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REVIEW ARTICLE

Water-energy nexus: desalination technologies and renewable energy sources

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Abstract
Rapid population growth and industrialization have contributed to a dramatic decline in the supply of freshwater. As a result, desalination is an important choice to solve the global problem of water scarcity. Nevertheless, the hyper-saline by-product, the high capital costs, and the high energy demands currently met by fossil fuels are key obstacles to the widespread adoption of desalination systems. Furthermore, desalination plants powered by fossil fuels have negative environmental impacts due to greenhouse gases (GHGs) emissions. In contrast to fossil fuels, renewable energy is abundant and clean and is therefore a promising alternative for powering desalination plants. This is why the water-energy nexus is a crucial step towards a sustainable future. Therefore, the integration of renewable energy sources (RES) into desalination is very important. The main objective of this review to analyze and evaluate desalination technologies (thermal-based and membrane-based) and RES (solar, wind, hydropower, geothermal, and biomass) that could be combined as an integrated process. Social-economic factors, environmental concerns, current challenges, and future research areas for both desalination and RES are discussed.

Keywords Desalination · Water-energy nexus · Technologies · Renewable energy sources · Brine treatment · Sustainability

Introduction

Even though two-thirds of the Earth's surface is made up of water, only a small portion of that water is suitable for human consumption (Fridell 2015). Furthermore, pollution and inefficient utilization of available freshwater resources have caused freshwater shortages. The World Health Organization (WHO) reports that one-fifth of the world's population lives in countries with freshwater shortages (WHO 2005). Only 3% of the total water resources available on Earth is freshwater, while the remaining 97% is saline water (Sherwin 2017). In this case, desalination seems to be a promising solution. Desalination is a process through which dissolved salts are separated from saline water, and thus, freshwater is recovered. This process is, therefore, an efficient way to produce freshwater (Liyanaarachchi et al. 2013; Panagopoulos 2020a). This is reflected in the fact that there were approximately 21,123 desalination plants producing approximately 142 million cubic meters of freshwater per day by the end of 2020, a quantity of freshwater equivalent to the volume of 56,800 Olympic-size swimming pools (Panagopoulos and Haralambous 2020b). It should be noted that within 20 years, the production capacity of desalination plants has increased by 6 times, while the number of desalination plants has only increased by 1.5 times (IWA 2016; IDA and GWI 2017). This can be due to the fact that in addition to several desalination benefits (e.g., immediate availability of freshwater in both dry and coastal areas), there are also adverse impacts. The main drawbacks of the desalination process are its relatively high energy intensity, the generation of a hyper-saline by-product (brine), and contribution to global warming through greenhouse gas (GHG) emissions. Commonly, fossil fuels are used to supply the energy required to operate the desalination plants

Highlights
- Renewable energy-based desalination is a solution to water scarcity.
- Membrane- and thermal-based desalination technologies are evaluated.
- Renewable energy options for desalination are analyzed.
- Challenges and prospects for RES-based desalination options are presented.

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(Panagopoulos 2020b). However, burning fossil fuels produces significant amounts of GHG emissions with detrimental environmental impacts. Global emissions from desalination systems powered by fossil fuels are expected to exceed an annual rate of 400 million tons of carbon equivalent by 2050 (World Bank 2012). It is therefore necessary to seek alternative sources of energy for desalination. Renewable energy is a very promising option. Renewable energies are energies that are constantly replenished by nature and obtained directly/indirectly from the Sun or other natural actions and mechanisms of the environment (Nalule 2018). Renewable energy sources (RES), such as solar energy, geothermal energy, and hydropower, can be used for desalination purposes (Letcher 2016). RES-based desalination has been mainly performed in areas with high solar radiation and/or high wind power, such as the Middle East, for the last decade; however, recent price drops and advances in renewable energy technologies have resulted in an increased interest (Manju and Sagar 2017).

The main aim of this review paper is to compare and assess the desalination technologies and RES that could be combined as an integrated process. Subsequently, current power generation technologies and water-energy nexus are highlighted. Furthermore, social-economic factors and environmental concerns related to both desalination and RES are discussed. Finally, existing challenges and future research areas for both desalination and renewable energy generation technologies are outlined.

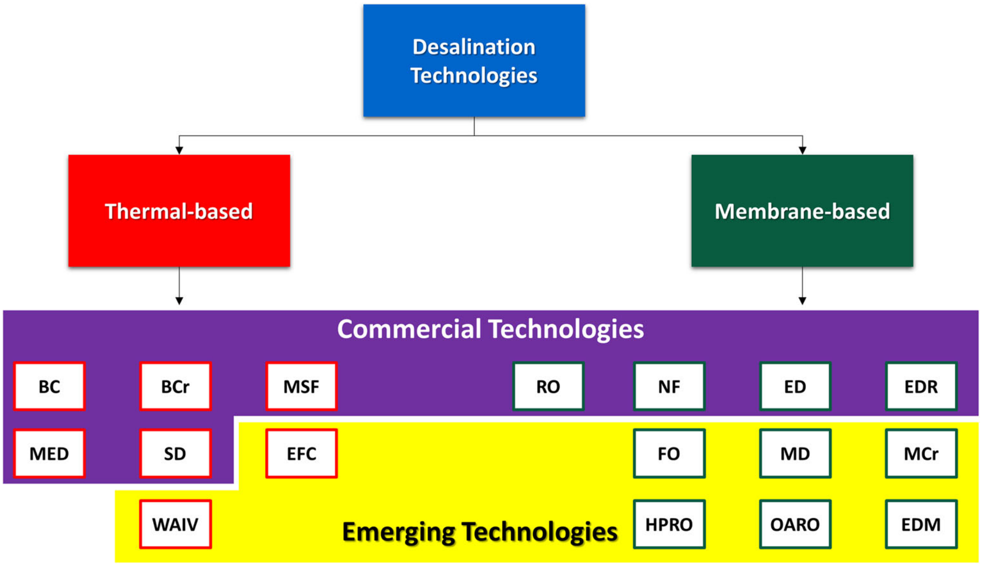
Current desalination technologies

Desalination technologies can be classified into two main categories: thermal-based (phase-change processes) and membrane-based technologies (non-phase-change processes) (Basile et al. 2018). Thermal-based technologies mimic the natural water cycle of evaporation and condensation. Membrane-based systems, on the other hand, are pressure-driven and operate with the allowance/prohibition of the movement of certain ions through semi-permeable membranes (Panagopoulos et al. 2019). Generally, thermal-based technologies require both thermal energy and electricity, whereas membrane-based technologies require only electricity. Thermal-based technologies include multi-stage flash distillation (MSF), multi-effect distillation (MED), brine concentrator (BC), brine crystallizer (BCr), eutectic freeze crystallization (EFC), wind-aided intensified evaporation (WAIV), and spray dryers (SD). On the other hand, membrane-based technologies include reverse osmosis (RO), nanofiltration (NF), electrodialysis (ED), ED reversal (EDR), high-pressure RO (HPRO), forward osmosis (FO), osmotically assisted RO (OARO), membrane distillation (MD), membrane crystallization (MCr), and ED metathesis (EDM) (Alnouri et al. 2017; Barrington and Ho 2014; Bazargan 2018). Both commercially available and emerging technologies exist in both categories, as shown in Fig. 1. Nonetheless, as shown in Fig. 2, commercial desalination technologies dominate (98%) the market. Specifically, Fig. 2 shows the share of different desalination technologies around the world. As shown in Fig. 2, RO is the main desalination technology used by nearly 70% of the desalination plants. Thermal-based MSF (18%) and MED (7%) are the next most commonly used technologies. Finally, the rest is made up of NF, ED/EDR, and other emerging technologies (Global Water Intelligence 2016). The advantage of membrane-based technologies over thermal-based technologies can be explained by the fact that membrane-based technologies are more compact and energy-efficient. However, membrane-based technologies have lower feed water salinity limits compared with thermal-based technologies (Panagopoulos 2021). Regarding the feed water salinity, Fig. 3 shows that seawater is mostly used (60.4%), followed by brackish water (20.79%), river water (7.92%), wastewater (5.94%), pure water (3.96%), and brine (0.99%) (Global Water Intelligence 2016). As anticipated, over 80% of desalination plants treat brackish water or seawater since these water streams are the most common. In contrast, the composition of wastewater and brine is more complex and these streams are therefore treated by very few desalination plants (Table 1).

Assessment of thermal-based technologies

Among this classification, the commercial MSF and MED technologies are the most popular in brackish water and seawater desalination. MSF and MED have been prevalent in areas such as the Middle East and North Africa (MENA) due to low energy costs and large-scale cogeneration plants (Khoshrou et al. 2017). However, thermal-based desalination plants suffer from scaling formations such as calcium carbonate ($CaCO_3$), magnesium sulfate ($MgSO_4$), and magnesium hydroxide ($Mg(OH)_2$) which limit plant's performance at high temperatures (Zhao et al. 2018). The remaining thermal-based technologies are of particular interest in the desalination brine treatment. Brine (55,000–77,000 mg/L TDS) is nearly twice as salty as seawater and therefore cannot be treated in conventional MSF/MED plants as high chloride (Cl^-) concentrations may corrupt the stainless steel equipment (Panagopoulos et al. 2020). As shown in Fig. 3, while brine is currently only 1% of feed water, brine treatment is an upcoming water sector due to several opportunities such as the recovery of freshwater and critical raw materials, which would otherwise be unrecovered (Panagopoulos 2021). BC/BCr are the main brine treatment technologies; however, their high capital costs are a barrier to their widespread use (Spellman 2015). SD can produce salt crystals at certain standards (e.g., particle size distribution and shape), while WAIV can be a cost-effective technology for crystallization (Petersen et al. 2017; Al-Khattawi et al. 2017;

Fig. 1 Classification of the desalination technologies



Basile et al. 2018). All these technologies, however, produce mixed solid salts. This downside does not exist in the EFC, as high freshwater recovery and pure solid salts can be obtained (Williams et al. 2015). Nonetheless, these technologies have high capital costs, which are why their implementation has so far been limited to laboratory/pilot scale (Panagopoulos et al. 2019).

Assessment of membrane-based technologies

As illustrated in Fig. 2, RO is currently the main membrane-based technology. RO, as well as, NF can be used both for brackish water and seawater; however, due to osmotic constraints, RO/NF cannot be used for hyper-saline feed water solutions (> 70,000 mg/L TDS) (Panagopoulos 2021). As a result, emerging technologies are focusing on the treatment of feed water solutions of more than 70,000 mg/L TDS. HPRO, a more advanced RO, can concentrate roughly 1.5 times more saline solution than RO (Davenport et al. 2018; Pall Corporation 2019). Nonetheless, other emerging technologies such as FO, MD, and OARO should be used for higher TDS feed solutions (Panagopoulos and Haralambous 2020b). In comparison to RO/HPRO, FO uses osmotic pressure gradients rather than hydraulic pressure and achieves better performance (Ahmed et al. 2019). Nevertheless, FO requires an extra solution called "draw solution" which must be recovered after the separation process. MD utilizes external thermal energy in the membrane separation and thus can treat extremely high-TDS feed solutions (up to 350,000 mg/L) (Tun and Groth 2011). The most recent membrane-based technology (since 2017), OARO, combines the principles of RO and FO (Bartholomew et al. 2017). The established electrical-driven technologies (ED and EDR) have so far been used in large-scale brackish water desalination plants; however, they can be used for feed water solutions of more than 70,000 mg/L TDS (Asraf-Snir et al. 2018; Qureshi and Zubair 2016; Tong et al. 2019). In contrast to the others, ED/EDR are quite appropriate for solutions with high silica content as silica is neutrally charged. EDM is a more advanced system of ED/EDR units that can recover useful materials such as sodium chloride (NaCl) and magnesium chloride ($MgCl_2$) (Camacho et al. 2017; Han 2018). Scaling, fouling, wetting, and polarization of membranes are key issues that limit the performance of membrane-based technologies (Chen et al. 2018; Deng et al. 2018). To address these issues, novel membranes such as omniphobic and superhydrophobic have recently been developed. So far, the results from the experiments have been promising (Deng et al. 2018; Xiao et al. 2019).

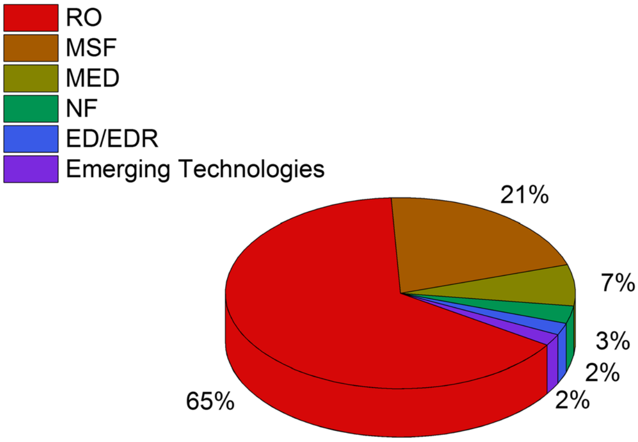


Fig. 2 Breakdown of desalination technologies applied around the world

Overall desalination technology assessment

Energy consumption in desalination varies from technology to technology, as illustrated in Fig. 4 (Basile et al. 2018; Bond

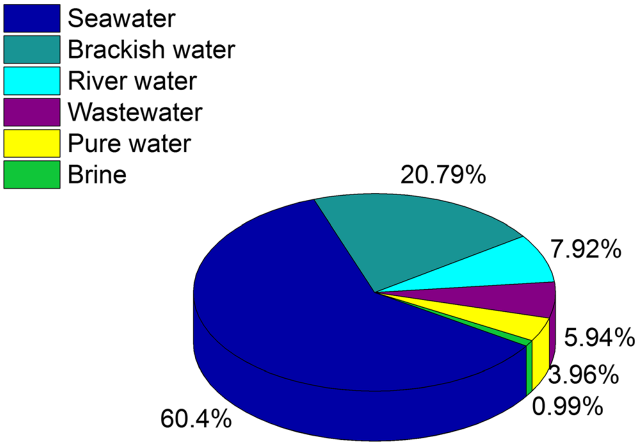


Fig. 3 Breakdown of feed water on the desalination plants applied around the world

et al. 2015; Filippini et al. 2018; Ihm et al. 2016; Kolliopoulos et al. 2018; Lokare et al. 2018; Murray et al. 2015; Nasr et al. 2013; Pronk et al. 2008; Ruiz Salmón and Luis 2018). Thermal-based systems, in particular, require both thermal and electrical energy for evaporation/crystallization and hydraulic transport of the streams (feed water, freshwater produced, and concentrated brine). Membrane-based technologies, on the other hand, require only electrical energy to achieve the membrane separation and the hydraulic transport of the streams. Thus, membrane-based technologies are less energy-intensive (0.6–19 kWh/m^3) compared with thermal-based technologies (7.7–70 kWh/m^3) due to a lack of energy losses associated with evaporation and condensation (Whitaker 2013). The only exceptions to this rule are MD and MCr (44–70 kWh/m^3) because they are the only membrane-based technologies that are also thermal-driven. Regarding the TDS of the feed water, all technologies can treat both brackish water and seawater. Furthermore, membrane-based technologies have lower maximum feed water salinity than thermal-based technologies. However, commercially successful technologies (RO, MSF, MED, and ED/EDR) are not appropriate for the treatment of high-TDS brine (> 240,000 mg/L) as shown in Fig. 5 (Basile et al. 2018; Bond et al. 2015; Filippini et al. 2018; Ihm et al. 2016; Kolliopoulos et al. 2018; Lokare et al. 2018; Murray et al. 2015; Nasr et al. 2013; Pronk et al. 2008; Ruiz Salmón and Luis 2018). Several factors have an impact on the desalination cost, such as (i) feed water characteristics and management of the concentrated brine and (ii) plant's capacity (iii) required energy (iv) operation and maintenance. Figure 6 presents the cost of freshwater produced from both membrane-based and thermal-based technologies (Valladares Linares et al. 2016; Schantz et al. 2018; Bartholomew et al. 2018; Lokare et al. 2018; Gilron et al. 2003; Spellman 2015; Randall et al. 2014). As shown in

Table 1 Characteristics of different feed water streams in the desalination industry

Parameters	Seawater (Waly et al. 2012)	Brackish water (Walker et al. 2014)	River water (Karmakar et al. 2019)	Wastewater (Ejraei et al. 2019)	Pure water (Naymushina 2017)	Brine (Istirokhatun et al. 2018)
Cl^- (mg/L)	21,535	3,346	-	600	3.2	42,500
SO_4^{2-} (mg/L)	2,772	991	-	400	2.5	6,420
NO_3^- (mg/L)	-	-	-	50	-	-
HCO_3^- (mg/L)	146	1,013	386.33	-	236.3	267
K^+ (mg/L)	434	-	1.88	-	0.8	-
Na^+ (mg/L)	12,245	879	-	-	8.6	17,000
Ca^{2+} (mg/L)	474	1,030	22.76	75	49.4	961
Mg^{2+} (mg/L)	1,356	515	1.46	100	8.3	2,940
NH_4^+ (mg/L)	-	-	-	2.5	-	-
NO_2^- (mg/L)	-	-	-	10	-	-
SO_3^{2-} (mg/L)	-	-	-	1	-	-
Biological oxygen demand (BOD_5) (mg/L)	-	-	-	30	-	-
Chemical oxygen demand (COD) (mg/L)	-	-	-	60	-	-
Dissolved oxygen (DO) (mg/L)	-	-	-	2	-	-
Total suspended solids (TSS) (mg/L)	-	-	-	40	-	-
Total dissolved solids (TDS) (mg/L)	39,017	7,890	160	1,269.7	265.5	70,088

Fig. 4 Energy consumption for each desalination technology

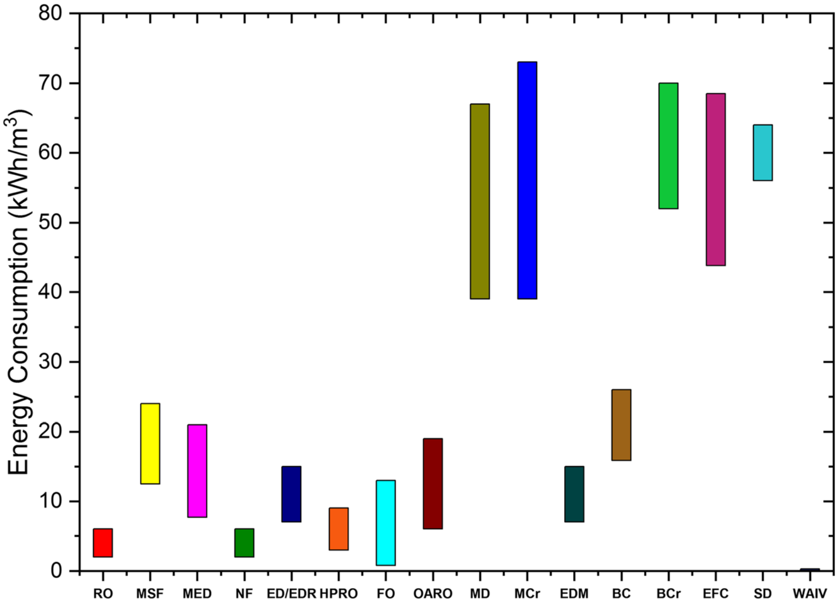


Fig. 6, crystallization technologies (e.g., EFC and BCr) and the very recent technology (OARO) are the costliest. Overall, a summary of the current desalination technologies is presented in Table 2.

Power generation technologies

The global power generation capacity is currently estimated at 7073 GW. However, this amount is going to be increased, as the International Energy Agency has estimated that this capacity will be increased to 10,394 GW in 2030 and 12,656 GW in 2040. In more detail, Table 3 presents the global power generation capacity by source for 2018 and projections for 2030 and 2040. The main power source in 2018 was coal (29.56%), followed by natural gas (26.3%), while the power generated from RES accounted for 34% of the total. As shown in Table 3, these figures are expected to change dramatically by 2040. Specifically, it is estimated that in 2040 the power from RES will account for more than 51% of the total capacity. Wind and solar power sources are expected to show the largest increase by 2040, 5× times and 3× times, respectively (International Energy Agency 2018). The upcoming increase in wind and solar power generation can be attributed to several factors, such as increased technology efficiency, comparatively low wind and solar photovoltaic prices, and public

Fig. 5 Maximum feed water salinity for each desalination technology

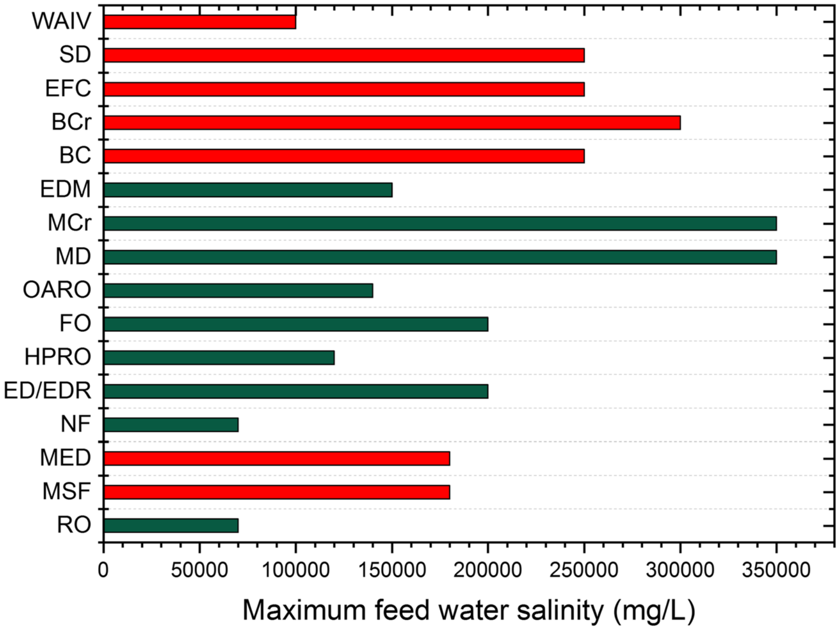
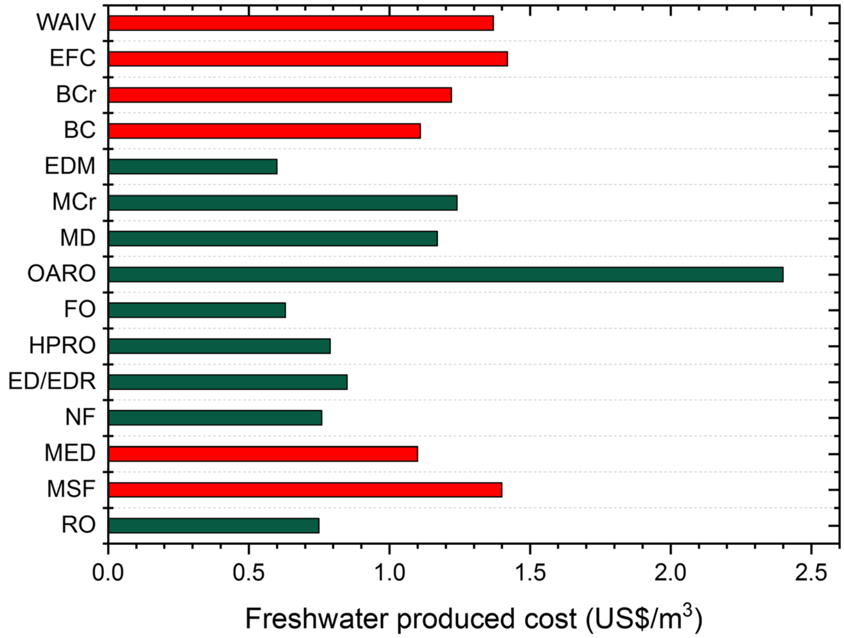


Fig. 6 Cost of freshwater produced from desalination technologies



awareness of global warming (Csereklyei et al. 2019; Ding et al. 2019). The salinity-gradient energy (also known as blue energy) that is based on the release of free energy when blending water streams with different salinities, such as between rivers and seas, is another type of renewable energy that has recently gained attention (Siria et al. 2017; Sun et al. 2020; Pan et al. 2018a). When RO brine is intentionally blended with recycled wastewater, more energy can be produced. Not only can this osmotic energy reduce the total energy usage of the desalination process but can also tackle the problem of brine disposal (Tollefson 2014). Several technologies, such as pressure retarded osmosis, reverse ED, capacitive mixing, and 2D nanopore diffusio-osmosis, can harvest blue energy in brine (Pan et al. 2020; Pan et al. 2018b).

Water-energy nexus and environmental impacts

Water and energy are the fundamental resources of the natural environment. Although we were used in the past to see these meanings as almost foreign to each other, they are interlinked both on a planetary scale and on the scale of human activity. Water is used at all stages of energy production, while energy is used for desalination (Thiede et al. 2017; Organisation for Economic Co-Operation and Development 2017). This is why understanding the interactions that occur in the water-energy nexus is so critical. The water-energy nexus is thus illustrated in Fig. 7.

However, there are concerns about environmental impacts and pollution from both desalination plants and power plants. Although efforts have been made in recent years to use RES, the majority of global energy supply is still generated by the combustion of fossil fuels or by coal production (Al-Shayji and Aleisa 2018). The principal environmental concerns arising from desalination are the GHG emissions, the disposal of the hypersaline by-product (brine) in the marine environment resulting in increased salinity and chemical concentrations. Brine contains toxic substances from different chemicals used in the pre-treatment/post-treatment (Table 4) (Panagopoulos et al. 2019). Similarly, the major environmental concerns arising from power plants are GHGs and solid residues resulting from solid fuels such as coal, biomass, and municipal solid waste (MSW) (Tang et al. 2013). Overall, Table 5 summarizes the different pollutants from both power generation and desalination plants.

Desalination plants powered by RES

Current status

As discussed previously, desalination techniques usually use fossil fuel energy and therefore have negative environmental impacts. To this aim, RES have the potential to provide energy with minimal environmental impact. Coupling desalination technologies with RES can be useful for two main reasons: (i) environmental and energy sustainability and (ii) future preservation of freshwater resources (Arafat 2017). The environmental friendliness of RES can be explained by the data in Table 6. As shown in Table 6, RES have significantly lower CO_2 emissions compared with other conventional sources (Sovacool 2008). In addition, with RES-based desalination systems, a reduction of up to 85% in air emissions can be

Table 2 Overview of the current desalination technologies

Technology	Principle	Main energy type	Status	Energy consumption (kWh/m^3)	Average cost (US\$/m^3 of freshwater produced)	References
RO and NF	Membrane separation	Hydraulic pressure	Commercial	2–6	0.75	Valladares Linares et al. (2016), Schantz et al. (2018), Alspach (2014), and Panagopoulos et al. (2019)
MSF and MED	Evaporation and crystallization	Thermal	Commercial	12.5–24 (MSF) 7.7-21 (MED)	1.40 (MSF) 1.10 (MED)	Ihm et al. (2016), Filippini et al. (2018), Kesieme et al. (2013), Deyab (2019), Panagopoulos et al. (2019)
ED and EDR	Membrane separation and electrochemical	Electricity	Commercial	7–15	0.85	Yan et al. (2018), Reig et al. (2014), Zhao et al. (2019), Mikhaylin and Bazinet (2016), and Panagopoulos et al. (2019)
HPRO	Membrane separation	Hydraulic pressure	Emerging	3–9	0.79	Alspach (2014), Schantz et al. (2018), The Dow Chemical Co (2017), and Panagopoulos et al. (2019)
FO	Membrane separation	Osmotic pressure	Emerging	0.8–13	0.63	McGinnis et al. (2013), Kolliopoulos et al. (2018), Valladares Linares et al. (2016), and Panagopoulos et al. (2019)
OARO	Membrane separation	Osmotic and hydraulic pressure	Emerging	6–19	2.40	Bartholomew et al. (2018), WDR (2018), and Panagopoulos et al. (2019)
MD	Membrane separation and Evaporation	Thermal	Emerging	39–67	1.17	Lokare et al. (2018), Kesieme et al. (2013), Sanmartino et al. (2017), and Panagopoulos et al. (2019)
MCr	Membrane separation and Crystallization	Thermal	Emerging	39–73	1.24	Ali et al. (2015), Ruiz Salmón and Luis (2018), Lokare et al. (2018), and Panagopoulos et al. (2019)
EDM	Membrane separation and Electrochemical	Electricity	Emerging	0.6–5.1	0.60	Bond et al. (2015), Nunen and Panicot (2018), and Chen et al. (2019)
BC and BCr	Evaporation and crystallization	Thermal	Commercial	15.86–26 (BC) 52–70 (BCr)	1.11 (BC) 1.22 (BCr)	Fluid Technology Solutions Inc (2016), Stanford et al. (2010), Spellman (2015), and Panagopoulos et al. (2019)
SD	Crystallization	Thermal	Commercial	52–64	-	Mackey and Seacord (2008), Nasr et al. (2013), GEA Process Engineering (2019)., and Panagopoulos et al. (2019)
EFC	Crystallization	Thermal	Emerging	43.8–68.5	1.42	Randall et al. (2014), Pronk et al. (2008), Chivavava et al. (2014), and Panagopoulos et al. (2019)
WAIV	Crystallization	Electricity	Emerging	0.3–1	-	Basile et al. (2018), Murray et al. (2015), Gilron et al. (2003). and Panagopoulos et al. (2019)

achieved (Raluy et al. 2006). To this end, several RES and RES-based desalination systems have been investigated (Mito et al. 2019; Khiari et al. 2019; Panagopoulos 2020c). Nevertheless, the number of RES-based desalination plants is currently extremely low, with only 131 desalination plants (Negewo 2012). Figure 8 illustrates the different types of

Table 3 Global power generation capacity by source (International Energy Agency 2018)

Source (in GW)	2018	2030 Projection	2040 Projection	Estimated difference between 2018 and 2040 (%)
Natural gas	1610	2352	2741	+70%
Solar	457	1679	2542	+456%
Coal	2091	2254	2384	+14%
Hydropower	1285	1632	1881	+46%
Wind	512	1209	1605	+213%
Nuclear	445	484	521	+17%
Other renewables	151	281	451	+199%
Liquid fuel (oil)	472	389	310	−34%
Battery storage	50	114	221	+342%

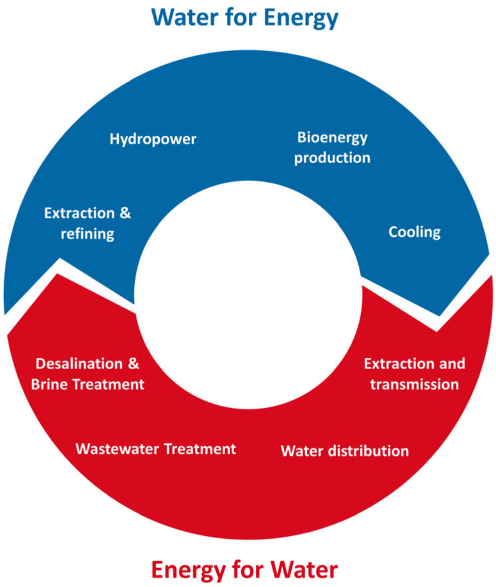


Fig. 7 The water-energy nexus

RES-based desalination systems around the world. As shown in Figure 8, solar photovoltaic (PV) RO is the most common (43%), followed by wind RO (13%) and solar MED (13%) (Panagopoulos and Haralambous 2020a).

Typical examples of renewable energy are geothermal, solar, wind, hydropower, and biomass (Miremadi et al. 2019; Ehrlich 2013). Table 7 presents an overview of the RES. The most abundant energy source available is solar, and it does not pollute the air or water. Another clean renewable energy is wind power, which does not disrupt the ecosystems, and the area around wind farms can be used. Hydropower is an RES that is cost-effective and can be produced in large quantities. As far as geothermal energy is concerned, it is an energy with a low average cost and it is efficient. Biomass energy is renewable energy that can have several applications, for example, biomass-based diesel in diesel engines (Panagopoulos and Haralambous 2020a). As shown in Table 7, each renewable energy has advantages and disadvantages. Thus, to achieve the highest efficiency, RES should be combined with the most applicable desalination technology. Selection of the most appropriate RES-based desalination technology depends on various factors such as plant size, salinity of feed water and product water, location of the renewable energy source, and utilization costs. Possible options for desalination based on RES are presented in Fig. 9 (Panagopoulos and Haralambous 2020a).

Environmental concerns, challenges, and future prospects

While RES can contribute to the reduction of GHGs, their implementation is associated with environmental issues and challenges. For example, the natural environment is altered, regardless of the form of renewable energy, as the construction and installation of a renewable energy system requires a large amount of land, preventing further simultaneous utilization of the area (Abdul-Wahab et al. 2019; Li et al. 2019b). This can be easily understood from the fact that the installation of solar PVs on the rooftops could have minimal impact on land usage. The author therefore recommends the installation of solar PVs on the rooftops to have a negligible impact on the land. The use of biomass as RES results in the release of global warming gases such as methane (CH_4) during the production of biofuels (Kucharska et al. 2018). Furthermore, there is a risk of deterioration of soil productivity. In particular, RES such as geothermal, hydropower, and wind can lead to soil erosion. Waterways can be contaminated by both geothermal and hydropower sources, whereas the wind energy source can lead to the killing of birds by blades (Hua et al. 2019). Adjusting the blade's rotation at a slower pace to prevent the death of flying birds could reduce that risk while minimizing the infrasound level. Based on previous observations, the author suggests that to achieve a continuous and stable power supply, hybrid RES systems involving a variety of RES could make a great combination. In addition to the technical aspects that have to be investigated and resolved, compared with conventional energy sources such as fossil fuels, RES have high investment costs. Thus, the large payback period remains a major barrier to the wider adoption of the RES (Li et al. 2019a; Wijesuriya et al. 2017). To reduce the cost of RES, we can extend their use in several sectors,

Table 4 Chemicals for pre-treatment and post-treatment operations in desalination plants (Panagopoulos et al. 2019)

Category	Typical chemicals	Purpose
Strong acids	HCl/ H_2SO_4	pH adjustment
Oxidizing agents	$Ca(ClO)_2$/$NaOCl$	Preventing bacterial growth
Antiscalants	Polyphosphates, phosphonates and polycarbonic acids	Increase of solubility of sparingly soluble salts (e.g., $CaSO_4$, $MgSO_4$, $CaCO_3$, $BaSO_4$)
Coagulants	$Fe_2(SO_4)_3$/$FeCl_3$	Suspended solids removal
Flocculants	Cationic polymer	Suspended solids removal
Reducing agents	HSO_3^-	Eliminating the impacts of oxidizing agents

Table 5 Water, air, and soil pollution dangers from power generation and desalination plants (Tang et al. 2013; Panagopoulos et al. 2019)

Plant	Water pollution	Air pollution	Soil pollution
Desalination	- Brine disposal - Chemical used in pretreatment and posttreatment operations	GHGs (CO_2, N_2O, NO_2 and SO_2)	- Brine disposal - Solid residue from brine
Power generation	- Water used in the processes - Danger of contamination	GHGs (CO_2, N_2O, NO_2 and SO_2)	Ash from burning solid fuels (coal, biomass, MSW, etc.)

Table 6 Estimated CO_2 emissions form energy sources (Sovacool 2008)

Energy source	Description	Estimate (gCO_2/kWh of energy generation)
Wind	2.5 MW, offshore	9
Hydroelectric	3.1 MW, reservoir	10
Wind	1.5 MW, onshore	10
Biogas	Anaerobic digestion	11
Solar thermal	80 MW, parabolic trough	13
Biomass	Forest wood steam turbine	22
Solar PV	Polycrystalline silicon	32
Geothermal	80 MW, hot dry rock	38
Nuclear	Various reactor types	66
Waste to energy	Various	440
Natural gas	Various combined cycle turbines	443
Fuel cell	Hydrogen from gas reforming	664
Diesel	Various generator and turbine types	778
Heavy oil	Various generator and turbine types	778
Coal with scrubbing	Various generator types with scrubbing	960
Coal without scrubbing	Various generator types without scrubbing	1050

such as transport. In addition, the implementation of smart grid technology will make renewable energy more common and help reduce costs. Overall, the major challenges are summarized in Fig. 10.

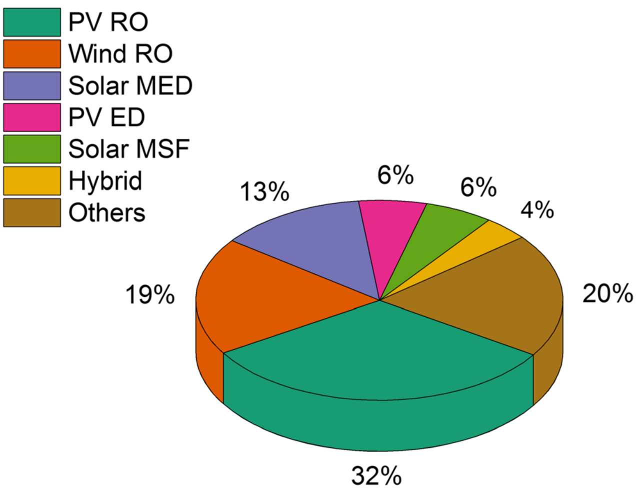


Fig. 8 Breakdown of RES-based desalination technologies applied around the world

With respect to the desalination activity, so far, only RES-based desalination plants related to brackish water and seawater are currently in operation (Alhaj and Al-Ghamdi 2019; Gude 2018). However, brine treatment is an upcoming sector of the water industry, and thus, studies on this sector should be conducted. According to the author, future studies should emphasize improving the key aspects of both desalination and renewable energy generation technologies. These improvements must be made in light of the synergies between these two types of technology. To assess the feasibility and the viability of RES-based desalination systems, process simulations, techno-economic analyses, and life-cycle assessments should be performed.

Conclusions

Water and energy are fundamental resources of our world. Desalination is considered to be a reliable option for

Table 7 Overview of the RES

Renewable Energy	Power generated by	Advantages	Disadvantages	Capital cost (US$/kWh)	Average cost (US$/kWh)	References
Solar	Sun	- No air or water pollution - Most abundant energy source available	- Dependent on the availability of the sunlight - PV cell panels require a large amount of land - High capital costs - Storage and backup are necessary	3000–5500 (PV) 4000–6000 (Thermal)	0.038 (PV) 0.165 (Thermal)	US EIA (2019), Twidell and Weir (2015), and Israel and Jehling (2019)
Wind	Wind	- No air or water pollution - Land around wind farms can be still utilized - Insignificant disruption of ecosystems	- Not applicable to all geographical locations - Windfarms require a large amount of land - Energy production is proportional to the wind speed - Can have an important visual impact on the landscape	1700–2800	0.106	US EIA (2019), Twidell and Weir (2015), and Nazir et al. (2019)
Hydropower	Water	- Abundant and clean - Ability to produce large energy amounts - Low average cost	- Dams can have a significant environmental impact - Can be used only at places with a water supply - Dams can be affected by drought - May cause flooding on the surround	1000–4000	0.039	US EIA (2019), Twidell and Weir (2015), and Hossain et al. (2018a, 2018b)
Geothermal	Earth	- No air or water pollution - Low average cost - Efficient	- Geothermal fields are limited - Expensive start-up costs - Increased maintenance costs due to potential corrosion	3000–4000	0.037	US EIA (2019), Twidell and Weir (2015), and Hossain et al. (2018a, 2018b)
Biomass	Plant and animal waste	- Abundant and renewable - Can be used in diesel engines - Can be used to burn waste products	- Burning biomass can lead to air pollution (e.g., increases emissions of nitrogen oxides) - Source must be located near usage to reduce transportation costs	2800–3500	0.092	US EIA (2019), Twidell and Weir (2015), and Manolis et al. (2019)

addressing water scarcity; however, the high energy demands met mainly by fossil fuel remain a major obstacle. In the desalination industry, RES can replace fossil fuels, resulting in reduced emissions of GHGs. Currently, the adoption of RES in desalination is limited due to the high capital costs; however, in recent years, both desalination

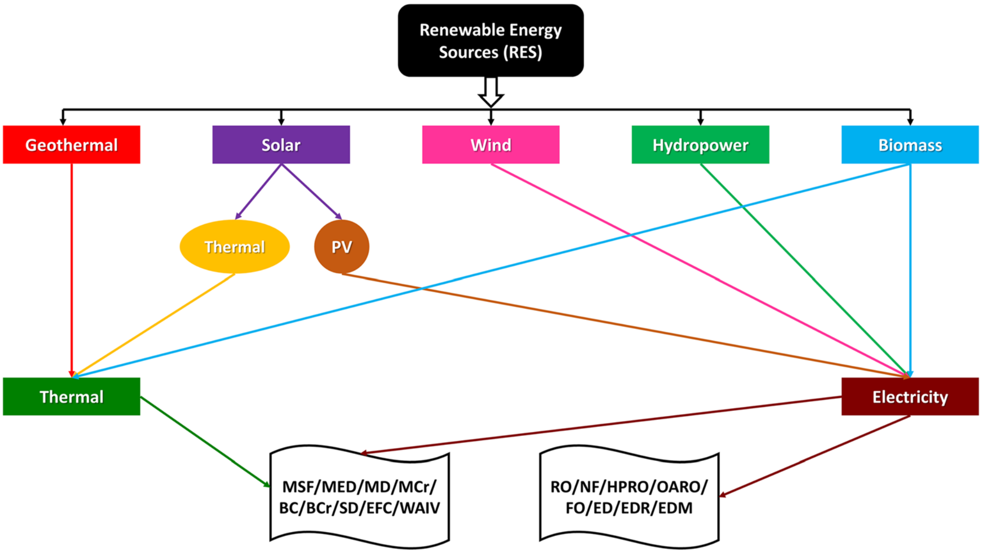


Fig. 9 Possible options for desalination based on RES

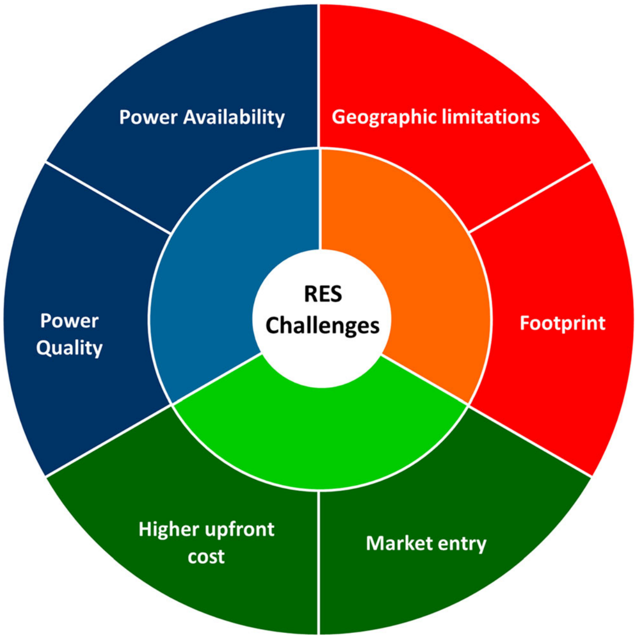


Fig. 10 The RES challenges

and renewable energy generation technologies have made significant progress in allowing desalination of different saline solutions (from brackish water up to brine). The integration of commercial/emerging desalination technologies with RES is expected to improve both water and energy efficiency. Future research should focus on bench-/pilot-scale studies, process simulations and techno-economic assessments of hybrid RES-based desalination systems.

Abbreviations BC, Brine concentrator; BCr, Brine crystallizer; BOD_5, Biological oxygen demand; COD, Chemical oxygen demand; DO, Dissolved oxygen; ED, Electrodialysis; EDM, Electrodialysis metathesis; EDR, Electrodialysis reversal; EFC, Eutectic freeze crystallization; FO, Forward osmosis; GHGs, Greenhouse gases; HPRO, High-pressure reverse osmosis; MCr, Membrane crystallization; MD, Membrane distillation; MED, Membrane crystallization; MED, Multi-effect distillation; MENA, Middle East and North Africa; MSW, Municipal solid waste; NF, Nanofiltration; OARO, Osmotically assisted reverse osmosis; PV, Photovoltaic; RES, Renewable energy sources; RO, Reverse osmosis; SD, Spray dryer; TDS, Total dissolved solids; TSS, Total suspended solids; WAIV, Wind-aided intensified evaporation; WHO, World Health Organization

Availability of data and materials All data generated or analyzed during this study are included in this published article.

Author contribution All the research has been done by the author: Argyris Panagopoulos.

Declarations

Competing interests The author declares that he has no competing interests.

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