form of heat, which may be pumped as steam or hot water that is used to run a turbine to produce electricity. The high temperature of the earth which may reach above 300 °F (148.9 °C) makes it attractive for use in different applications. It can also be used for evaporating a low-boiling point liquid that is possible to use then to run a turbine.

Geothermal energy is a known technology for producing electricity. In 2010, more than 10,000 MW of energy was produced from geothermal energy in different regions, supplying 60 million people with their electricity needs (Mahmoudi et al. 2010). Wells that are more than 100 m in depth may be used to produce electricity for desalination (Kalogirou 2005).

Geothermal energy could be a possible option in many regions that suffer from water scarcity. High-pressure wells allow the use of shafts on mechanically driven desalination. If the temperature of the geothermal fluids is high, then it can be utilized to produce electricity for RO units. In some cases, the geothermal heat might be used straight for thermal desalination. Many studies show the economic and technical feasibility of geothermal energy for desalination; it has the advantage of being the uninterrupted source of renewable energy (Ophir 1982; Bourouni and Chaibi 2001; Bourouni and Deronzier 1999).

The study of Yu and Yu (2019) suggested various systems for gaining freshwater and power. The systems are a steam system (SS), a single-flash system (SFS) and a trilateral flash system (TFS). Based on the results of their experiments, they found that TFS is better for the production of freshwater compared to old power systems. The utilisation of TFS can provide 2.7 times higher potable drinking water by using a

20% efficient turbine. TFS is also suitable for regions with geothermal sources.

Gude (2019) focused on the usage of geothermal energy for the production of potable water. In the study, the advantages, as well as some setbacks of geothermal energy, are explained. Geothermal energy used in different ways such as multistage flash distillation or multi-effect distillation is suitable for the production of power and potable water at the same time. In addition, the plant-based geothermal energy is constructed with low-cost materials, the rates of corrosion are lower as well as scaling or heat losses, the start-up periods are shorter and the life of the plant is longer.

Chandrasekharam et al.'s (2019) review discovered that Egypt might be able to fulfil 1000 m³/year per capita of water usage by 2025 by using geothermal energy. Due to the global increase in CO₂ emissions, it is no longer possible to use outdated technologies for the production of freshwater. Furthermore, the study shows that the use of geothermal energy for desalination is more economical compared to the use of fossil fuels.

The utilisation of blue energy for water desalination

The salinity difference energy or blue energy is osmotic energy which resulted from interfacing two solutions of the salinity difference. It is a form of sustainable and renewable energy with a global potential ranging from 1.4 to 2.6 TW, of which about 980 GW is extractable according to the technology used (Veerman et al. 2010, 2008; Post et al. 2010). This amount of blue energy is enough to satisfy 20% of the current world needs (Folley et al. 2008). Blue energy would decrease dependence on fossil fuel to produce energy, and if some membrane operations are integrated, freshwater and energy can be produced. The problem of brine disposal can be solved at the expense of energy production.

Desalination techniques and renewable energy sources

Renewable energy will continue to be more economically attractive as the cost of renewable technologies decreases and the cost of fossil fuel increases. The combination of renewable energy and desalination techniques makes desalination environmentally friendly and more sustainable (Buonomenna and Bae 2015); Charcosset 2009). The most common membrane desalination techniques used with renewable energies are RO and ED (electrodialysis). However, with recent advances in the membrane industry, some new interesting membrane operations like RED (reverse electrodialysis), MD (membrane distillation), PRO (pressure retarded osmosis), FO (forward osmosis) and MD

(membrane distillation) are emerging. They can overcome difficulties faced by traditional desalination.

It is essential to select a favourable combination between desalination technology and the suitable renewable energy type to be able to process freshwater in an efficient, economical, sustainable and environmentally friendly way. There are various forms of using renewable energy for desalination such as thermal, mechanical (shaft) and electrical.

There are some factors that should be considered when choosing a suitable renewable energy technique for desalination. To mention but some—type of renewable resources available, kind of water (seawater or brackish water), existence of grid electricity, size of plant and remoteness of the area—these factors will determine which combinations are suitable (Eltawil et al. 2008; Tzen and Morris 2003). Among the desalination technologies in the market, RO is considered the least energy-consuming technique; thus, it is the one most used to combine with renewable energy units for water desalination (Li et al. 2018). Currently, RO is the most efficient water treatment technology, with consumption ranging between 2 and 5 kWh/m³ (according to the type of treated water, i.e. brackish or seawater). No thermal energy is required for driving the RO process. In general, thermal techniques can be said to require a greater amount of energy than membrane technologies (Xevgenos et al. 2016).

Usually, RO is interfaced with PV for plants in sunny areas. In grid-available locations, hybrid units are suggested to ensure contentious operations whereas in off-grid locations intermittent renewable desalination systems are suggested. According to a recent study, the IPCC (Intergovernmental Panel on Climatic Change) is overlooking the potential of solar energy (Creutzig et al. 2017). By 2050, solar PV would play a dominant role in electricity generation with a share of 30–50% (Creutzig et al. 2017). The installed photovoltaic system capacity worldwide is projected to

increase from 600 to 3000 GW between 2019 and 2030. However, a major issue in photovoltaic conversion is that 75–96% of the absorbed solar energy is converted as waste heat.

The International Desalination Association announced that in 2015 the amount of installed desalination plants was 18,426 in 150 countries, providing more than 300 million people across the world with freshwater. The worldwide capacity is about 86.8 million m³/day, and seawater comprised about 60% of the inlet water used (IDA 2018).

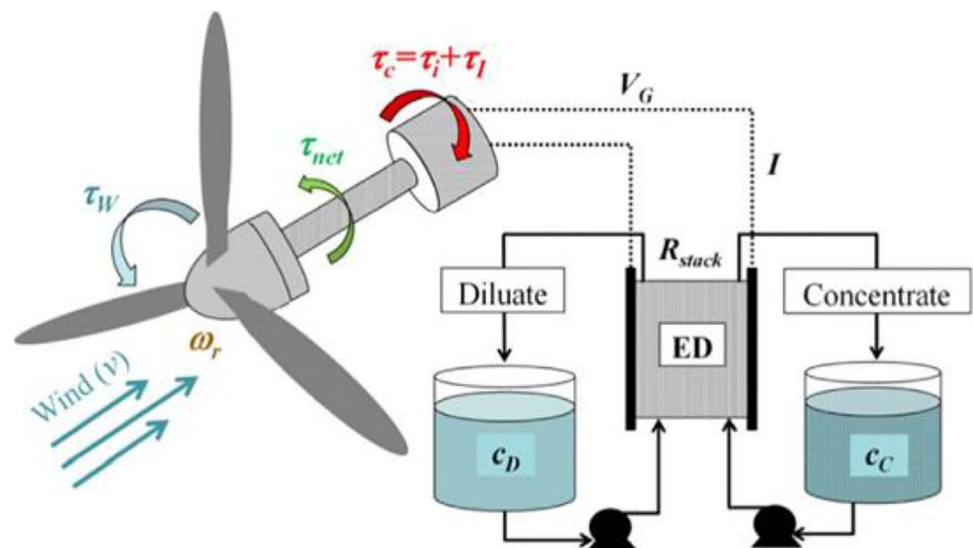
For countries that depend on desalination to sustain the livelihood of local communities, coupling desalination with renewable energy is an important factor for the desalination sector to grow; it reduces the usage of fossil fuels as well as the accompanying release of CO₂ (Eltawil et al. 2008; Mathioulakis et al. 2007; Miler et al. 2015).

Solar systems which concentrate solar power (CSP) to produce larger amounts of heat are suitable for both FO (forward osmosis) and MD (membrane distillation). Photovoltaic (PV) and wind turbines which produce electricity are suitable for reverse osmosis and electro dialysis units (RO, ED); storage of electricity when production exceeds demand during peak hours to be used when there is no electricity production is still a challenge.

The economic feasibility of photovoltaic and RO or ED depends on the capital cost and operational cost. The capital cost is estimated mainly according to pumps, required membrane area, valves, storage tanks, piping, control and electrical instrumentation, energy recovery equipment and water pretreatment devices. The operational cost is determined based on the cost of membrane, pretreatment chemicals, pre-filter replacement and cost of maintenance.

Another important source of renewable energy used for desalination is wind energy. Figure 2 represents a system combining wind energy together with electro dialysis (ED)

Fig. 2 Wind-based electro dialysis unit used for desalination of brackish groundwater (Malek et al. 2016)



and electrodialysis reversal (EDR) for desalination to produce freshwater. To evaluate the operational modes of the system and constrains in off-grid operation, a set of tests were done on on-grid operations to compare; experiments were done in Gran Canaria Island (Spain) (Veza et al. 2001).

Finding the right combination between a desalination process and renewable energies has been the focus of many researchers across the world. It depends on what is required from the desalination process and what type of energy is possible to gain from the renewable resource. The regions which have market potential for desalination in the world have been identified, where there is a water shortage and renewable energies (RES) are available, with the objective to identify the best combinations for renewable energy powered desalination (Jemaa et al. 1999; Vujcic and Kmeta 2000).

Compared to the total desalination capacity worldwide, renewable energy (RES) desalination is limited, although the many advantages of RES which can be utilized are used to power desalination systems (Delyannis and Belessiotis 2020). This is attributed to many factors such as the following: (i) Areas with severe water stress do not always have potential RES available. (ii) Despite the contentious cost reduction, the initial capital investment installation cost is still high. (iii) The technological design combining energy conversion and desalination systems, which enhance efficiency and reduce cost, is not easy to find. (iv) Finding the associated technologies that match the low-level infrastructures present in most areas with severe water stress is not always possible; in many cases, applying desalination technologies in remote regions failed because of lack of qualified technical support (adapted from Mathioulakis et al. 2007).

Reverse osmosis (RO) and multistage flash (MSF) desalination account for about 80% of the world's desalination capacity (Jones et al. 2019). In the Middle East (especially in the United Arab Emirates, Kuwait and Saudi Arabia), MSF units are used extensively and account for approximately 40% of the world's desalination capacity (Ettouney et al. 1999).

Technically, RO and ED as well as photovoltaic (PV) technologies are currently commercially available technologies. The possibility of having PV-powered RO or ED desalination units in remote areas has been validated (MEDRC R&D Report 2000). PV-powered desalination units are commercially available (Espino et al. 2003); the main drawbacks of these technologies are availability of the PV cells and the high capital cost. The problem with the early PV-RO desalination systems is the large PV array required mainly due to the poor efficiency of both the storage batteries and the RO units, which would increase the capital and also the maintenance cost, and in turn raised the cost of freshwater produced from such systems. As a result of the stressing water and energy problems today, desalination-based renewable energy appeared as a reasonable and technically mature

option. Although there is a large amount of research conducted worldwide, installation of RES-based desalination systems is still low. Skills and expertise have been gained, and there are contentious attempts to install large-scale and effective RES-based desalination plants. This would be very important for developing countries that face water scarcity and do not have the means to conventional energy supply to power desalination plants.

The most mature technologies of RES suitable for desalination are photovoltaic and wind-based membrane desalination and solar distillation. In coastal areas and mountains where the wind is available day and night, wind-based desalination stations can operate without the need to store energy.

Membrane desalination techniques such as RO and ultrafiltration in combination with wind energy have been studied and proven technically and economically feasible (Malek et al. 2016). Using regulating and storing facilities coupled with the wind turbines before passing the energy to the desalination unit is usually coupled with excessive capital and running costs and low efficiency; however, direct coupling of the desalination unit and the wind turbine is a more efficient, economical and simpler approach. The combination of photovoltaic energy with a wind generator was proposed to provide continuous power (Tzen et al., 2008) which is shown in Fig. 1.

Combination of solar energy with reverse osmosis desalination

A 2012 study by the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) indicated that the most predominant desalination technique on the market was reverse osmosis, reaching more than 60% of the total units commissioned (IEA 2013). Today, RO combined with solar energy is the most widely utilized technique to produce freshwater from seawater. This could be due to the fast progress in this technology which is considered one of the most efficient techniques for desalinating water with high salt concentrations (above 35,000 ppm) (Ali et al. 2018). Despite all efforts made in recent years to decrease the amount of energy consumed in RO desalination, it is still the component with the highest cost, and energy consumption accounts for 40–45% of costs (Bets 2004).

The most promising technology in the desalination-based renewable energy sector is the coupling between solar energy and reverse osmosis membrane desalination, where it has the potential to significantly reduce the dependence on fossil fuel and substantially decrease the operational cost of desalination plants.

Most of the studies of solar-powered RO desalination were conducted in regions where solar radiation is abundant and there is severe water stress; the solar radiation in these areas is much higher than the world average. These regions

are Mediterranean, North African and Middle East (MENA) countries, as well as the southern region of Australia and Europe; most units installed are for small-scale desalination in distant places where grid power is not accessible and there is intense water scarcity.

Many full-scale units work in Saudi Arabia (Alawaji et al. 1995), the US Virgin Islands (Headley 1997), the Maldives (Kanzari et al. 2005), Australia (Harrison et al. 1996), Mexico (Kunczynski 2003) and Tunisia (Castellano and Ramirez 2005), but most of them are prototype or demonstration systems. Unit capacities range from $0.1 \text{ m}^3 \text{ day}^{-1}$ for prototype systems and up to $75.7 \text{ m}^3 \text{ day}^{-1}$ for full-scale plants. Three different solar based RO-desalination systems were investigated: (i) photovoltaic-powered reverse osmosis (PV-RO), (ii) hybrid solar desalination and (iii) solar thermal-powered RO. The hybrid units are compound of solar power in addition to power from a different source like grid electricity, wind or diesel generator.

RO desalination powered by photovoltaic modules

Until recently, most desalination processes consume 7–10 kWh of primary energy to produce 1 m^3 of water and emit around 3–4 kg of CO_2 emission (Munawwar and Ghedira 2014). In a recent study, it is shown that thermal desalination is still used largely to produce freshwater, then comes photovoltaic-based membrane desalination (Shahzad et al. 2017). The intermittent nature of the solar energy is the main drawback in its wide range application (Mito et al. 2019). Until recently, about 130 renewable power desalination plants supply only 1% of the total desalination capacity of the world.

Photovoltaic arrays (PV) combined with RO membranes are the arrangement which is utilized most in solar energy-based RO desalination. This is probably because photovoltaic arrays were the first commercialized technology for harvesting solar energy. In PV-RO, the electrical current

produced by semiconductors of the solar cells is utilized to power the pumps, which produce the required pressure to force the feed water to penetrate the RO membranes. PV-RO systems are used for desalting water at an economical cost and with lower environmental impacts. The modular nature and easy operation of PV-RO systems also result in their suitability for decentralized and decentralized applications (Alhaj and Al-Ghamdi 2019).

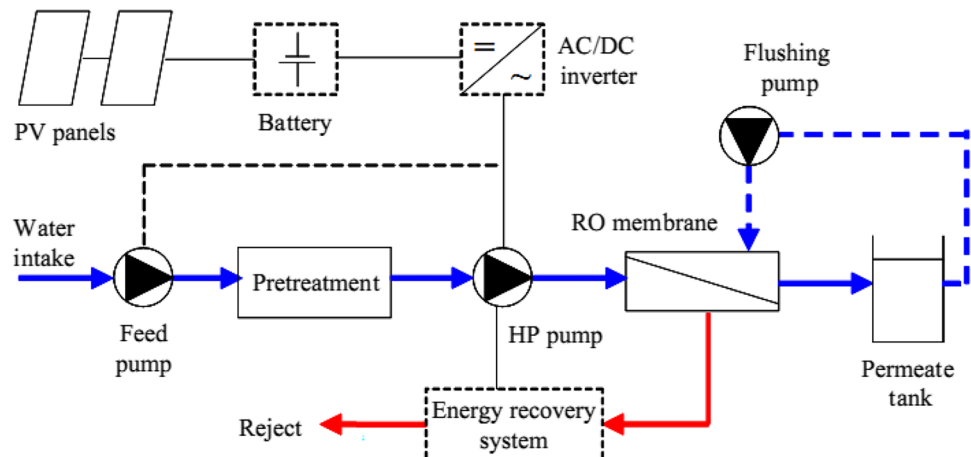
In spite of the improvements in the PV technology recently, the efficiencies of sun ray conversion of PV units is still low, hardly exceeding 15–16% (Goetzberger et al. 2003), and the commercial price of PV units is very high, causing the cost to be a limiting factor in the economical evaluation of PV-RO desalination. PV-RO was utilized in many countries for desalinating both brackish and seawater, but the capacity of such units is small (Bouguecha et al. 2005; Joyce et al. 2001; Richards and Schäfer 2003), and in spite of the much-gained experience since 1978 (Petersen et al. 1979), no standard design has been achieved, but some components are common to all PV-RO desalination set-ups (Fig. 3).

Solar system PV units

Both fixed and adjustable modules are used in experimental systems. It was realized that the module orientation is a very important element in determining the amount of electrical power produced and in turn the overall performance of the desalination unit. Fixed modules are positioned at a constant angle, while modules with adaptable axes can be positioned according to seasonal variations, or if a drive motor and tracking system are installed, the module will follow the daily path of the sun in the sky automatically. Both multicrystalline and monocrystalline silicon modules were utilized in experimental systems.

In Saudi Arabia, a PV-RO desalination plant increased the yearly permeate flow from 15 to $17 \text{ m}^3 \text{ day}^{-1}$ when

Fig. 3 Simple general scheme of a photovoltaic reverse osmosis (PV-RO) desalination plant. Dashed lines show items and connections which can be absent



seasonal optimum tilt angle variation was utilized (Alawaji et al. 1995). In Jordan, for a $0.1 \text{ m}^3 \text{ day}^{-1}$ PV-RO testing unit, Abdallah et al. (2005) reported an increase in electrical power and permeate flow of 25% and 15%, respectively, when using a one-axis tracking system instead of using a fixed-tilt plate.

It is mentioned in a study done by Harrison et al. (1996), in desalination systems with a small capacity of $0.05 \text{ m}^3 \text{ day}^{-1}$, that a tracking solar array produces 60% higher freshwater flow than a fixed array. However, the high cost of tracking systems has limited their wide use in PV-RO systems. Power optimizers like maximum power point tracker (MPPT) circuits are installed to maintain system operation and ensure efficiency in times of low irradiance.

Feed water pump(s)

The pumps that are used to transfer the seawater or the groundwater to the pretreatment unit of RO are powered by the arrays of PV unit (Alawaji et al. 1995; Kanzari 2005; Castellano and Ramirez 2005; Petersen et al. 1979; Touryan et al. 2006; Thomson and Infeld 2003), or by other renewable sources like wind turbines (Malki et al. 1998) or conventional electricity (grid) or a combination of them (Tzen et al. 2008). Pumps powered by solar energy are used often because they are reported to be more reliable in remote areas and require less maintenance (Alawaji et al. 1995; Kanzari 2005).

Feed water pretreatment unit

In the RO pretreatment unit, a coarse filter with a pore size of 20–25 μm or greater was used, followed by the main filter barrier with a pore size of 5 μm . For the removal of free chlorine, which can cause damage to RO membranes, an activated carbon filter is used.

Disinfection by ozonation (Cheah 2004) or chlorination is used if the bacterial counts in the inlet water are high, to protect the RO membranes from fouling. Ultrafiltration (UF) pretreatment was used in some experimental tests with different types of brackish groundwater in Australia (Richards et al. 2008; Richards and Schäfer 2003). The cost of ultrafiltration is higher than that of usual pretreatment, but it removes much more microorganisms, which reduce the need for disinfection and membrane cleaning by delivering high-quality feed water to RO.

Developments in RO desalination

Sidney Loeb and Srinivasa Sourirajan (Sidney and Srinivasa 1963) were able to produce a synthetic RO membrane from a cellulose acetate polymer, after which the progress in RO we see today started. The final result of RO desalination is

the production of freshwater and concentrated brine. The flow rate of the system depends on the difference between the osmotic pressure (pressure difference between brine and freshwater compartments) and the applied pressure.

Compared to thermal desalination, RO membranes are selective and require less energy (about 10 times less than their thermal counterparts), the area is smaller and the equipment used is not corrosive and is more safe. Due to these advantages, RO comprise more than 60% of the total desalination market.

RO membranes which are available on a commercial scale can retain 98–99.5% of the dissolved salt in the inlet water (Wilf 2004), using pressure ranges between 55 and 65 bar for seawater and for brackish water between 10 and 15 bar (Fritzmann et al. 2007). The quantity of freshwater which can be produced ranges from 45 to 50% for seawater RO systems and up to 90% for brackish water (Wilf and Klinko 2001).

In any trial to reduce the carbon footprint produced from desalination operations, RO would be the main substituent technology. In spite of all technological progress achieved, RO being the most economical technique on a commercial scale, it is still using much energy around 3 to 4 kW h/m^3 , which is more than twice the theoretical energy required (1.06 kW h/m^3) for desalinating seawater with 35,000 ppm salt and 50% recovery (Tedesco et al. 2015) which directly increase the water cost that many nations facing freshwater scarcity cannot afford. A recent study showing the capacity of desalination sector represents this reality (WHO 2011). The countries where desalination is used most are the countries with high purchasing capacity like United Arab Emirates, Kuwait, Saudi Arabia, certain parts of North America, Spain and Australia where citizens have high living standards and strong purchasing power (March 2015). The cost of desalination must be lower for the desalination sector to grow and expand in other stressed parts of the world (Manju and Sagar 2017).

The combination of different types of renewable energy with RO has seen many developments recently. The most utilized source of renewable energy with RO desalination is solar energy. The costs of producing power from renewable sources are 0.05 to 0.09, 0.05 and 0.07\$/kWh for solar, wind and geothermal, respectively, compared to 0.05 to 0.09 \$/kWh for fossil fuel, which is in favour of using renewable energy rather than fossil fuel (Gnaneswar et al. 2010).

Economics of REs-RO

One of the most significant elements of any water treatment project is the cost of water. Continuous trials to decrease the cost and increase the quality of the produced water are the main reasons for membrane desalination technology to

continue. The cost of a desalination project is mainly a capital cost and an operational cost. Capital costs include land, construction and equipment costs. Operational costs include energy, maintenance salaries and chemicals. (Ghonemy 2012; Enas 2016). Figure 4 shows the dependence of energy and cost on salinity of feed water for RO and ED units. RO has a higher specific cost than ED systems (Ghonemy 2012).

Several research and commercial bodies have developed cost estimation programs that can evaluate the capital and operating cost of desalinating both seawater and brackish water using different technologies. Several equations representing cost models and graphical forms have been developed for cost estimates (Watson et al. 2003).

To get an accurate method for estimating the cost is a difficult task since desalination is site specific and many parameters are considered when estimating the cost, e.g. cost of energy, land, labour. It is found that for a desalination plant producing 100,000 m³/day, the unit cost estimation is similar to what is reported in the literature for plants with similar capacities. Methods for cost estimation, such as DEEP and WT-Cost software, show similar unit costs \$0.99/m³ and \$0.96/m³. Capital cost always shows variation between published and estimated due to differences in interest rates, design and local conditions, etc. Unit cost can be reduced by reducing costs of labour and performing the periodic maintenances. Also, to reduce the cost of RO, the cost of the following factors should be reduced: chemicals required, membrane replacement cost, manpower cost and effective pretreatment.

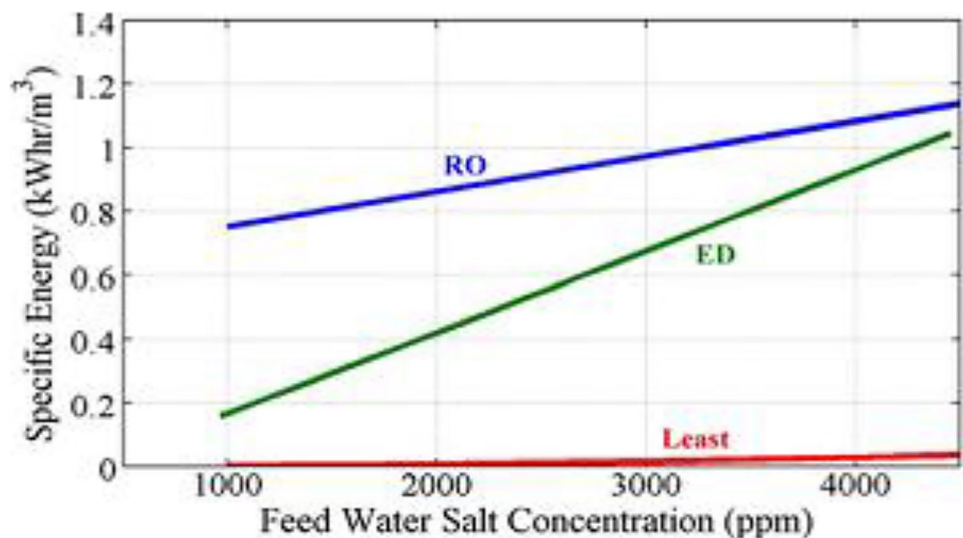
Karagiannis & Soldatos (2008) provided a water desalination cost review and concluded that the cost of water depends on the location. Al-Karaghoul and Kazmerski (2013a) stated that renewable energy desalination technologies are proven technology and economically competitive in remote regions. A comparison of different combinations

of renewable desalination has been done for a plant capacity of 500 m³ (Koroneos et al. 2007). The results show that RO-Wind has a specific cost of 1.61\$/m³. RO-PV costs 2.99\$/m³. Koroneos et al.'s (2007) work was done for a plant capacity of only 500 m³, and they did not study other promising renewable desalination combinations. In an economical study in Saudi Arabia, Al-Jaber and Ben-Mansour (2018) predicted that an RO-Wind system produced desalinated water at a cost of \$1.366/m³ for a daily demand of 1000 m³. This was in favour of ROPV and MED-Solar systems with costs of \$2.119/m³ and \$2.282/m³, respectively. For desalination, the most used source of renewable energy is solar photovoltaic (PV), representing approximately 43% of the total capacity; the following source is solar, thermal and after that wind energy (ADIRA 2008). The correct combination of a desalination technique and renewable energy resource is a very important factor to satisfy water and power demands efficiently, economically and environmentally friendly.

It is reported that energy cost represents 43% of the total seawater-reverse osmosis (SW-RO) desalination cost, while in the case of thermal desalination, energy represents 59% of total water production cost in large-scale plants (National Research Council 2004). Therefore, the energy cost, local availability and other site-specific factors are major elements in the economic feasibility of desalination processes. A potential solution for the production of freshwater from saline water in remote and desert regions provides desalination technology.

The continuous decrease in energy consumption and the increase in efficiency of PV power systems will eventually lead to a cost reduction and wider spread of RO-PV systems in remote areas, which face water scarcity and grid unavailability, as a repository of freshwater. The advantage of utilising RO-PV in arid areas is that it is favoured by

Fig. 4 With the increase in the salinity of the input water to the RO and ED units, the specific energy for desalination increases. A case of groundwater salinity range that is usually found in India is considered (Strathmann 2014)



high solar irradiation which is estimated to be twice the solar irradiation in developed countries.

Cost reduction in RO-PV systems is promising due to the contentious developments of RO and PV systems, and water production cost is also anticipated to be reduced with high production capacities. In addition to the economic and technical developments, RO-PV systems are environmentally friendly (with no gaseous emissions). Photovoltaic (PV) driven reverse osmosis (RO) (Ghaffour et al. 2014; Kalogirou 2005) and solar thermal MED (Kalogirou 2005) are the most utilized renewable energy techniques in the desalination sector.

The presented system is able to produce a continuous supply of 20 kg/day of water per square meter of the solar collector area. Furthermore, it is possible to increase the value by the optimisation of the 3 subsystems' interaction, i.e. temperature losses of the heat in the storage, effectiveness of the desalination system and effectiveness of the solar collectors. The productivity in a 360-m² collector is increased when the feed flow is 1.7 kg/s and the diameter of the heat storage tank is 1.9 m. The cost of desalination calculated at approximately \$1.29/m³ is much cheaper compared to other solar thermal desalination systems (Qian et al. 2020).

In a review done by Karagiannis and Soldatos (Karagiannis 2008), they concluded that water cost depends on the location. In a different study by Al-Karaghoul and Kazmerski (2013b), they mentioned that in remote areas, renewable energy-based desalination technologies are proven competitive economically.

Most of the comparisons made between different renewable energy-based desalination techniques were based on different energy sources, the capacity of the system, the components of the system and the salinity of the feed water, making the comparison difficult from an economic perspective.

Today, RO combined with solar energy is the most widely utilized technique to produce freshwater from seawater. This could be due to the fast progress in this technology which is considered one of the most efficient techniques for desalinating water with high salt concentrations (above 35,000 ppm) (Ali 2018). Despite all efforts made in recent years to decrease the amount of energy consumed in RO desalination, it is still the component with the highest cost, and energy consumption accounts for 40–45% of costs (Bets 2004).

The most promising technology in the desalination-based renewable energy sector is the coupling between solar energy and reverse osmosis membrane desalination, where it has the potential to significantly reduce the dependence on fossil fuel and substantially decrease the operational cost of desalination plants.

Conclusions

Desalination, with no doubt, will play a major role in the supply of potable water, even in areas which are now enjoying enough water availability. It is time to address the limitations of desalination that hamper its widespread utilisation, mainly energy and cost.

Desalination seems to be the only alternative that possesses the potential to cross the gap between needed and available freshwater in many places that are suffering from water scarcity. Energy is a major limiting factor facing the sector; if oil is used (recent estimation is 850 million t/year), then we have two major problems, cost and environmental issues (76 million tons of CO₂/year, expected to reach 218 million tons by 2040), in addition to the depletion of the resource. Renewable energy-coupled desalination is emerging as a potential solution to oil depletion and environmental concerns; however, the sector is facing two problems, the large amount of energy required and difficulties in storing the energy for off-peak periods. Currently, reverse osmosis is the most favoured and the least energy-consuming desalination technique, mainly combined with solar energy, then we have more problems, mainly high capital cost (especially the cost of the PV panels and the tracking systems), low conversion efficiencies, intermittent nature of the resource and low production of freshwater. However, the energy produced from renewable resources has increased about five times between 2005 and 2015, most of it through solar and wind resources. Research is still needed to increase the efficiency of sunlight conversions by PV units, lower its commercial price and lower the cost of the solar array tracking system required to increase production; more research is also needed in the area of applying changing flow rates and in integrating renewable-renewable energy sources to prolong working hours. Different studies have shown that wind, wave and geothermal can compete with solar desalination with better theoretical conversion efficiency for RO and concentrated solar power for thermal desalination, but more research is required to investigate the reasons for their low or no market share.

Regardless of the techno-economic conditions of hybrid renewables systems, these types of systems are crucial solutions for providing power and freshwater for remote areas.

Recent studies reviewed indicated that solar photovoltaic integrated RO desalination process, hybrid solar photovoltaic-wind integrated RO desalination process, hybrid solar photovoltaic-thermal (PVT) integrated RO desalination process and hybrid solar photovoltaic-thermal multi-effect distillation (PVT-MED) desalination process are the leading methods in the desalination market and extensive studies are carried out to increase efficiency and reduce investment costs for these processes.

Author contribution Hesham R. Lotfy: writing — original manuscript; writing — review and editing. Jan Staš: writing, review and editing. Hynek Roubik: conceptualisation, supervision, writing — review and editing.

Data availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication All authors agree with publishing.

Competing interests The authors declare no competing interests.

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