

12-1-2023

## Small scale desalination technologies: A comprehensive review

Hamed Kariman  
*Edith Cowan University*

Abdellah Shafieian  
*Edith Cowan University*

Mehdi Khiadani  
*Edith Cowan University*

Follow this and additional works at: <https://ro.ecu.edu.au/ecuworks2022-2026>



Part of the [Engineering Commons](#)

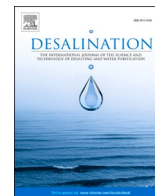
---

[10.1016/j.desal.2023.116985](https://doi.org/10.1016/j.desal.2023.116985)

Kariman, H., Shafieian, A., & Khiadani, M. (2023). Small scale desalination technologies: A comprehensive review. *Desalination*, 567, article 116985. <https://doi.org/10.1016/j.desal.2023.116985>

This Journal Article is posted at Research Online.

<https://ro.ecu.edu.au/ecuworks2022-2026/3040>



## Small scale desalination technologies: A comprehensive review

Hamed Kariman, Abdellah Shafieian, Mehdi Khiadani<sup>\*</sup>

School of Engineering, Edith Cowan University, 270 Joondalup Drive, Joondalup, Perth 6027, WA, Australia

### HIGHLIGHTS

- Small-scale desalination system comprehensively reviewed.
- Cost of water production in large and small desalination systems was compared.
- The technological usage of small-scale desalination technologies was compared.
- Challenges and future perspectives of small-scale desalination systems were highlighted.

### ARTICLE INFO

#### Keywords:

Small scale desalination  
Domestic desalination  
Reverse osmosis  
Electro dialysis  
Membrane desalination  
Renewable energies  
Hybrid desalination

### ABSTRACT

In recent decades, problems related to fresh water has become a very important issue for humans. Small-scale desalination (SSD) systems, besides large-scale desalination (LSD) systems, fulfil an important role in meeting freshwater demand by eliminating the cost of transmission and have the advantage of treating water on-site. In this study, for the first time, a comprehensive review of previous studies has been carried out on SSD systems (less than 25 m<sup>3</sup>/d water production). These systems are powered using renewable, non-renewable or hybrid sources of energy, incorporating different treatment technologies such as: reverse osmosis (RO); electro dialysis (ED); capacitive deionization (CDI); membrane desalination (MD); humidification–dehumidification processes (HDH); multi-effect desalination (MED); and hybrid technologies, including a combination of RO-UF, RO-ED and RO-MED. The advantages and drawbacks of the systems that operate using fossil fuels and renewable energy (RE) systems have been studied, considering membrane, evaporation and salinity features. Among these, solar-based desalination systems are the most popular. Accordingly, numerous studies on RO, ED, MD, HDH and MED technologies for solar-SSD systems have been compared in terms of their freshwater productivity, energy consumption and cost of produced water. Attention has also been paid to SSD systems powered via wind, geothermal, tidal and hybrid energies. It has been determined that the RO system holds the largest market share in both non-renewable (25 %) and renewable energy (40 %) systems. In addition, a comparison of low-cost SSD and LSD systems shows that SSD systems are economically competitive with LSD systems. The outlook for the future shows that the use of SSD systems powered using non-renewable energy is likely to decrease, except in areas where energy costs are very low. In addition, the use of solar-SSD systems is likely to increase, where systems that operate solely on wind or geothermal energy will be replaced by hybrid renewable energy systems.

### 1. Introduction

About 97 % of available water on earth is saline, whereby it is not suitable for domestic and agricultural consumption [1–8]. One of the most important reasons for decreases and scarcity of freshwater resources is the world's growing population and its increased demand for freshwater [9]. It was estimated that by 2014, about 40 % of the world's population would experience freshwater shortage, with this amount to be at 25.3 % (2 billion people) in 2020 [10], and in 2022 it reached to

about 27.5 % (2.2 billion people) [11]. With advancements in technology, saline water in seas and oceans are being considered as essential sources for meeting current freshwater demand [12]. Many methods and technologies have been proposed to solve global water difficulties, including: water recycling and reuse, in addition to implementing advanced wastewater treatment technologies [13]; rainwater harvesting, collecting and storing rainwater for later usage [14]; use of efficient irrigation techniques like drip irrigation and precision agriculture [15]; utilizing smart water management technologies like sensors, data

<sup>\*</sup> Corresponding author.

E-mail address: [m.khiadani@ecu.edu.au](mailto:m.khiadani@ecu.edu.au) (M. Khiadani).

<https://doi.org/10.1016/j.desal.2023.116985>

Received 1 July 2023; Received in revised form 12 September 2023; Accepted 12 September 2023

Available online 14 September 2023

0011-9164/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

**Table 1**  
Energy requirement for treating different water sources [63,64].

Water source	Energy (kWh/m <sup>3</sup> )
Surface water (lake or river)	0.37
Groundwater	0.48
Wastewater treatment	0.62–0.87
Wastewater reuse	1.0–2.5
Seawater	2.58–9

analytics and remote monitoring [16]; raising awareness about the importance of water conservation through education [17]; and desalination systems, where among all these techniques, desalination is one of the most important and efficient methods [18]. According to the International Desalination Association (IDA), the number of desalination plants around the world totals approximately 18,436 units, providing approximately 92.5 million m<sup>3</sup>/d of fresh water for the populations that live around them [19–24].

While there are different types of desalination systems overall, they are generally divided into thermal and membrane systems. Dominant thermal systems can then be divided into multi-effect desalination (MED), multi-stage flash (MSF), humidification–dehumidification processes (HDH) and vapor compression (VC). Membrane processes systems can be divided into reverse osmosis (RO), electro dialysis (ED), membrane desalination (MD) and capacitive deionization (CDI) [25–30]. Additionally, there are other types of desalination systems, such as freezing desalination (FD) [31–33], hydrate formation [34,35], forward osmosis (FO), adsorption desalination (AD) and pressure reverse osmosis (PRO), which are not yet sufficiently developed and are in initial stages of research [36–38].

Large-scale desalination (LSD) systems have developed considerably in recent decades, accounting for a large portion of the global market, and for global freshwater production capacity. In contrast, SSD systems represent a smaller share of the global market [39]. Additionally, household and agricultural uses, along with industrial uses, represent a very high share of usage [40]. The domestic and agriculture sectors

require a large amount of fresh water, whereby they should be given more attention. In addition to this, human water consumption remains lowest when compared to animals and irrigation sectors. Further, the recommended salt concentration for irrigation is the lowest (500 mg/l) as compared to others [39,41,42].

In terms of freshwater productivity, desalination systems can be divided into three categories, large-scale desalination (LSD) systems, medium-scale desalination (MSD) systems and small-scale desalination (SSD) systems. Systems with a freshwater production rate of less than 25 m<sup>3</sup>/d fit into the category of SSD systems [43–46]. LSD plants have many environmental issues, and also require a high amount of energy for transportation and distribution. The high demand of the domestic and agricultural sectors, the environmental problems of LSD plants, and the energy required to transfer and distribute fresh water to residential areas have led to considerations for SSD freshwater production systems being deployed to residential and rural communities. Within these systems, effluent and domestic grey water can also be treated and used. In addition, these systems are reliable, simple to operate, and can be located in isolated communities without requiring high labour costs [44,45,47,48]. The water production rate of SSD systems can vary between a few l/d to several m<sup>3</sup>/d. Factors that influence the choice of SSD systems include technical and social considerations, as well as the number of consumers and economic considerations. Factors influencing the cost of SSD systems include initial purchase, operational and maintenance costs, which are quite different from LSD systems [49–51]. The main technologies of SSD systems include reverse osmosis (RO), membrane desalination (MD), humidification–dehumidification (HDH), electro dialysis (ED), multi effect distillation (MED), and Capacitive deionization (CDI) [52–62].

Desalination is an intensive energy process that depends on the quality of water resources. Table 1 shows the amount of energy that is needed to convert salted water to distilled water [63,64]. Surface waters with 0.37 kWh/m<sup>3</sup> need the least amount of energy, while seawater with 2.58–8.5 kWh/m<sup>3</sup> needs the highest amount of energy [63,64].

Statistics show that only 1 % of desalination systems are powered by

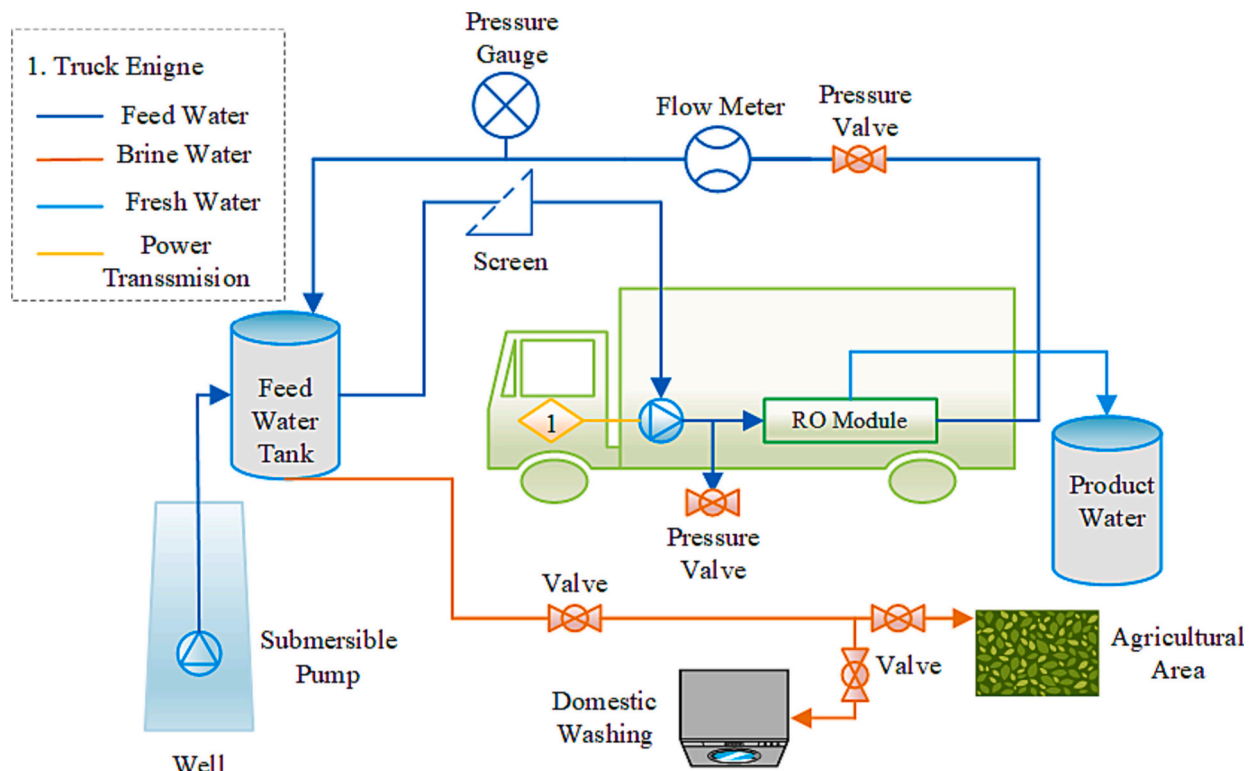


Fig. 1. The schematic of a mobile RO-SSD system - reproduced from [82].

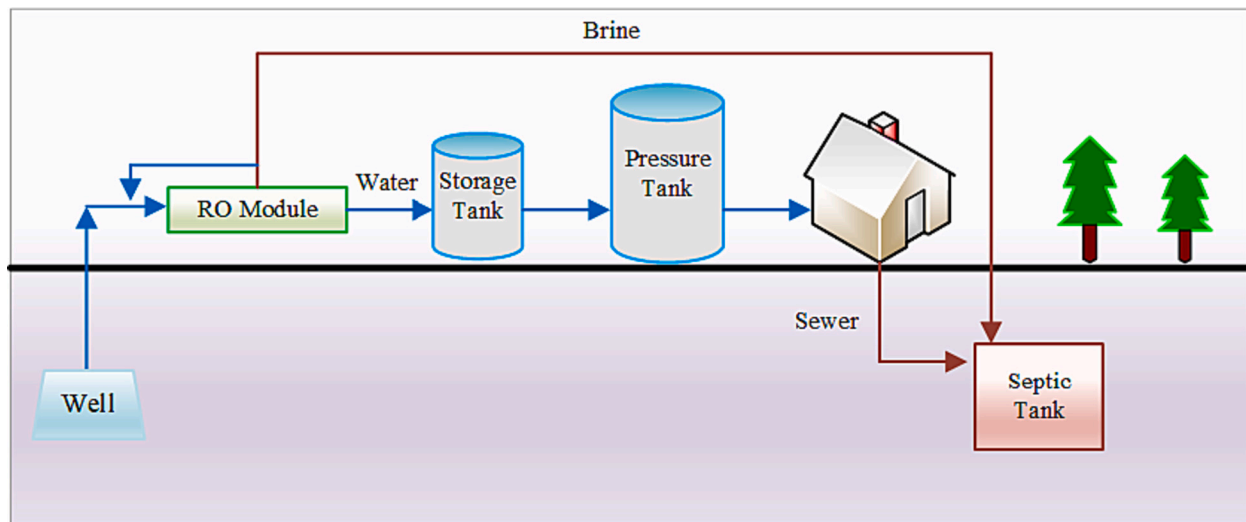


Fig. 2. The schematic of the FLERO system for a sample house - reproduced from [85].

renewable energy (RE). Effective reasons for the use of RE in LSD systems include reduced energy costs, less dependency on fossil fuels and reduced environmental pollution. In addition, the cost of fuel transfer, risks, and uncertainties to deliver fuel to remote areas have led to significant improvements in the design and use of SSD systems that depend on RE [39,53,65–70].

The main purpose of this study is to extensively review and compare SSD systems in terms of technologies, energy sources, rates and costs of water production. This study will also cover advantages and drawbacks, target population, and climate conditions for each system of operation. To the authors' knowledge, no review to date has been conducted to analyze and compare SSD systems regarding their technologies, energy sources, production rates and cost of water production. SSD systems are divided into two categories: non-renewable and renewable, determined in terms of their energy source. There are many types of SSD systems, but some are currently in their research phase, whereby limited experimental results are available. Accordingly, the main focus of this review is on well-known systems that are popular and have been developed and used experimentally or practically. Therefore, various evaporative and membrane SSD systems that widely use fossil fuels, electricity or renewable energy, such as solar, wind, geothermal, tidal and hybrid energies have been reviewed and compared in this study. These systems are also compared with LSD in terms of their cost of water production. Finally, the future of SSD systems has been explored, whereby technologies that may emerge in future have also been discussed.

## 2. Small-scale desalination systems powered by non-renewable energy

There are many SSD systems that use fossil fuels, such as gas, gasoline and electricity, to convert saline water to fresh water. In this section, several types of these systems are studied and compared in terms of their technology, energy consumption and water production.

### 2.1. Reverse osmosis (RO) based systems powered by non-renewable energy

RO desalination is a water purification process that removes salt and other impurities from seawater or brackish water, converting it into freshwater suitable for drinking or industrial use. The process relies on a pump to overcome natural osmotic pressure and force water through a semi-permeable membrane, allowing water molecules to pass through while blocking larger ions, molecules and contaminants [71]. RO systems possess some advantages and disadvantages. On the one hand, RO systems can efficiently remove salts, minerals and impurities, resulting in the production of high-quality, potable water that is safe for drinking and various applications and small-scale sizes. Further, RO systems are suitable for a diverse range of water sources, such as seawater, brackish water and wastewater, and can be easily scaled to meet varying water demands, making them adaptable for small-scale applications. On the other hand, RO systems have several disadvantages, which include: generating concentrated brine as a by-product, posing challenges in terms of proper disposal and potential environmental impacts. Further, the semi-permeable membranes utilized in RO can become fouled by organic matter, minerals and other substances, whereby they require regular maintenance, cleaning and replacement, which in turn leads to additional costs [42,72].

Li et al. have introduced a RO-SSD system to purify water in a laboratory model using electricity to power their system. The results of using this laboratory system showed that this system was able to produce 0.3 l/d of fresh water with 0.5 cm<sup>2</sup> membrane area [73,74]. Garofalo et al. have successfully manufactured a membrane with a length of 30 cm for use in a vacuum membrane desalination unit, which showed a best performance able of producing 1800 l/d of distilled water. In addition, scanning electron microscope (SEM), X-ray diffractometry (XRD), analyzes showed no structural changes after prolonged exposure to saline solutions [75,76].

RO-SSD systems have been used in parts of Tunisia, where one of

**Table 2**  
The prominent RO-SSD systems and their features.

Ref.	System technology.	Production (l/d).	Energy consumption. (kWh/m <sup>3</sup> )	Membrane Area (m <sup>2</sup> )	Cost of fresh Water production. (\$/m <sup>3</sup> )
(Mohamed et al., 2005 [78])	RO	2200	3.7	1.27	3.92
(Li et al., 2018 [82])	RO	4608	9.13	12	4.5
(Lee et al., 2019 [83])	RO	15,840	0.5	2.5	–
(Choi et al., 2019 [85])	RO	8800	0.1	2.6	0.477
(Mansour et al., 2020 [88])	RO	2400	0.937	2.8	–
(Song et al., 2022 [89])	RO	6000	3.62	–	–

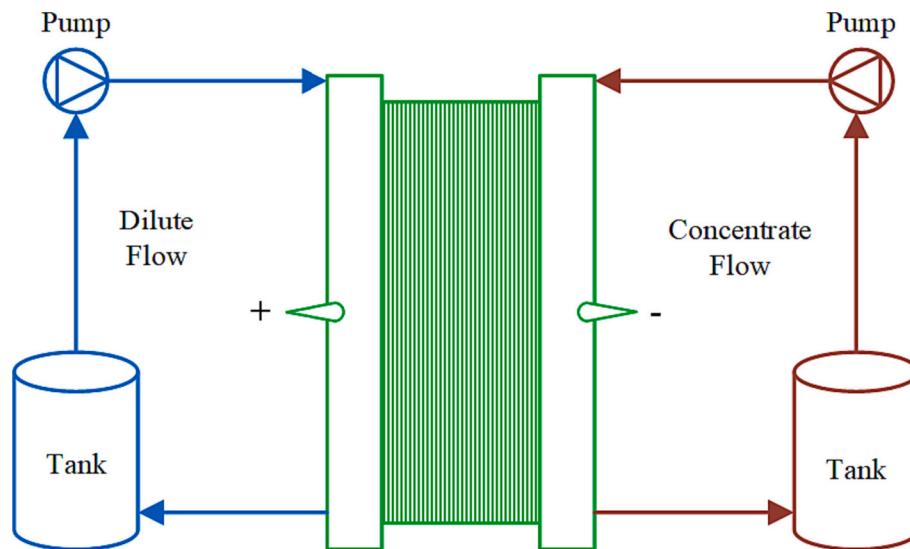


Fig. 3. The schematic of ED-SSD system - reproduced from [95].

these systems powered with electricity has been shown to produce 100 l/d of fresh water with a unit recovery rate of 25 %. The salt rejection in this system was more than 75 % for monovalent ions, and 95 % for divalent ions [77]. Mohamed et al. have introduced an RO-SSD unit in Athens that produced 2200 l/d of fresh water using battery and electricity, with an energy consumption of 3.7 kWh/m<sup>3</sup> [78]. Katz et al. have applied a modified membrane bioreactor (MBR) treatment as a pre-treatment unit for RO-SSD systems, concluding that the MBR chemical coagulation process could technically be considered a pre-treatment process for household effluents before applying RO-SSD systems for producing soft effluents with low organic matter and nutrient content. This RO-SSD system produced approximately 650 l/d of fresh water and removed 99 % of phosphate content [79]. Researchers at the University of California, Los Angeles, have developed a portable RO-SSD electricity-powered system that can produce 23,000 l/d of freshwater [80]. Gao et al. have proposed an RO-SSD electricity-powered system that can be directly integrated with an ultrafiltration (UF) pre-treatment unit. Their system had a 50 m<sup>2</sup> UF membrane area, where the benefits of this design included the elimination of the need for an intermediate UF filter tank and reverse wash pump, increasing the system's operational flexibility. Accordingly, this system was able to produce approximately 75.5 l/d of fresh water [81].

Rising water consumption in India, especially in the coastal areas of the country, has led to the proposal of a fuel-powered RO-SSD system able to produce 4608 l/d of fresh water, consuming 8 kWh/m<sup>3</sup> of energy. Further, this system had a 12 m<sup>2</sup> membrane surface area. The schematic of this mobile RO-SSD system is presented in Fig. 1 [82].

Lee et al. have examined a flexible RO-SSD system using a pressure booster pump and partial concentrated recycling, with a focus on

operational flexibility and specific energy consumption. They performed operational analysis, combined with experimental evaluation using a small-scale helical wound system. The amount of freshwater production in this system was 15,600 l/d [83]. Further to this, they also tested a semi-batch RO-SSD system through process modelling and a small-scale screw pilot with a single-pass RO-SSD system. The system had a 2.5 m<sup>2</sup> active membrane surface and 99.5 % salt rejection, producing 15,840 l/d of fresh water, whereby its energy usage was 0.5 kWh/m<sup>3</sup> [84]. Choi et al. have studied the feasibility of water treatment with a small community resource using a new portable RO unit to remove nitrate and reduce salinity. Their system had 2.6 m<sup>2</sup> of membrane surface area with a water production rate of 8800 l/d, salt rejection of 99 % and energy

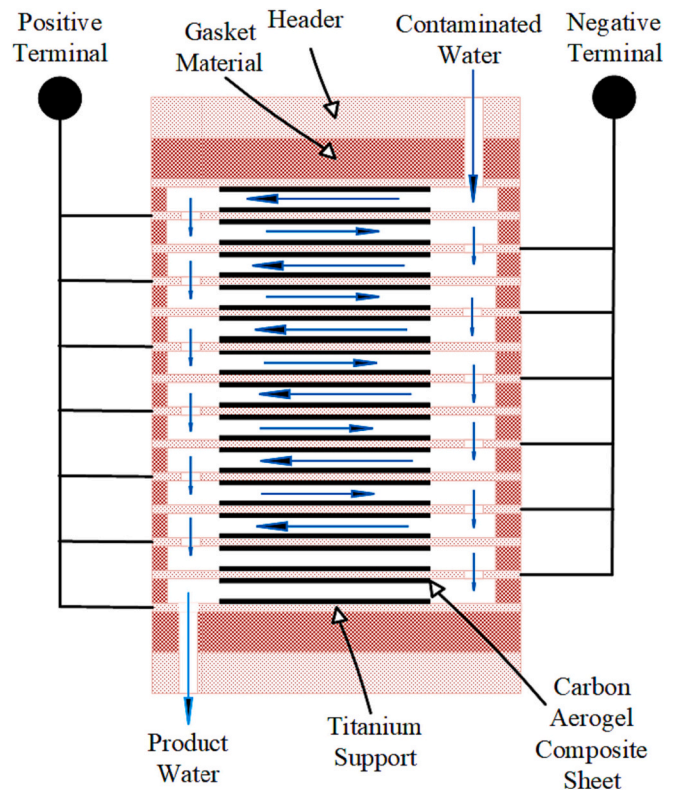


Fig. 4. The schematic of the CDI-SSD system - reproduced from [72].

**Table 3**  
The prominent ED-SSD systems and their features.

Ref.	System technology.	Production (l/d).	Energy consumption. (kWh/m <sup>3</sup> )	Effective surface area. (m <sup>2</sup> )
(Sadrzadeh and Mohammadi, 2008 [101])	ED	2160	–	1.56
(Pilat, 2003 [98])	ED	3600	2.5	–
(Ortiz et al., 2005 [99])	ED	18,000	0.84	4.4
(Banasiak et al., 2007 [100])	ED	4320	–	7.28

consumption of 0.1 kWh/m<sup>3</sup>. The schematic of the FLERO system for a sample house is shown in Fig. 2 [85].

Walha et al. have reported the possibility of producing drinking water from saline water using NF, RO and ED processes in the southern part of Tunisia. Two water samples were analyzed, and the results were reported. The NF process was insufficient to obtain drinking water from one of the samples due to the leakage of the TDS. The RO process was efficient, where it drastically reduced the mineral content of the raw water (80 % rejection). After purification, the obtained permeable water had a low TDS value, within the WHO requirement. The final fresh water obtained from both samples had a good level of TDS [86].

Thampy et al. have explored an RO-SSD system with freshwater production and energy consumption rates of 182 l/d and 7.8 kWh/m<sup>3</sup>, respectively. Their system was then combined with an ED system, which was able to produce 1220 l/d with an energy consumption of 9 kWh/m<sup>3</sup> [87]. Mansour et al. have also enhanced the efficiency RO-SSD systems with an Energy Recovery System. The water production of their system was 2.4 m<sup>3</sup>/d, the membrane active area in this system was 2.8 m<sup>2</sup>, and the energy consumption of this system after recovery was 0.937 kWh/m<sup>3</sup> [88]. Song et al. have introduced an SSD-RO system with a three-piston pump energy recovery device, whereby this system had 6000 l/d of water production and 3.62 kWh/m<sup>3</sup> of energy consumption [89].

A comparison of the most noticeable RO-SSD in terms of freshwater production, energy consumption and other features is reported in Table 2.

As shown in Table 2, among the studied RO-SSD systems, the system presented by Lee et al. had the highest freshwater production rate, at 15,840 l/d [83]. Additionally, the system developed by Choi et al. had the lowest energy consumption and the lowest cost of water production, at 0.1 kWh/m<sup>3</sup> and 0.477 \$/m<sup>3</sup>, respectively [85].

## 2.2. Electrodialysis (ED) based systems powered by non-renewable energy

ED is another freshwater production system that utilizes different structures. The ED desalination system consists of a series of ion-selective membranes, typically made of synthetic materials. These membranes have selective permeability, allowing either positive ions (cations) or negative ions (anions) to pass through, while blocking opposite charged ions. When an electric field is applied across the cell stack, positive ions are attracted to the negative electrode (cathode) and negative ions are attracted to the positive electrode (anode). As a result, cations move through the cation-exchange membranes towards the cathode, and anions move through the anion-exchange membranes towards the anode. As the water flows through the electrodialysis cells, the ions are effectively removed from the water, leaving behind purified water with reduced salt content in the product stream [90]. The asymmetrical design requires a pressure of 2–3 bar, while the primary particle purification cartridge system can be operated by approximately 0.3–1 bar pressure. Therefore, pumps are not required for electrodialysis systems in order to boost pressure under normal household conditions [45,91,92]. This technique provides various advantages, where firstly, ED desalination typically consumes less energy compared to other desalination technologies, making it more environmentally friendly.

**Table 4**  
CDI-SSD systems and their features.

Ref.	Electrode area (cm <sup>2</sup> )	Energy consumption. (kWh/m <sup>3</sup> )	Production (l/d)	Applied voltage (V)	Removal efficiency (%)	Electrode materials
(Tsouris et al., 2011 [112])	110	–	115	1.2	35	Mesoporous carbon
(Chang et al., 2011 [113])	13	–	–	1.2	34	Activated carbon-TiO <sub>2</sub>
(Haro et al., 2011 [114])	–	–	–	1	20	Carbon xerogel
(Jung et al., 2007 [115])	128	–	1150	1.5	6.3	Nano-carbon aerogel
(Liang et al., 2013 [111])	31	–	23	1.2	90	Activated carbon fiber
(Lee et al., 2019 [116])	400	0.12	15	1.2	92	Activated carbon fiber

**Table 5**

Energy requirement of membrane-based SSD systems.

Ref.	Energy requirement (kWh/m <sup>3</sup> )	Desalination technology
(Metcalf and Eddy, 2014 [117])	0.46–0.65	Reverse osmosis (RO) with energy recovery.
(Metcalf and Eddy, 2014 [117])	1.10–2.20	Electro dialysis (ED)
(Farmer et al., 1997 [118])	0.137	Capacitive deionization (CDI)
(Welgemoed and Schutte, 2005 [119])	0.390	Capacitive deionization (CDI)
(García-Quismondo et al., 2014 [120])	0.1	Capacitive deionization (CDI)
(Yu et al., 2016 [121])	0.34	Capacitive deionization (CDI)
(Lee et al., 2019 [116])	0.32	Capacitive deionization (CDI)
(Dlugolecki and van der Wal, 2013 [122])	0.26	Membrane capacitive deionization (MCDI)

Secondly, ED systems can be easily adjusted to meet different water demands, making them suitable for a wide range of applications and small-scale sizes. Lastly, unlike other desalination methods, ED does not experience membrane fouling issues, reducing the frequency of cleaning required. However, this technique does have some disadvantages, where the ED desalination process can be intricate, requiring precise control of electrical currents and ion-selective membranes. Further, despite lower fouling concerns, ED systems still require regular maintenance and the initial capital costs can be relatively high [93,94]. The schematic of the ED-SSD system is shown in Fig. 3 [95].

Nayar et al. have tested an ED system that could produce 288 l/d of fresh water with a recovery rate of 80 %. The cost of their system was estimated to be \$270, which is low compared to an RO system [96].

In order to enhance research and development in the market for SSD systems, Pilat et al. has assessed an ED-SSD system and found for a freshwater production rate of 1200 l/d, the required energy was 1.2–2.5 kWh/m<sup>3</sup> [97]. In another study, the authors increased the water productivity of their system to 3600 l/d with an energy consumption of approximately 2.5 kWh/m<sup>3</sup> [98]. Due to issues of water scarcity in southeastern Spain, Ortiz et al. have identified an ED-SSD system with an active membrane area of 550 cm<sup>2</sup> and a total effective area of 4.4 m<sup>2</sup>. The freshwater production of this system was 18,000 l/d, with an energy consumption of 0.84 kWh/m<sup>3</sup> [99]. To show the ability of ED-SSD systems compared with RO-SSD and other types of SSD systems, Banasiak et al. have investigated an ED-SSD model with an effective membrane area of 7.28 m<sup>2</sup>, where it produced 156 l/d with a recovery rate of 90 % [100]. Further, Sadrzadeh and Mohammadi have performed laboratory analysis of an ED-SSD system with an active membrane area of 1.56 m<sup>2</sup>, where they were able to produce 2160 l/d of distilled water with a recovery rate of 84 % [101].

The ED-SSD system has also been used to address freshwater shortage problems in Australia. Accordingly, a system was applied with 7 cation exchange membranes and 6 anion exchange membranes, each one having a 58 cm<sup>2</sup> surface area, and producing a water production rate

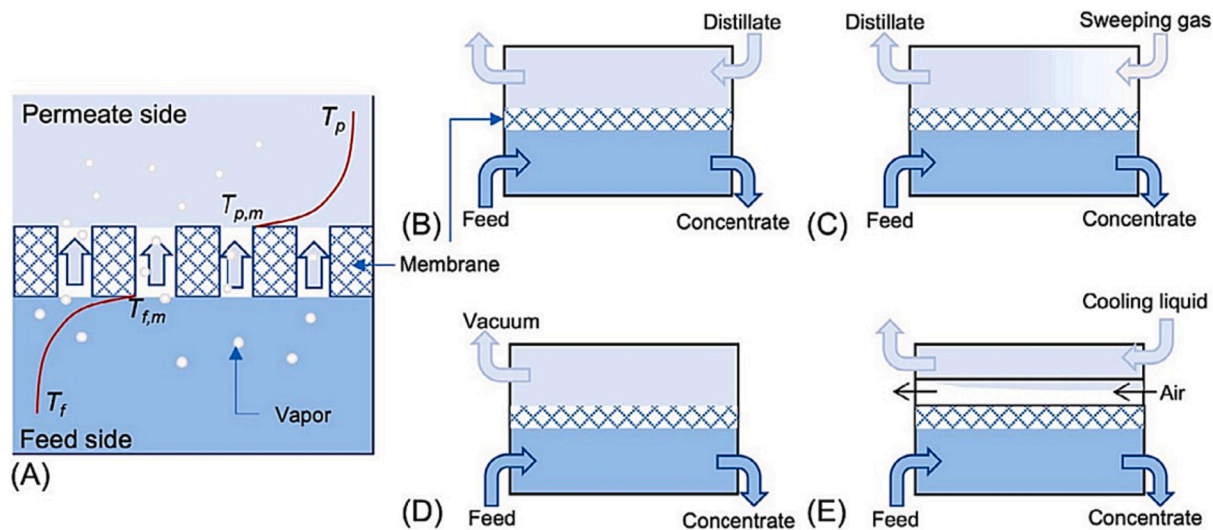


Fig. 5. (A) MD-SSD desalination technique, (B) DCMD, (C) SGMD, (D), VMD, and (E) AGMD [141].

of 4320 l/d. The recovery rate of this system was 94.9 % [102]. Shah et al. have analyzed an ED-SSD system with a freshwater production rate of 15 l/h and a recovery rate of 90 %. Their system also had an energy consumption of 2.5 kJ/l and an active membrane surface of 85 cm<sup>2</sup>. The cost of water production in their system was 0.17 \$/m<sup>3</sup> [95].

Prominent ED-SSD systems are reported in Table 3, comparing freshwater production, energy consumption and other features.

As shown in Table 3, the system developed by Ortiz et al. had the highest freshwater production rate of 18,000 l/d and the lowest energy consumption rate of 0.84 kWh/m<sup>3</sup> [99].

### 2.3. Capacitive deionization (CDI) based systems powered by non-renewable energy

Capacitive deionization (CDI) is a potential method for removing salt from an aqueous solution using a two-layer electric device called a flow capacitor. In this technique, when the electrode is electrically charged by an external power supply, positively or negatively charged particles, such as anions and cations, are attracted to the electrical double layer at the solution-electrode interface. Once the electrode is saturated, it can be easily regenerated by eliminating the potential difference between the electrodes. In these systems, solutions are passed through a number of carbon aerogel electrodes, each with a very high specific surface area and a very low electrical resistance. After polarization, the non-reducing

and non-oxidizable ions are removed from the electrolyte by an imposed electric field, and are stored in dual electrical layers formed at electrode surfaces. Lastly, the effluent from the cell is treated with a stream of purified water. This process is also able to remove other types of impurities at the same time. For example, dissolved heavy metals and suspended colloids can be removed by electrical deposition and electrophoresis, respectively. CDI carbon aerogel has several potential advantages over other conventional technologies. Unlike ion exchange, no acid, base or saline solution is needed to rebuild the system. Reconstruction is done by electrically draining the cell so that no secondary waste is generated. Unlike thermal processes such as evaporation, CDI carbon aerogels are much more energy efficient than RO or ED systems, since no high-pressure membrane or pump is required. However, compared to other SSD systems such as RO or ED, these systems have lower water recovery and higher electrode discharge time, whereby low recovery rate increases the cost of water desalination and causes more environmental pollution. The schematic of a CDI-SSD system is presented in Fig. 4 [27,103–108].

Wang et al. have distilled various saltwater solutions using the CDI method, with a system operating at 1.2 V and the amount of water produced was 2880 l/d [109].

The cations in saline water that enter the cell through the spacer channel are adsorbed to the negatively charged porous carbon electrode (cathode). Simultaneously, the anions are absorbed into the anode [110]. Several CDI-SSD systems were examined in several studies and their results were compared. Their comparison considering different influencing factors is presented in Table 4 [111].

As shown in Table 4, systems with activated carbon fiber electrodes have higher salt removal efficiency.

Table 5 compares the energy consumption for several membrane-based SSD systems including RO, ED and CDI. Overall, CDI systems consumed less energy than ED and RO systems.

### 2.4. Membrane desalination (MD) based systems powered by non-renewable energy

Membrane distillation (MD) is a developing membrane technology that relies on vapor pressure difference across a porous hydrophobic membrane. Due to this characteristic, only volatile vapor molecules can pass through the membrane, while the feed liquid that directly touches the membrane must be prevented from entering the dry pores of the hydrophobic membranes. The main types of membrane desalination systems are Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Vacuum Membrane Distillation (VMD),

Table 6  
The most efficient MD-SSD systems.

Ref	System technology	Production (l/d)	Energy consumption (kWh/m <sup>3</sup> )	Membrane area size (m <sup>2</sup> )
(Criscuoli et al., 2013 [137])	VMD	3000	130	5
(Mohamed et al., 2017 [139])	VMD	1200	700	6.4
(Jia et al., 2021 [140])	VMD	8000	748	65.6
(Duong et al., 2015 [143])	DCMD	1800	2000	5
(Woldemariam et al., 2016 [145])	AGMD	720	875	4.6
(Kyu Lee et al., 2020 [147])	AGMD	10,000	182	155.5
(Elsheniti et al., 2023 [141])	SGMD	411	11	1.17

and Sweep Gas Membrane Distillation (SGMD) [123–125]. DCMD systems involve a hydrophobic membrane for direct contact with hot saline water, allowing water vapor to pass through and leaving impurities behind [126]. AGMD systems are similar to DCMD systems but add an air gap to improve heat and mass transfer control [127]. VMD systems use a vacuum on the permeate side to draw water vapor through the membrane, where they are suitable for various feedwater salinities [128]. SGMD systems employ a sweep gas to carry away water vapor, enhancing efficiency for high salinity applications [129]. MD systems provide a multitude of benefits, encompassing superior water quality aimed at efficiently eradicating salts, minerals and impurities. This endeavor leads to the creation of exceptional potable water. Additionally, MD systems exhibit remarkable versatility, as they can be adeptly tailored to accommodate diverse water sources, such as seawater, brackish water and wastewater. This adaptability renders MD systems highly suitable for effectively mitigating varied water scarcity scenarios [130,131].

Nevertheless, this approach does possess a number of drawbacks, encompassing energy intensity, which in turn leads to the substantial consumption of significant energy quantities and results in elevated operational expenses. Furthermore, the approach is marked by complexity, demanding meticulous management of diverse operational parameters. Initial capital costs also pose a challenge, possibly entailing substantial upfront financial investments. Additionally, the generation of concentrated brine as a byproduct involves requirements of proper disposal to avert potential environmental repercussions [132,133]. To delve into MD-SSD systems, a comprehensive analysis of several research studies was undertaken. For instance, Elmarghany et al. have devised a laboratory-based MD-SSD system possessing the capacity to generate 11 l/d of water. This system employed a membrane area of 0.02 m<sup>2</sup> and incurred an energy consumption of 1037 kW h/m<sup>3</sup> [134]. Zhao et al. have conducted an inquiry into a multi-stage VMD-SSD system. Their particular configuration encompassed a membrane area of 5 m<sup>2</sup> and exhibited the capacity to yield 1000 l/d, accompanied by a GOR of 1.6 [135]. Criscuoli et al. have reported a VMD-SSD system with the capability to generate 54 l/d of water, utilizing a membrane area of 0.18 m<sup>2</sup> [136]. Continuing their investigation, the authors subsequently introduced an additional VMD-SSD system with the capability to generate 3000 l/d of water, employing a membrane area of 5 m<sup>2</sup>,

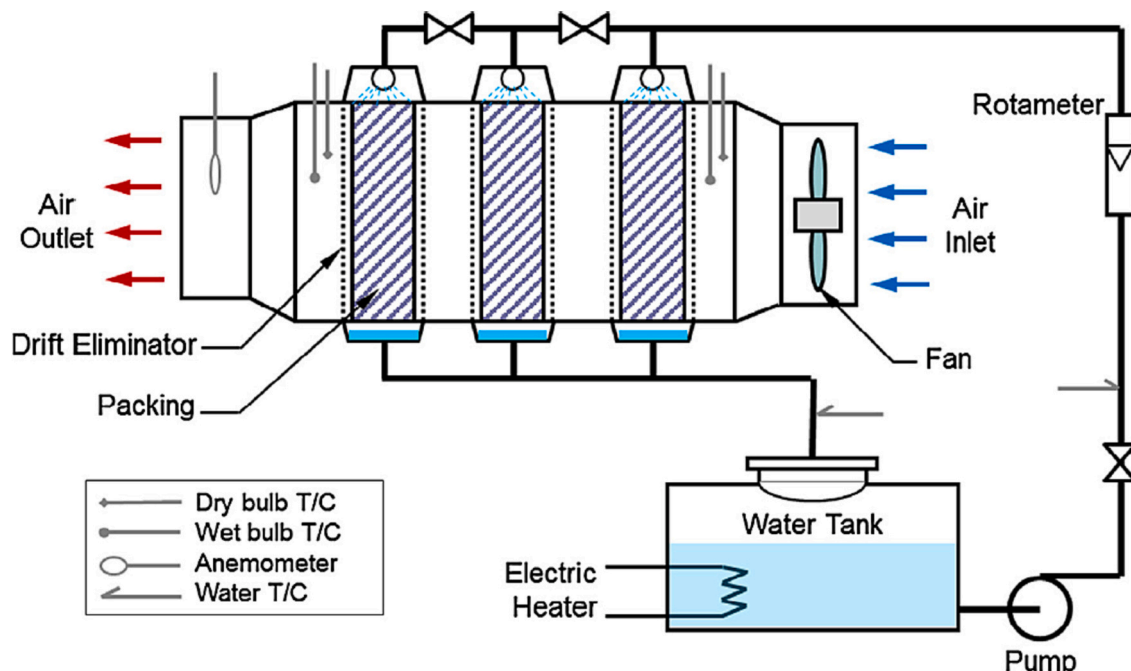
**Table 7**

The most efficient HDH-SSD systems.

Ref	System technology	Production (l/d)	Energy consumption		Features
			Ref (kW)	(kWh/m <sup>3</sup> )	
(Agouz, (2010) [160])	HDH	197	5.8	706	• Cost of water production was 115 \$/m <sup>3</sup>
(Narayan et al., (2013) [161])	CAOW-HDH	700	12.7	435	• The GOR in this system was about 4
(Sharqawy et al., (2014) [162])	HDH	240	2.98	298	• The GOR in this system was about 2.19

yielding an energy consumption of 130 kW h/m<sup>3</sup> [137]. Naidu et al. have introduced a VMD-SSD system exhibiting the capacity to yield 60 l/d of water and utilizing a membrane area of 0.16 m<sup>2</sup> [138]. In another research study, Mohamed et al. introduced a VMD-SSD system with the ability to produce 1200 l/d of water, with a membrane area of 6.4 m<sup>2</sup> and energy consumption of 700 kW h/m<sup>3</sup> [139]. Jia et al. have presented a VMD-SSD system on a larger scale and with enhanced capacity, where their system demonstrated the potential to manufacture 8000 l/d of water, utilizing a membrane area of 65.6 m<sup>2</sup>, alongside an energy consumption of 748 kW h/m<sup>3</sup> [140]. Elsheniti et al. have introduced an SGMD-SSD system with the capacity to generate 411 l/d of water. This system incorporated a membrane area of 1.17 m<sup>2</sup> and involved an energy consumption of 11 kWh/m<sup>3</sup>, whereby the cost of water production in this system was 1.3 \$/m<sup>3</sup> [141]. The schematic of all the configurations of MD-SSD systems is shown in Fig. 5 [141].

Song et al. have reported on a DCMD-SSD system encompassing a membrane area of 0.66 m<sup>2</sup>, yielding 871 l/d of water production [142]. Duong et al. have developed a high-capacity DCMD-SSD system capable of producing 1800 l/d of water, with a membrane area of 0.5 m<sup>2</sup> and an energy consumption of 2000 kWh/m<sup>3</sup> [143]. Mabrouk et al. have reported an additional DCMD-SSD system demonstrating the capability to

**Fig. 6.** The schematic of HDH packed-bed cross-flow [163].

**Table 8**

The outstanding MED-SSD systems.

Ref	System technology	Production (l/d)	Energy consumption		Features
			Ref (kW)	(kWh/m <sup>3</sup> )	
(Renaudin et al., (2005) [172])	MED	950	12	303	• The system had six stages and a vacuum pump
(Kariman et al., (2020) [167])	MED	500	13	624	• It was a vacuum-circular system with a brine-tank
(Kariman et al., (2020) [174])	MED	2200	1.5	16	• It was a mechanical vapor recompression circulation system.
(Aly et al., (2022) [176])	MED	25,000	–	4.8	• The cost of water production is 0.46 \$/m <sup>3</sup> .
(Karambasti et al., (2022) [175])	MED	19,920	2.5	3	• The cost of water production is 1.6 \$/m <sup>3</sup> .

280 l/d of water, employing a membrane area of 0.09 m<sup>2</sup> [144]. Wol-demariam et al. have investigated a AGMD-SSD system that has the ability to produce 720 l/d of water with a membrane area of 4.6 m<sup>2</sup> and an energy consumption of 875 kWh/m<sup>3</sup>, reporting the cost of water production with this system to be 34.5 \$/m<sup>3</sup> [145].

Khalifa and Alawad have introduced a laboratory-grade AGMD-SSD system showcasing the potential to generate 12 l/d of water. Their system encompassed a membrane area of 0.007 m<sup>2</sup> and incurred an energy consumption of 10 kWh/m<sup>3</sup> [146]. Kyu Lee et al. have presented an AGMD-SSD system with a greater production capacity, yielding 10,000 l/d of water. Their system featured a membrane area of 155.5 m<sup>2</sup> and incurred an energy consumption of 182 kWh/m<sup>3</sup> [147]. Pawar et al. have introduced an additional AGMD-SSD system with the ability to generate 1497 l/d of water, utilizing a membrane area of 26 m<sup>2</sup> [148]. The most efficient MD-SSD systems are summarized in Table 6.

As depicted in Table 6, the system introduced by Kyu Lee et al. exhibits the largest membrane surface area and the highest production rate, reaching 155.5 m<sup>2</sup> and 10,000 l/d, respectively [147]. Further to this, the reporting system detailed by Elsheniti et al. presents the most economical energy consumption figure, measuring at a value of 11 kWh/m<sup>3</sup> [141].

## 2.5. Humidification-dehumidification (HDH) based systems powered by non-renewable energy

The humidification–dehumidification process (HDH) is an interesting desalination process, one that can be used for decentralized desalination purposes. This technique has various advantages such as flexibility in capacity, medium installation cost, simplicity, possibility of using low thermal energy and the possibility of limited production. The thermodynamic cycle used in HDH systems is similar to the natural rain cycle, where water vapor is evaporated from saline water into air (which acts as a carrier gas) and condenses once the humid air cools. There are two main components of this system, a humidifier and a dehumidifier, in which air and water experience a similar cycle. A direct-contact dehumidifier is used for direct contact to humidify the carrier gas stream, whereas an indirect dehumidifier dehumidifies water from humid air. Between the two components, a heater, which may heat the air or water,

is added to guide the process. Various studies have shown that the amount of water production, the difference in vapor content, and the moisture efficiency of the system are strongly dependent on the temperature of the saline water in the evaporator chamber, the headwater difference and the air velocity [26,149–154]. Further to this, HDH systems are generally divided into two categories: closed-air open water (CAOW) and closed-water open air (CWOA), whereby each is divided into air-heated and water-heated subsets. The air cycle in these systems can be natural or via a mechanical device [155–157]. Eslamimanesh et al. have created a cost analysis of an HDH-SSD system and an RO-SSD system, concluding that: 1) the HDH process is a simple and inexpensive technology, suitable when some equipment such as membranes are not available; 2) RO-SSD units are more suitable for domestic use than HDH-SSD units due to the low space occupied by the equipment; 3) it is more convenient to use an HDH-SSD device when there is no energy cost; 4) for laboratory purposes where the properties of freshwater such as TDS are very important, it is better to use the RO method in which these properties can be controlled by carefully selecting the membranes; and 5) for industrial use, the choice of process depends on the economic study of the target capacity [158].

Amer et al. have studied an HDH-SSD system and concluded the water production rate to be 139 l/d at 85 °C<sup>0</sup> using wooden slats and forced air circulation [159]. Agouz has reported an HDH-SSD system that consumes 706 kWh/m<sup>3</sup> of electricity, and following economic assessment, reported that the system could produce 197 l/d of fresh water at a cost of 115 \$/m<sup>3</sup> [160]. Narayan et al. have built an HDH-SSD system that produced 700 l/d of fresh water using 435 kWh/m<sup>3</sup> energy to heat the water [161].

Sharqawy et al. have assessed and evaluated the production of fresh water and energy consumption of an HDH-SSD system using two different methods: water-heated and air-heated methods. Their results showed that the amount of freshwater production in both systems was 240 l/d, but that the amount of energy consumption in the water-heated system and the air-heated system were 334 kWh/m<sup>3</sup> and 298 kWh/m<sup>3</sup>, respectively, so the air-heated system had a higher gain output ratio (GOR) of 2.19 [162]. They also explored an HDH packed-bed cross-flow system and showed that it produced about 189 l/d water with an energy consumption of 1015 kWh/m<sup>3</sup> [163]. Soomro et al. have investigated an

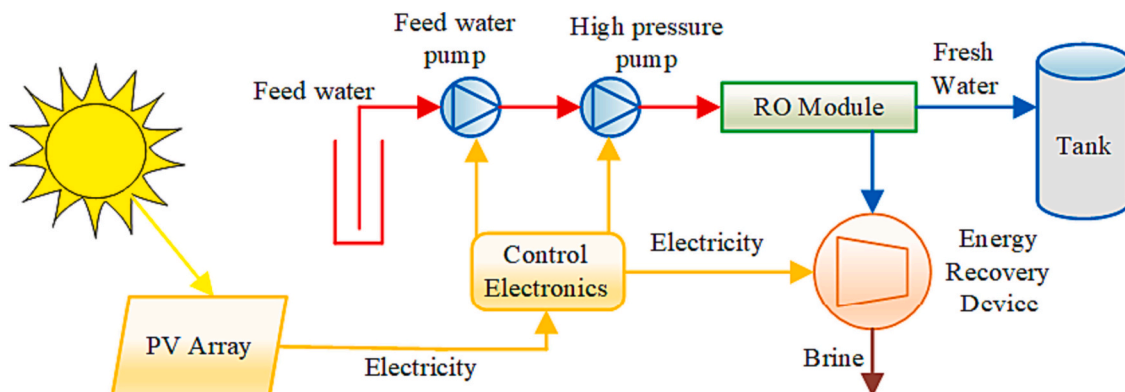


Fig. 7. The schematic of PVRO-SSD system - reproduced from [180].

HDH-SSD system that could produce 6.5 l/d of water, where the heat exchange area of the dehumidifier was 7.06 m<sup>2</sup> [164]. The schematic of HDH packed-bed cross-flow is shown in Fig. 6 [163].

Tow et al. have examined a bubble column (BC) of HDH-SSD systems, and developed a model that can be used to predict the performance of each stage using a multi-stage dehumidifier to design and optimize HDH-SSD systems [165]. Khan et al. have demonstrated a BC\_HDH system, with results showing that this system could produce 11 l/d fresh water by consuming approximately 2618 kWh/m<sup>3</sup> of energy [166]. The most efficient HDH-SSD systems are summarized in Table 7.

Table 7 shows that the system introduced by Narayan et al. has the highest production with 700 l/d of fresh water and 435 kWh/m<sup>3</sup> energy consumption and GOR of 4 [161]. In contrast, the system introduced by Sharqawy et al., has the lowest energy consumption at 298 kWh/m<sup>3</sup> with 240 l/d of fresh water [162].

## 2.6. Multi-effect desalination systems (MED) based systems powered by non-renewable energy

In multistage evaporative desalination (MED) systems, water undergoes evaporation through various mechanisms within the evaporator chamber. After passing through different effects and releasing its heat, the water condenses back into a liquid and exits the system as distilled water. Simultaneously, the remaining portion of the feed water within the evaporators is separated from the system as brine. Pumps are responsible for circulating the feed water, brine and distilled water throughout the process [167]. MED systems have some advantages and

disadvantages, where on the one hand, these systems can be easier to install and manage in locations with limited space or resources. Further, these systems have fewer moving parts compared to some other desalination methods, which can lead to lower maintenance requirements. Additionally, these systems can produce high-quality, potable water due to the distillation process, effectively removing impurities, salts and contaminants. Lastly, MED systems can operate with a variety of heat sources, including electricity, solar energy, geothermal energy, or waste heat from industrial processes. On the other hand, MED systems still require a heat source, which can make them dependent on a stable energy supply. This might be challenging in areas with unreliable or insufficient energy infrastructure. Additionally, despite their simplicity, MED systems can still involve substantial initial capital investments, especially when integrating with renewable energy sources or specialized materials [168–170].

Kafi et al. have introduced a new system of SSD called Easy MED, consisting of a combination of simple “human-sized” stem cells. The plates, frames and grids that make up each cell were easily constructed and transported. Their initial system could produce 350 l/d of fresh water by consuming 925 kWh/m<sup>3</sup> of electricity [171], after which Renaudin et al. combined the cells in parallel and in series to reduce the amount of energy wasted in the system by increasing the capacity and thermal efficiency of the system. With this modification, they could increase the product water to 950 l/d while consuming 303 kWh/m<sup>3</sup> of energy [172].

Following the research on Easy MED systems, Kariman et al. improved the previous systems by adding brine tanks to these systems.

**Table 9**  
Solar RO-SSD systems.

Ref	Production (l/d)	Energy consumption		Cost of water production (\$/m <sup>3</sup> )	Features
		Ref	(kWh/m <sup>3</sup> )		
(Herold et al. (1998) [181])	1000	4.8 kW	115	16	<ul style="list-style-type: none"> <li>• Solar collector area: 39 m<sup>2</sup></li> <li>• Recovery ratio: 23 %</li> <li>• Unit cost: 53530 \$</li> <li>• Recovery ratio: 98 %</li> <li>• Solar collector area: 45m<sup>2</sup></li> </ul>
(Tzen et al., (1998) [182])	3720	60 kWh	16	32.84	
(Herold et al., (2000) [183])	3000	4.8 kW	38	–	<ul style="list-style-type: none"> <li>• Solar collector area: 23.2 m<sup>2</sup></li> <li>• Water production cost: 6.52 \$/m<sup>3</sup></li> <li>• Recovery ratio: 94 %</li> <li>• Membrane area: 0.3 m<sup>2</sup></li> <li>• Recovery ratio: 50 %</li> <li>• solar collector area: 22 m<sup>2</sup></li> </ul>
(Al Suleimani et al. (2000) [184])	5000	3.25 kW	15.6	6.52	
(Joyce et al., (2000) [185])	500	150 W	7.2	5.47	<ul style="list-style-type: none"> <li>• Unit cost: 28701 \$</li> <li>• This system was NF-RO</li> <li>• Recovery ratio: 95 %</li> <li>• membrane area: 0.8 m<sup>2</sup></li> <li>• system efficiency: 93 %</li> <li>• Recovery ratio: 15 %</li> <li>• solar collector area: 36 m<sup>2</sup></li> <li>• solar collector area: 2 m<sup>2</sup></li> </ul>
(Ahmad et al., (2001) [186])	3420	5.2kWh	1.5	3.73	
(Thomson and Infield, (2002) [187])	3000	2.4 kW	19.2	2.26	<ul style="list-style-type: none"> <li>• Recovery ratio: 30 %</li> <li>• Solar collector efficiency: 39 %</li> <li>• solar collector area: 7.2 m<sup>2</sup></li> <li>• Solar collector efficiency: 8.8 %</li> <li>• Recovery energy: 16 %</li> <li>• Recovery ratio: 40 %</li> <li>• Solar collector area: 44 m<sup>2</sup></li> </ul>
(Richards et al., (2002) [188])	1000	1.7 kW	40.8	–	
(Thomson et al., (2002) [189])	3680	3.5 kWh/m <sup>3</sup>	3.5	–	<ul style="list-style-type: none"> <li>• Recovery ratio: 38 %</li> <li>• Recovery ratio: 70 %</li> <li>• Recovery ratio: 92 %</li> <li>• membrane area: 0.1 m<sup>2</sup></li> <li>• Membrane area 2.2 m<sup>2</sup></li> <li>• Solar collector area: 43 m<sup>2</sup></li> </ul>
(Tzen et al., (2004) [190])	1040	4.86 kW	112	26.04	
(Joseph and Renganarayanan (2004) [191])	8.5	1 kW	2823	9	<ul style="list-style-type: none"> <li>• Recovery ratio: 99 %</li> <li>• Water production cost: 3.94 \$/m<sup>3</sup></li> <li>• Recovery ratio: 30 %</li> <li>• Solar collector efficiency: 39 %</li> <li>• solar collector area: 7.2 m<sup>2</sup></li> <li>• Solar collector efficiency: 8.8 %</li> <li>• Recovery energy: 16 %</li> <li>• Recovery ratio: 40 %</li> <li>• Solar collector area: 44 m<sup>2</sup></li> </ul>
(Mohamed et al. (2005) [192])	1700	3.3 kWh/m <sup>3</sup>	3.3	4.17	
(Bouguecha et al., (2005) [193])	16	0.9 kW	1350	80.39	<ul style="list-style-type: none"> <li>• Recovery ratio: 38 %</li> <li>• Recovery ratio: 70 %</li> <li>• Recovery ratio: 92 %</li> <li>• membrane area: 0.1 m<sup>2</sup></li> <li>• Membrane area 2.2 m<sup>2</sup></li> <li>• Solar collector area: 43 m<sup>2</sup></li> </ul>
(Mohamed et al., (2007) [194])	350	4.6 kWh/m <sup>3</sup>	4.6	8.83	
(Dallas et al., (2008) [195])	400	0.12 kW	7.2	–	<ul style="list-style-type: none"> <li>• Recovery ratio: 38 %</li> <li>• Recovery ratio: 70 %</li> <li>• Recovery ratio: 92 %</li> <li>• membrane area: 0.1 m<sup>2</sup></li> <li>• Membrane area 2.2 m<sup>2</sup></li> <li>• Solar collector area: 43 m<sup>2</sup></li> </ul>
(Bilton et al., (2010) [180])	300	0.16 kW	12.8	5	
(Banat et al., (2012) [196])	500	0.43 kW	20.6	–	<ul style="list-style-type: none"> <li>• Recovery ratio: 38 %</li> <li>• Recovery ratio: 70 %</li> <li>• Recovery ratio: 92 %</li> <li>• membrane area: 0.1 m<sup>2</sup></li> <li>• Membrane area 2.2 m<sup>2</sup></li> <li>• Solar collector area: 43 m<sup>2</sup></li> </ul>
(Penate et al., (2014) [197])	16,000	10.5 kW	15.75	–	
(Wright et al., (2015) [198])	1600	0.5 kW	7.5	–	<ul style="list-style-type: none"> <li>• Recovery ratio: 38 %</li> <li>• Recovery ratio: 70 %</li> <li>• Recovery ratio: 92 %</li> <li>• membrane area: 0.1 m<sup>2</sup></li> <li>• Membrane area 2.2 m<sup>2</sup></li> <li>• Solar collector area: 43 m<sup>2</sup></li> </ul>
(Alghoul et al., (2016) [199])	5100	1.1 kWh/m <sup>3</sup>	1.1	–	
(Ayou et al., (2022) [200])	11,600	2.3 kWh/m <sup>3</sup>	2.3	9	

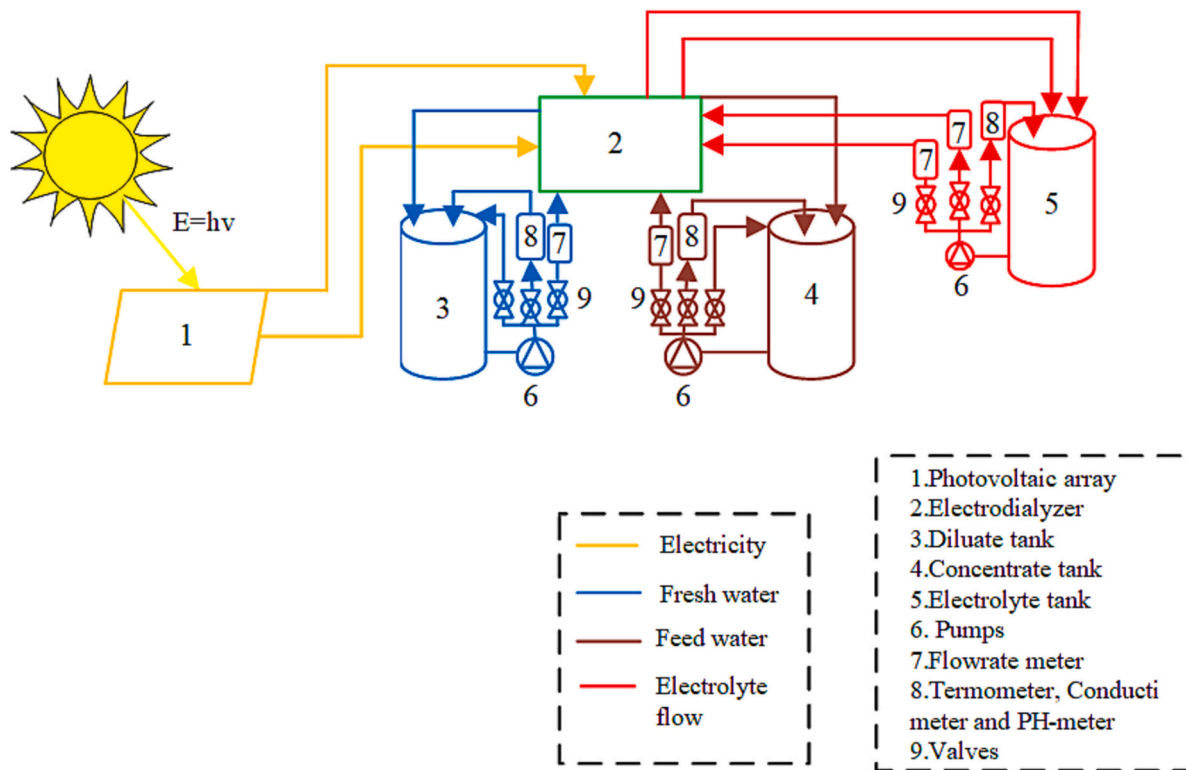


Fig. 8. The diagram of solar ED-SSD system - reproduced from [207].

They increased freshwater production in a single Easy MED cell to 500 l/d, consuming 624 kWh/m<sup>3</sup> of energy. The brine tank in this system helped with temperature recovery and maximum use of inlet feed water [167,173]. These authors also introduced a circulation evaporative desalination system that operates under vacuum pressure, and analyzed and optimized the system. As a result, it was observed that this system could produce 2200 l/d consuming 16.36 kWh/m<sup>3</sup> kWh of energy [174]. Karambasti et al. optimized a MED-SSD system that had 19,920 l/d of water production and energy consumption of 3 kWh/m<sup>3</sup> and coupled it with a power Stirling engine, using the flue gas as the heating source to produce fresh water. Further, the cost of after production in this system was 1.6 \$/m<sup>3</sup> [175]. Aly et al. have reported on a MED system boasting

an expanded capacity that was capable of generating 25,000 l/d of water. This system's energy consumption measured at 4.8 kWh/m<sup>3</sup>, whereby their economic analysis revealed a water production cost of 0.46 \$/m<sup>3</sup> [176].

A summary of some outstanding MED-SSD systems is given in Table 8. Among the MED-SSD systems, the one by Karambasti et al. with produced water of 19,920 l/d and energy consumption of 3 kWh/m<sup>3</sup>, had the lowest energy consumption [172]. Further, the system introduced by Aly et al. had the highest water production at 25000 l/d [176].

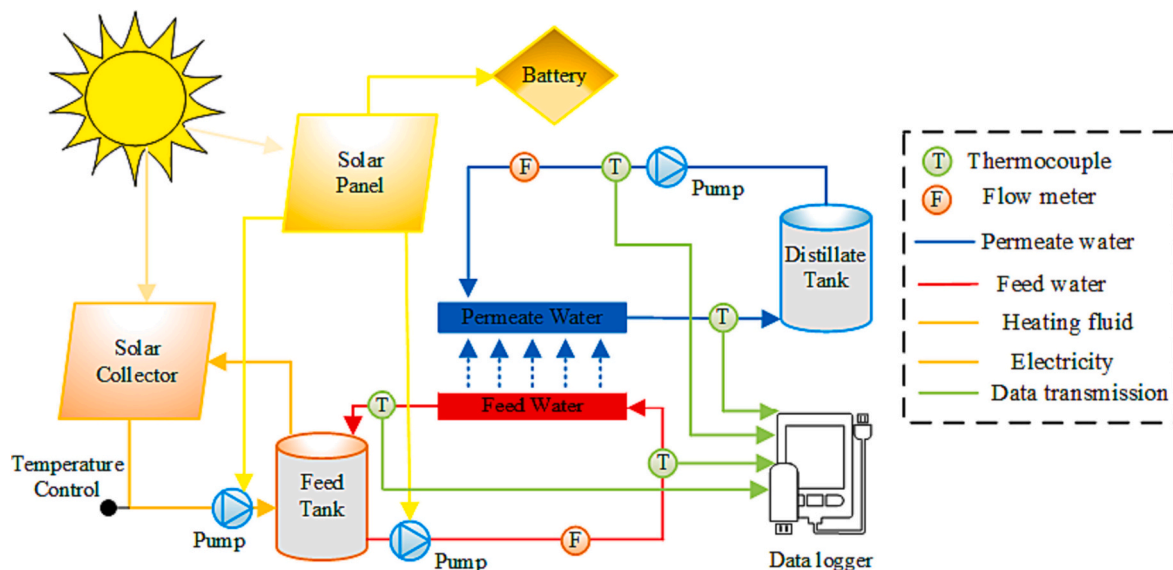


Fig. 9. Schematic of solar MD-SSD system - reproduced from [208].

**Table 10**  
Solar MD-SSD systems.

Ref	Technologies type	Production (l/d)	Energy consumption (kWh/m <sup>3</sup> )	Cost of water production (\$/m <sup>3</sup> )	Membrane area (m <sup>2</sup> )
(Hogan et al. (1991) [209])	DCMD	50	–	13.76	1.8
(Banat et al., (2006) [210])	DCMD	120	300	–	10
(Banat et al., (2007) [211])	DCMD	500	69	18	–
(Chafidz et al., (2014) [212])	VMD	99.9	129	–	0.15
(Ma et al., (2018) [213])	VMD	5.6	239	–	0.7
(Andrés-Mañas et al., (2018) [214])	VMD	1305	200	–	6.4
(Andrés-Mañas et al., (2020) [215])	VMD	193	17	–	6.4
(Shafieian et al., (2020) [216])	DCMD	80	600	–	0.21
(Chang et al., (2022) [217])	VMD	10	4084	421	0.085
(Choi et al., (2022) [218])	DCMD	1100	959	5.65	5.94
(ElKasaby et al., (2023) [219])	VMD	170	195	14.7	0.5
(Baaqeel et al., (2020) [220])	DCMD	500	5280	–	16.8

### 3. Small-scale desalination (SSD) systems powered by renewable energy (RE)

Some countries have large conventional energy sources, such as oil and gas, while others have energy problems related to fossil fuel imports, environmental constraints and rising fossil fuel prices. These are the main limitations of technologies that use fossil fuels [177]. In areas without access to electricity and other fossil fuels, shortages of drinking water are a major problem due to issues with access to energy for powering desalination systems. In these areas, SSD systems powered by RE can be very suitable for treating water from wells or other water sources. It is important to note here that the use of RE to meet the energy

needs of varied systems in these areas helps to maintain a clean and healthy environment [178,179]. In this section, SSD systems that are powered by different sources of RE are reviewed.

#### 3.1. Solar (thermal and PV) SSD systems

One suitable method for obtaining fresh water via SSDs is the use of combined PVRO-SSD systems. The schematic of a PVRO-SSD system is shown in Fig. 7 [180]. This system can provide 10,000 l/d of water employing 2.8 m<sup>2</sup> of membrane area and 4 kWh/m<sup>3</sup> energy consumption [180].

In Table 9, previous studies on the use of solar RO-SSD systems are

**Table 11**  
HDH-SSD systems powered by solar energy.

Ref	Production (l/d)	Energy consumption		Cost of water Production (\$/m <sup>3</sup> )	Features
		Ref	(kWh/m <sup>3</sup> )		
(Younis et al., (1989) [224])	9800	90.9 kW	222	–	<ul style="list-style-type: none"> <li>The system was a CWOA-HDH</li> <li>The system was a CAOW-HDH</li> <li>Total solar collector area: 2 m<sup>2</sup></li> <li>The system was a mechanical vapor compression HDH</li> </ul>
(A1-Hallaj et al., (1998) [225])	10	2 kW	4800	–	
(Vlachogiannis et al., (1999) [226])	2.88	70 kW/m <sup>3</sup>	583	–	
(Muller-Holst et al., 1990 [227])	2000	220 kWh/m <sup>3</sup>	220	12.45	<ul style="list-style-type: none"> <li>This system was a 24-h continuous operation system</li> </ul>
(Dai et al., (2000) [228])	800	1.6 kW	48	–	<ul style="list-style-type: none"> <li>Thermal efficiency of system was 80 %</li> <li>Solar water heater area: 2 m<sup>2</sup></li> <li>Solar air heater area: 2 m<sup>2</sup></li> <li>Solar water heater area: 2 m<sup>2</sup></li> <li>Solar air heater area: 0.5 m<sup>2</sup></li> <li>Thermal efficiency of system was 92 %</li> </ul>
(Fath et al., (2002) [229])	8	1.6 kW	4800	–	
(Nafey et al., (2004) [230])	10	14 kWh	1400	–	
(Al-Enezi et al., (2005) [231])	6	5 kWh/m <sup>3</sup>	5	–	<ul style="list-style-type: none"> <li>The system was a CWOA-HDH</li> <li>Total solar collector area: 10 m<sup>2</sup></li> <li>Solar water heater area: 2 m<sup>2</sup></li> <li>Solar air heater area: 2 m<sup>2</sup></li> <li>Total solar collector area: 140 m<sup>2</sup></li> </ul>
(Yamali et al., (2006) [232])	10	0.8 kW	1920	–	
(Yuan et al., (2006) [233])	43	8 kW	4465	–	
(Orfi et al., (2006) [234])	80	1.86 kW	558	–	<ul style="list-style-type: none"> <li>The system was a CWOA-HDH</li> <li>Solar water heater area: 12 m<sup>2</sup></li> <li>Solar air heater area: 16 m<sup>2</sup></li> <li>Thermal efficiency of system was 60–80 %</li> <li>Solar water heater area: 12 m<sup>2</sup></li> <li>Solar air heater area: 100 m<sup>2</sup></li> </ul>
(Muller-Holst, (2007) [235])	500	120 kWh/m <sup>3</sup>	120	10.04	
(Yamali et al., (2008) [236])	2160	1 kW	11	–	
(Zhani et al., (2010) [237])	20	10.8 kW	12,960	90.58	<ul style="list-style-type: none"> <li>The system was a CAOW-HDH</li> <li>The GOR was 2.1</li> <li>The system was a BC-HDH</li> <li>The system was a CWOA-HDH</li> <li>This system was a BC-HDH</li> <li>The system was a CAOW-HDH</li> <li>The GOR was 1.93</li> <li>The GOR was 1.3</li> <li>Phase changed materials (PCM) were used in this system</li> <li>Total solar collector area: 2.4m<sup>2</sup></li> <li>The system was a BC-HDH</li> </ul>
(Hermosillo et al., (2011) [238])	12.8	1 kW	1875	–	
(Yuan et al., (2011) [239])	1200	55 kW	1100	3.03	
(Antar et al., (2012) [240])	6	4 kW	16,000	–	<ul style="list-style-type: none"> <li>The system was a CAOW-HDH</li> <li>The GOR was 2.1</li> <li>The system was a BC-HDH</li> <li>The system was a CWOA-HDH</li> <li>This system was a BC-HDH</li> <li>The system was a CAOW-HDH</li> <li>The GOR was 1.93</li> <li>The GOR was 1.3</li> <li>Phase changed materials (PCM) were used in this system</li> <li>Total solar collector area: 2.4m<sup>2</sup></li> <li>The system was a BC-HDH</li> </ul>
(Chang et al., (2014) [241])	440	4 kW	218	4.42	
(Ghazal et al., (2014) [242])	6	0.7 kW	2800	–	
(Yildirim et al., (2014) [243])	33	0.9 kW	654	–	<ul style="list-style-type: none"> <li>The system was a CWOA-HDH</li> <li>This system was a BC-HDH</li> <li>The system was a CAOW-HDH</li> <li>The GOR was 1.93</li> <li>The GOR was 1.3</li> <li>Phase changed materials (PCM) were used in this system</li> <li>Total solar collector area: 2.4m<sup>2</sup></li> <li>The system was a BC-HDH</li> </ul>
(Behnam et al., (2016) [244])	74.4	10 kW	3225	28	
(Zubair et al., (2017) [245])	80	6 kW	1800	38.1	
(Aburub et al., (2017) [246])	92	2 kW	521	–	<ul style="list-style-type: none"> <li>The system was a CWOA-HDH</li> <li>Solar water heater area: 12 m<sup>2</sup></li> <li>Solar air heater area: 16 m<sup>2</sup></li> <li>Thermal efficiency of system was 60–80 %</li> <li>Solar water heater area: 12 m<sup>2</sup></li> <li>Solar air heater area: 100 m<sup>2</sup></li> </ul>
(Mahmoud et al., (2019) [247])	100	0.8 kW	192	–	
(Patel et al., (2019) [248])	13	3.5 kW	6461	29.44	

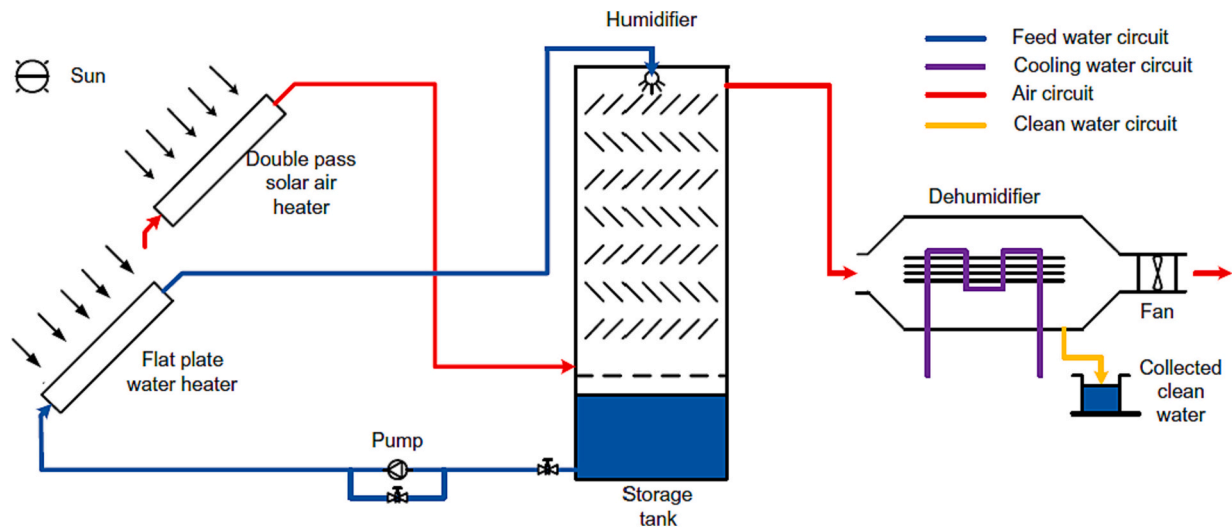


Fig. 10. The schematic of solar HDH-SSD system [242].

reported and compared in terms of freshwater production, energy consumption and other influencing parameters.

As can be seen in Table 9, solar RO-SSD systems can provide a wide range of freshwater production. The system with the most water production belongs to Penate et al. producing 16,000 l/d [197]. Ayoun et al. have analyzed a PVRO-SSD system in Madura Island with 11,600 l/d of water production and 2.3 kWh/m<sup>3</sup> of energy consumption. Further, this system had 2.2 m<sup>2</sup> of effective membrane area, whereby economic analysis revealed that the cost of water production in this system was 9 \$/m<sup>3</sup> [200]. Additionally, the solar RO-SSD system proposed by Alghoul et al. had the lowest energy consumption of 1.1 kWh/m<sup>3</sup>, with water production of 5100 l/d, which is very suitable for areas with low energy access [199]. In addition, the solar RO-SSD system proposed by Thomson et al. had a minimum production cost of 2.26 \$/m<sup>3</sup> of freshwater [187].

Solar desalination of water can be reliably achieved using an electrodialysis process that works with photovoltaic cells. This method can be effective because electrodialysis requires a D.C. power supply as the driving force to remove salt ions. The possibility of using solar energy in ED systems and the advantages of this system have been examined,

where the results show that solar energy can be a good alternative to non-renewable energy [201–204]. In this regard, Al Madani has investigated solar ED-SSD systems in Bahrain, with four photovoltaic modules used in the proposed system. Results show that this system could produce 568 l/d of freshwater consuming 5.57 kWh/m<sup>3</sup> of energy [205]. Xu et al. have presented a solar ED-SSD system featuring a total effective surface of 0.04 m<sup>2</sup> and a solar cell surface of 0.64 m<sup>2</sup>, capable of producing 59 l/d of water [206].

Ortiz et al. have studied a solar ED-SSD system that runs on solar energy, with an active membrane area of 500 cm<sup>2</sup> per cell, and a total effective surface area of 3.5 m<sup>2</sup>. The number of solar modules in this system was 8, and the amount of energy consumption was 1.69 kWh/m<sup>3</sup>. Further, the amount of water production in this system was 6000 l/d. The cost per unit volume of produced water in this system was 0.36 \$/m<sup>3</sup>. A working diagram of this solar ED-SSD system is presented in Fig. 8 [207].

The integration of solar energy and MD systems presents a viable choice for SSD systems. Therefore, a related schematic of a solar MD-SSD is shown in Fig. 9 [208]. This system could provide 72 l/d of water production, employing 0.2 m<sup>2</sup> of membrane area and 2400 kWh/m<sup>3</sup> of

Table 12  
solar MED-SSD systems.

Ref	Production (l/d)	Energy consumption		Cost of water production (\$/m <sup>3</sup> )	Features
		Ref	(kWh/m <sup>3</sup> )		
(Rahim et al., (1992) [254])	40	1.4 kWh	35	–	<ul style="list-style-type: none"> <li>This system had a fan-condenser for condensing the water vapor</li> </ul>
(Muller et al., (1998) [255])	437	120 kWh/m <sup>3</sup>	120	30.12	<ul style="list-style-type: none"> <li>This system was a 24-h continuous operation system</li> <li>Total solar collector area: 8.5 m<sup>2</sup></li> <li>The maximum system efficiency was 45 %</li> </ul>
(Boucekima et al., (2000) [256])	64	6 kW	2250	–	
(Fath et al., (2005) [257])	10,000	50 kWh	5	4.12	<ul style="list-style-type: none"> <li>A complex system for producing water, food, electrical power and salts</li> <li>Total solar collector area: 72 m<sup>2</sup></li> <li>Total solar collector area: 5 m<sup>2</sup></li> <li>The maximum collector efficiency was 53 %</li> <li>Total solar collector area: 4 m<sup>2</sup></li> <li>This system had six stages</li> <li>The maximum collector efficiency was 39 %</li> </ul>
(Ben Amara et al., (2004) [258])	160	13.1 kW	1965	–	
(Schwarzer et al. (2003) [259])	43	7.2 kWh	167	–	
(Bouguecha et al., (2005) [193])	7.5	0.8 kW	2560	49.82	
(Muller et al., (2007) [235])	500	120 kWh/m <sup>3</sup>	120	8.17	<ul style="list-style-type: none"> <li>Total solar collector area: 8 m<sup>2</sup></li> </ul>
(Auti, (2012) [260])	20	3.5 kW	4200	–	<ul style="list-style-type: none"> <li>Total solar collector area: 4.15 m<sup>2</sup></li> </ul>
(Sapre et al., (2013) [261])	9	0.8 kW	2133	–	<ul style="list-style-type: none"> <li>Total solar collector area: 0.6 m<sup>2</sup></li> </ul>
(Auti et al., (2017) [262])	11	0.83 kW	1810	–	<ul style="list-style-type: none"> <li>Total solar collector area: 0.6 m<sup>2</sup></li> </ul>

**Table 13**  
Wind-powered SSD systems.

Ref	Production (l/d)	Wind speed (m/s)	Energy consumption		Cost of water production (\$/m <sup>3</sup> )
			Ref (kW)	(kWh/m <sup>3</sup> )	
(Petersen et al., (1979) [270])	6000	7	6	24	–
(Petersen et al., (1981) [271])	9000	9	6	16	–
(Robinson et al., (1991) [272])	213	3.2	0.15	17	11
(Maurel et al. (1991) [273])	12,000	5	4	8	–
(Habali et al., (1994) [274])	22,000	5–20	24	26	2.37
(Neris et al., (1995) [275])	20,000	4–22	34	41	–
(Infield, (1997) [276])	1120	3–25	3	64	–
(Liu et al., (2002) [277])	18,720	5–9	1.2	1.53	–
(Miranda et al., (2003) [278])	10,000	10	2.2	5.28	–
(Gökçek et al., (2016) [279])	24,000	5–25	6	6	2.96–6.47

energy consumption [208].

In Table 10, previous studies on the use of solar MD-SSD systems are reported and compared in terms of types of technologies, water production, energy consumption and other influential parameters.

As can be seen from Table 10, solar MD-SSD systems cover a wide range of freshwater production. The system that has the most water production is the solar VMD-SSD system belonging to Andrés-Mañas et al., producing 1305 l/d with 6.4 m<sup>2</sup> membrane surface area and 200 kWh/m<sup>3</sup> energy consumption [214]. The system with the lowest energy consumption also belongs to Andrés-Mañas et al., with 17 kWh/m<sup>3</sup> of energy consumption and 193 l/d of water production [215]. In addition to this, among systems that reported the cost of water production, the system introduced by Choi et al. had the lowest amount of cost of water production, measured at 5.65 \$/m<sup>3</sup> [218].

HDH-SSD systems operated by solar energy are uniquely suited to providing water and electricity in remote areas, where solar energy conditions are good but there is a shortage of water and electricity infrastructure [221–223]. Previous studies on HDH-SSD systems operated by solar energy are reported in Table 11.

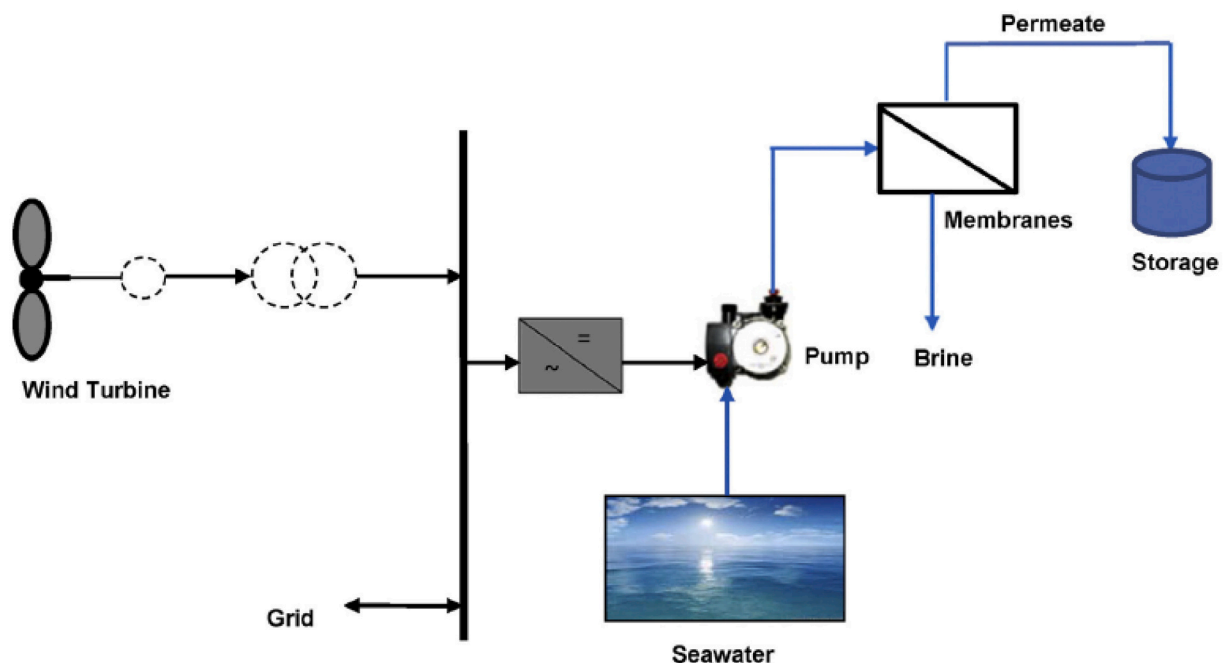
The results in Table 11 show that the amount of freshwater production in HDH-SSD systems is very low in many cases, where these are only suitable for laboratory systems [225,226,229,230,233,237,240,242,243,248], although some systems produced more than 1000 l/d and could supply fresh water for several homes [224,227,236,239].

The schematic of solar HDH-SSD systems is shown in Fig. 10 [242].

MED systems powered by solar energy can produce a good amount of fresh water with low initial capital requirements, low operating costs and low emissions. The development of these systems is very suitable for arid regions and countries with more limited facilities [249–253]. Suitable MED-SSD systems operating on solar energy are presented and compared in Table 12.

In Table 12, the system developed by Fath et al. is depicted, producing 10,000 l/d of fresh water at a cost of 4.12 \$/m<sup>3</sup>, featuring as one of the suitable systems in this category [257]. In addition to this, the system introduced by Muller et al. could be appropriate for freshwater production of 437–500 l/d [235,255].

Some solar SSD technologies can be combined to achieve higher volume and quality of freshwater. In this regard, Schafer et al. have investigated a hybrid solar RO-UF-SSD system, building a laboratory model of this system in Australia that produced 712 l/d of fresh water and consumed 5.5 kWh/m<sup>3</sup> [263]. They also improved their system in terms of energy production and consumption. In another study, the authors were able to produce 1000 l/d by consuming 5 kWh/m<sup>3</sup> of energy [264]. Finally, they introduced a hybrid RO-UF-SSD system that could produce 2000 l/d of fresh water with a consumption of 1.2 kWh/m<sup>3</sup> [265]. Bales et al. have introduced an MCDI-SSD system that produced 8000 l/d if it works 8 h/d, whereby the energy consumption of this system was 1.28 kWh/m<sup>3</sup> [266].



**Fig. 11.** The schematic of a wind RO-SSD system [279].

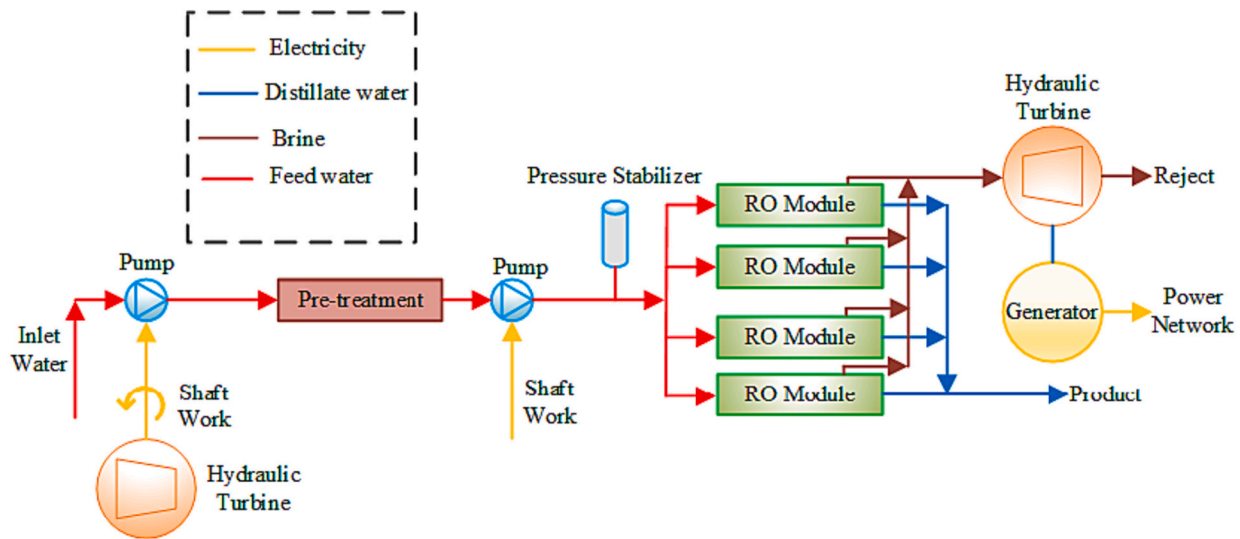


Fig. 12. The schematic of the Tidal RO-SSD system - reproduced from [295].

### 3.2. Wind powered SSD systems

Wind energy can significantly reduce the cost of freshwater production using RO desalination plants [267,268]. Accordingly, to produce 1.5 l/d of fresh water on a sunny and cloudy day by wind energy, a wind speed of approximately 6 m/s is required [269]. A number of studied wind-powered SSD systems are presented in Table 13.

Most of wind powered SSD systems are RO-based systems. As can be seen in Table 13, these systems can be used in areas where wind speed ranges between 3 and 25 m/s. Accordingly, the freshwater productivity, energy consumption and cost of these systems indicate that, subject to the availability of wind, these systems can be a good option for SSD use. However, wind energy also possesses certain drawbacks, encompassing issues such as blade noise, visual aesthetics and environmental concerns related to bird and bat collisions [270–279]. The schematic of a wind SSD-RO system is shown in Fig. 11 [279].

### 3.3. Geothermal-powered SSD system

Geothermal energy has many advantages over other renewable energy sources, whereby the amount of this energy can be stable. Solar and wind energy are sometimes unavailable, they require more technically sophisticated collection devices and are usually more expensive energy storage devices. In comparison, geothermal energy does not require complex systems and storage tools, but also has disadvantages, such as high exploration costs, high investment risk and high installation costs if new geothermal reservoirs are targeted. These high costs are normally offset by the free source of geothermal heat generation. The cost of providing heat from geothermal energy is generally less than the cost of solar energy; therefore, it can be very beneficial in areas where adequate geothermal resources are available [280–285]. Bourouni et al. have proposed a geothermal MED-SSD system that could produce 576 l/d with 1.44 kWh/m<sup>3</sup> of consumed energy. Further, their study showed that the cost of producing fresh water in this system was 1.20 \$/m<sup>3</sup> [286]. Additionally, Mohammad et al. have studied another geothermal evaporation-SSD system, the schematic of which is shown in Fig. 6. This

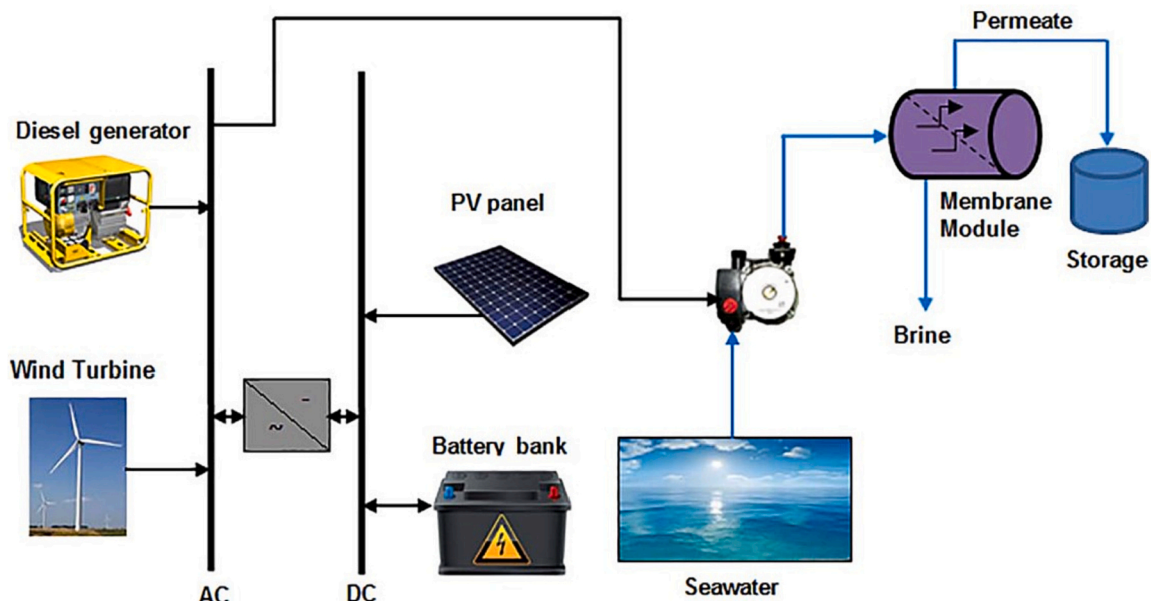


Fig. 13. The schematic of SSD system combined with solar-wind-diesel generator energy [308].

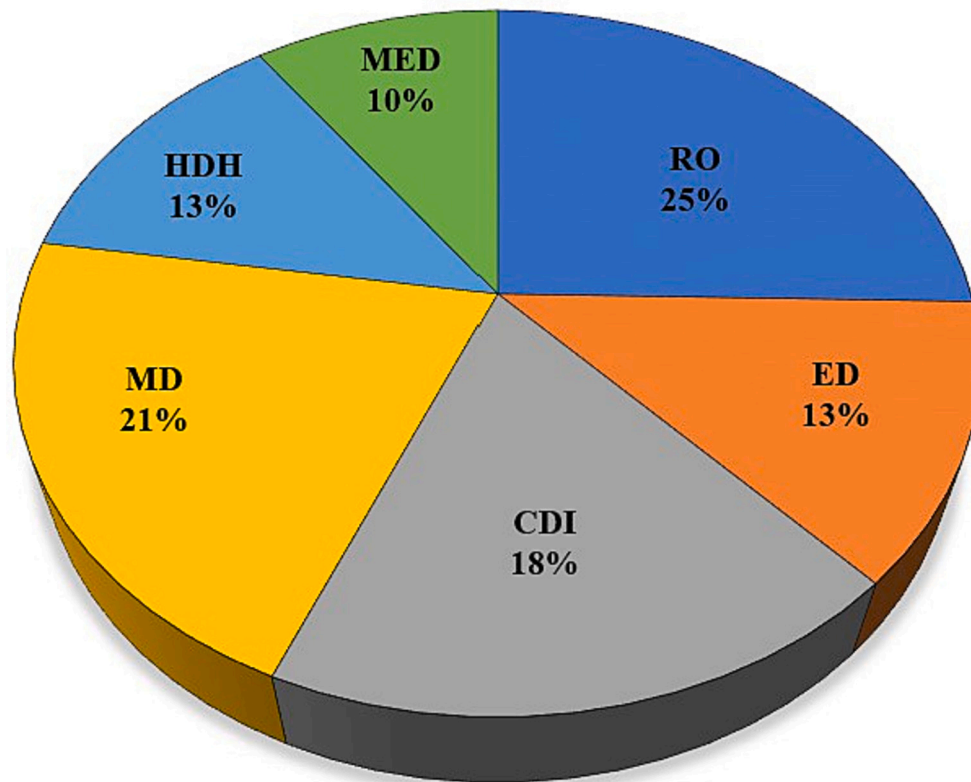


Fig. 14. Distribution of SSD technologies powered by non-RE.

system can produce 24 l/d [287].

To solve problems of fresh water in Mexico, Gutiérrez and Espíndola have applied the possibility of using geothermal energy to desalinate water in some parts of the country. They surveyed geothermal MED-SSD system for these areas, and they were able to desalinate approximately 20,000 l/d of fresh water. The geothermal well in their proposed design could also produce 16.8 kWh/m<sup>2</sup> of energy [288].

### 3.4. Tidal-powered SSD systems

Along with growing use of renewable energy for water desalination, tidal energy is also being considered, whereby this energy can provide fresh water for many areas at a low cost, especially coastal areas experiencing water shortages [289,290]. To make good use of this energy, higher height of waves and their shorter duration leads to better source of available energy [291,292]. In terms of the environmental aspects of using this type of energy, it is very important to know areas with environmental constraints, such as the existence of protected species, reserves or marine/terrestrial habitats [293]. In order to use tidal energy to desalinate water off the coast of India, an RO-SSD system was modeled and simulated using MATLAB and experimented on a laboratory scale model for this purpose. The production capacity of this system was 14,400 l/d, which consumed about 8 kWh/m<sup>3</sup> of energy [294]. The cost-benefit of using RO technology along with tidal energy for producing fresh water was investigated by Ling et al. In their system, the cost of producing fresh water was 0.6 \$/m<sup>3</sup>, which was less than the cost of the original system without tidal energy. In turn, this system could produce 22,700 l/d of fresh water [295]. In addition, Suchithra et al. have investigated a tidal RO-UF-SSD system producing 2400 l/d using about 8.36 kWh/m<sup>3</sup> [296]. Evaporative technologies have also been used within tidal SSD plants for decades, whereby Kumar et al. have proposed an evaporation system capable of producing 480 l/d. The quality of freshwater produced by this system was very good [297]. The schematic of a RO-SSD system powered by tidal energy is presented in

Fig. 12 [295].

### 3.5. SSD systems powered by hybrid renewable energies

It is also possible to combine several RE sources to desalinate water in arid areas. By combining RE sources, the cost of electricity generation for desalination systems can be reduced [298]. Further, the productivity

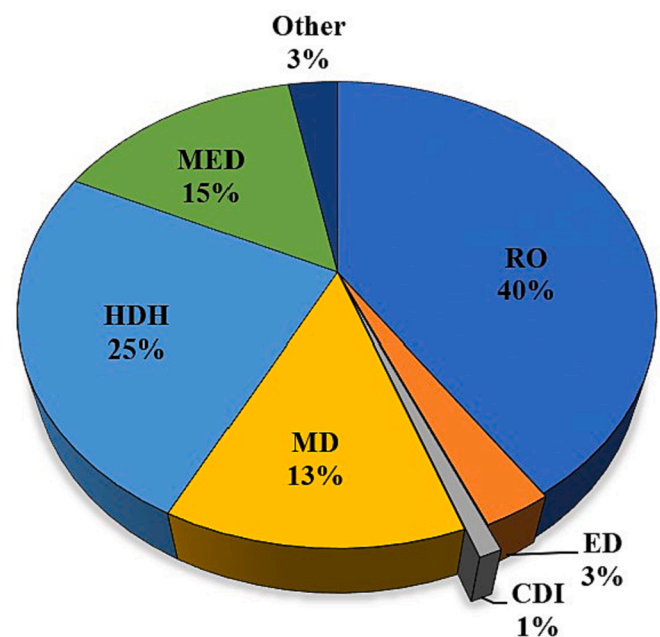
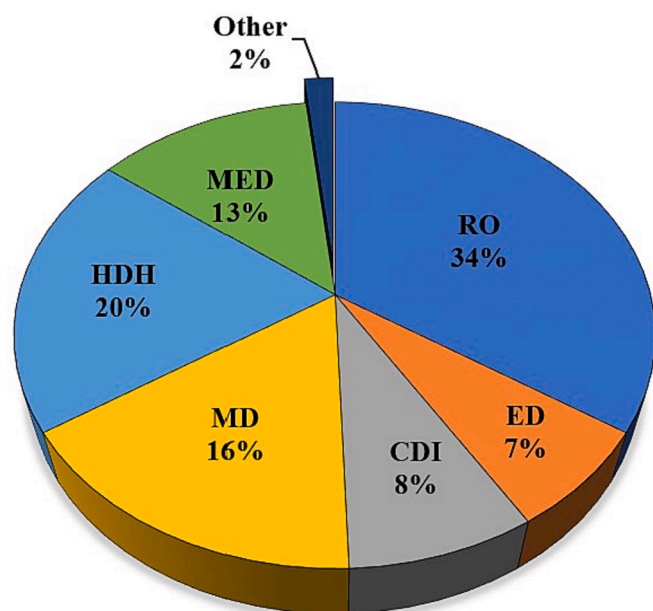


Fig. 15. Percentage distribution of technologies among SSD systems powered by RE.



**Fig. 16.** Percentage distribution of SSD technologies comprise of powered by renewable and non-renewable energies.

of fresh water of the system can also be improved this way, but the system needs to supply energy from the grid in the absence of renewable energy [299–302]. In order to prove the positive effect of RE composition on the productivity of desalination systems, studies have been conducted by a number of researchers. For example, Weiner et al. have described the process of designing, installing and operating an RO-SSD system powered by photovoltaic and wind energy. For their system, a battery for energy storage and a diesel generator for the required times were installed. The lifespan of this system was 15 years, producing 3000 l/d of fresh water and using approximately 3.3 kWh/m<sup>3</sup> of energy when powered by wind energy alone, whereby the maximum product capacity of the systems when using combined wind and solar energy was 9000 l/d with 5 kWh/m<sup>3</sup> energy being consumed [303]. Setiawan et al. have examined a mini-grade RO system powered by combined solar-wind-diesel energy, with results showing this combined system to be capable of supplying electricity 24 h a day, producing 5000 l/d with a consumption of 12 kWh/m<sup>3</sup>. [304]. To solve the problem of freshwater shortage in Mediterranean countries such as Greece, an RO-SSD system that works with solar and wind energy was evaluated, whereby it was observed that this system can produce 5800 l/d of fresh water with a consumption of 6.3 kWh/m<sup>3</sup> energy. The cost of freshwater production for this system was 5.88 \$/m<sup>3</sup> [305]. Mokheimer et al. have described a combined solar-wind RO-SSD system, where their experimental system could produce 5000 l/d, in addition to 4.8 kWh/m<sup>3</sup> of energy at a cost of 3.8 \$/m<sup>3</sup> of fresh water [306].

In another study, Mousa et al. have investigated the economics of optimizing a solar-wind system combined with a RO-SSD system. The cost of fresh water in their combined system was 1.21\$/m<sup>3</sup> [307]. Further to this, an RO-SSD combined with wind-photovoltaic-diesel-battery energy in Turkey and Bozcaada Island was studied via HOMER software. The amount of freshwater production in this system was 24,000 l/d, with results of economic analysis showing that the combination of a diesel generator of 8.9 kW, 20 kW of solar energy and 10 kW of wind energy, at an energy cost of 0.308 \$/kWh, could produce freshwater production at a cost of 2.2 \$/m<sup>3</sup>. The schematic of an SSD system combined with solar-wind-diesel generator energy is shown in Fig. 13 [308].

#### 4. Discussion

SSD systems that run on traditional fossil fuels and electricity can be used in areas where energy costs are low, whereby these resources are easily accessible. However, in recent years, the use of this type of system has decreased and replaced by renewable energy-powered systems [82,85]. Among these technologies, membrane systems such as RO, ED, MD and CDI can be very effective options because their energy consumption is normal and appropriate, as presented in Table 5. CDI systems consume less energy (0.1–0.4 kWh/m<sup>3</sup>) than other membrane systems (0.46–2.2 kWh/m<sup>3</sup>) [102,107,116,309]. Further, evaporative systems that operate with non-renewable energies require more energy than membrane systems due to their need to overcome the latent energy of water evaporation. Therefore, these systems are more suitable in areas where energy costs are not high, as they have a very good production rate. Additionally, they are simple and do not require complex systems or membrane costs. However, these systems require more space than membrane systems, whereby this could be an important consideration where a residential area has limited space [161,163]. To achieve higher system efficiency and reduce energy consumption, several desalination technologies can be combined, whereby more production or higher production quality can be achieved. Suitable technologies for these combined systems include RO technology, which can be combined with ED, UF and even evaporative systems [265]. The percentage distribution of SSD systems that are powered by non-renewable energy is presented in Fig. 14.

As depicted in Fig. 14, RO systems represent the largest share at 25 %. Additionally, both HDH and ED systems exhibit equal proportions, each contributing 13 % to the overall distribution. Furthermore, MD, CDI and MED systems represent shares of 21 %, 18 % and 10 %, respectively. In areas where access to fossil fuels is not feasible or transportation of fuels is costly, the use of SSD systems that operate on RE is recommended [178,179,310]. Among SSD systems that are powered by renewable energy, SSD solar-based systems have the largest share, where reasons for this could include: 1) access to renewable energies, 2) receiving an appropriate amount of energy (if combined with the battery system, they can be suitable for RO, ED, MD, HDH and MED) and 3) suitable n to power ED systems as they need DC current and do not need to have a current converter [196,207,242,257,311–313].

SSDs powered by wind can only be used in areas where the wind speed ranges between 3 and 25 m/s. These systems can be suitable if combined with batteries, where to date, these have only been studied for RO systems because the ability to overcome the latent evaporation energy by wind-powered systems is not possible. Due to some of these disadvantages, research on wind powered SSDs has decreased significantly in the last two decades [277,278].

SSDs powered by geothermal systems can also be suitable for use in areas with good sources of geothermal energy. Unlike other REs such as solar and wind, they are permanent and steady and do not require complex technology, but the cost of drilling and creating conditions for operation are high. However, not much research has been done on them to date, where this type of energy has been used for evaporative systems because the cost of heat supply in this type of energy is less than solar energy [281,282].

To meet needs for fresh water in coastal areas, tidal energy can reliably supply the necessary energy for desalination systems. However, due to the damage they may cause to the surrounding environment, it is very important to pay attention to the impact that they can have on animals, plant species and the surrounding environment in general. RO technology is commonly used with this source of energy for SSD systems [295,314].

The use of renewable energy to produce fresh water on an SSD has its drawbacks, as solar and wind energy cannot supply energy permanently and require a storage system, or they cannot provide enough energy for water to evaporate. Hence, these systems sometimes require an additional fossil-powered energy source, such as electric heaters or diesel

### Comparison of water production cost among SSD systems

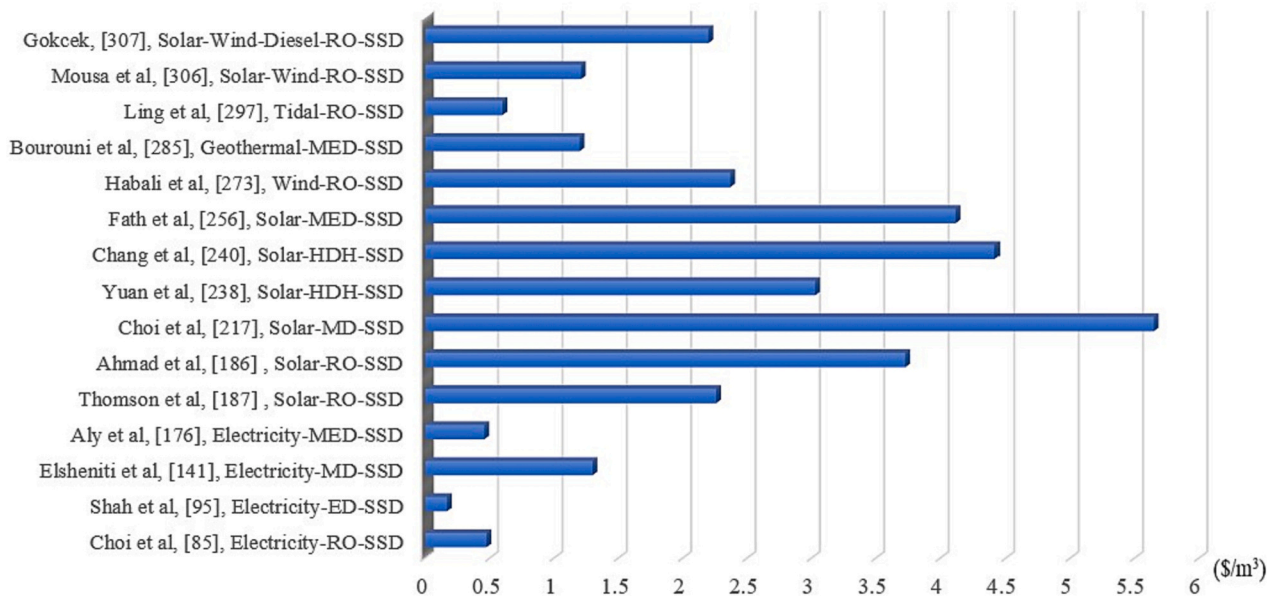


Fig. 17. Water production cost in SSD systems with various technologies.

generators. For these reasons, and in order to increase system efficiency and reduce dependency on fossil fuels and reduce the cost of water production, several types of renewable energy sources can be used in hybrid modes for SSD systems [315,316].

Laboratory systems with very low water production are more common among thermal SSD systems (HDH and MED) than membrane SSD systems (RO, ED, MD and CDI). In order to more accurately identify and compare SSD systems within this study, the unit of energy consumed for all systems was converted to kWh/m<sup>3</sup>, whereby it was concluded that evaporative systems have more kWh/m<sup>3</sup> than other systems. Accordingly, they need more energy and are more suitable for areas where

access to energy is feasible and economical. The percentage distribution of technologies among SSD systems powered by RE is shown in Fig. 15.

It is apparent from Fig. 15 that RO systems encompass nearly 40 % of the total array of technologies. Subsequently, HDH, MED and MD systems secure subsequent positions, accounting for 25 %, 15 % and 13 %, respectively. Furthermore, this figure illustrates that both ED and CDI systems make modest contributions, nearly on par with the values of hybrid systems and other technologies.

Fig. 16 shows the percentage distribution of SSD technologies within the comprehensive collection of RE and non-RE systems investigated in this research.

### Comparison of water production cost among SSD & LSD systems

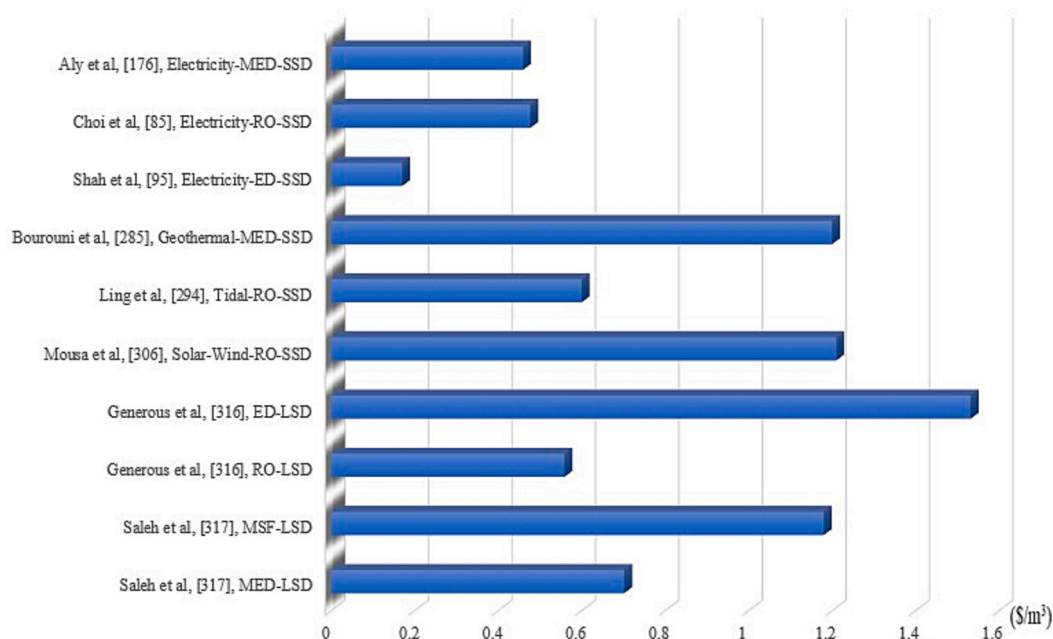


Fig. 18. Water production cost in SSD and LSD systems with various technologies.

From Fig. 16, it is evident that RO systems have the highest popularity among SSD systems, representing a substantial share of 34 %, following by HDH, MD and MED systems that account for 20 %, 16 % and 13 %, respectively. In contrast, CDI, ED and other combined systems show relatively modest participation, with a less significant share of SSD systems. One reason for the popularity of RO systems among SSD systems could be that this technology emerges as a versatile and effective solution for water treatment across various applications and small-scale sizes. Accordingly, its efficiency in purifying water, its compact design, its adaptability to different water sources, its adaptability to integrating with different REs, and its cost-effectiveness make it an appealing choice for SSD systems. The technology's minimal environmental impact, low chemical usage and established maintenance procedures further contribute to its viability [42,72,200].

Given that the technologies and structures of SSD systems powered by non-RE and RE differ significantly, it is not feasible to provide a comprehensive comparison between them in terms of technology, energy consumption and energy sources. However, comparing their water production costs can be highly beneficial and practical for assessing SSD systems overall. Water production costs in some SSD systems with various technologies are compared in Fig. 17.

As shown in Fig. 17, the water production cost in the SSD systems driven by non-renewable energy is the lowest compared to other systems [85,95], and among RE-SSD systems, tidal, geothermal and hybrid power systems can compete with the SSD systems driven by non-renewable sources [286,295,307]. Further, SSD systems that are powered by just one type of RE have a higher water production cost than others, where thermal-SSD systems (MED, HDH) that are driven by solar energy have the highest water production cost [239,241,259].

To compare SSD and LSD systems, the water production cost in several SSD and LSD systems have been compared in Fig. 18 [317,318].

As shown in Fig. 18, among SSD thermal systems, SSD-geothermal-MED systems can compete with LSD evaporation systems, and SSD membrane systems have water production costs almost equal to their similar technologies in LSD systems. Furthermore, SSD systems that are powered by electricity have the lowest water production cost.

An important and influential parameter in the economic analysis of LSD systems and centralized systems is the cost of transferring water to residential areas, where this can increase the cost of water production overall. Therefore, if LSD systems are to be accurately compared with SSD systems, this important parameter must be considered. In this way, LSD and SSD systems can be better compared. For example, to reduce the water transfer cost to residential areas where fossil fuels are cheap and energy is easy to access, also in coastal areas where tidal energy is available or areas with good wind and solar energy potential, SSD systems can be utilized.

## 5. Challenges and future perspectives

The challenges and future perspectives of SSD systems can be summarized as.

- Insufficient research has been conducted on quantifying the energy waste along transmission routes of fresh water from LSD (Large-Scale Desalination) systems to residential areas. Conducting research in this area is crucial as it can highlight the significance of SSD (Small-Scale Desalination) systems. Additionally, comparing the energy efficiency of SSD and LSD systems would be beneficial in providing valuable insights. These research endeavors would shed light on the energy-saving potential of SSD systems and help identify the most efficient water transmission methods.
- Considering the advantages of SSD systems over LSD systems, such as the capability to distribute scattered water without energy loss during transmission and to supply fresh water to remote and hard-to-reach regions, it is anticipated that the use of SSD systems will increase in the future.
- In addition, among the SSD systems that source their energy from fossil fuels, membrane systems are projected to have a larger market share in the future when compared to thermal SSD systems, due to their superior efficiency and lower energy consumption.
- It is expected that in the coming years, due to less production of fossil fuels and the high level of pollution that this source of energy can cause to the environment, the use of SSD systems powered by this source of energy will decrease.
- Among renewable energy-powered systems, solar SSD systems are expected to have the largest share. Further to this, among solar SSD systems, solar RO-SSD systems are predicted to have largest share due to their higher efficiency and lower energy consumption compared to solar thermal-SSD systems.
- Limited research has been conducted on combined desalination technologies involving SSD systems. These integrated approaches, such as MED-RO-SSD and RO-ED-SSD, have the potential to enhance the productivity and efficiency of SSD systems. Further investigation is warranted to explore the research opportunities associated with these systems.
- Insufficient research has been conducted on the integration of hybrid renewable energies with SSD systems. Promising combinations, such as solar-wind-SSD, solar-geothermal-SSD, tidal-wind-SSD, and others, have not been adequately explored. Conducting future research on these systems holds significant potential for improving efficiency and reducing reliance on fossil fuels, thus benefiting sustainable energy efforts.
- Finally, investigating the potential environmental effects of SSD systems and their overall scattered production is of paramount importance in the future. This research will provide valuable insights into the sustainability and ecological implications of such systems, filling an important knowledge gap.

## Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

## Data availability

Data will be made available on request.

## References

- [1] I.C. Karagiannis, P.G. Soldatos, "Water desalination cost literature: review and assessment," (in English), *Desalination* 223 (1–3) (Mar 1 2008) 448–456, <https://doi.org/10.1016/j.desal.2007.02.071>.
- [2] R. Yargholi, H. Kariman, S. Hoseinzadeh, M. Bidi, A. Naseri, "Modeling and advanced exergy analysis of integrated reverse osmosis desalination with geothermal energy," (in English), *Water Supply* 20 (3) (May 2020) 984–996, <https://doi.org/10.2166/ws.2020.021>.
- [3] S. Hoseinzadeh, R. Yargholi, H. Kariman, P.S. Heyns, "Exergoeconomic analysis and optimization of reverse osmosis desalination integrated with geothermal energy," (in English), *Environ. Prog. Sustain.* 39 (5) (Sep 2020) doi:ARTN e13405 10.1002/ep.13405.
- [4] F. Belmehdi, S. Otmani, M. Taha-Janan, "Global trends of solar desalination research: a bibliometric analysis during 2010–2021 and focus on Morocco," (in English), *Desalination* 555 (Jun 1 2023) doi:ARTN 116490 10.1016/j.desal.2023.116490.
- [5] Z.M. Ghazi, S.W.F. Rizvi, W.M. Shahid, A.M. Abdulhameed, H. Saleem, S.J. Zaidi, "An overview of water desalination systems integrated with renewable energy sources," (in English), *Desalination* 542 (Nov 15 2022) doi:ARTN 116063 10.1016/j.desal.2022.116063.
- [6] W. He, G. Huang, C.N. Markides, "Synergies and potential of hybrid solar photovoltaic-thermal desalination technologies," (in English), *Desalination* 552 (Apr 15 2023) doi:ARTN 116424 10.1016/j.desal.2023.116424.
- [7] M. Ayaz, M.A. Namazi, M.A.U. Din, M.I.M. Ershath, A. Mansour, E.M. Aggoune, "Sustainable seawater desalination: Current status, environmental implications and future expectations," (in English), *Desalination* 540 (Oct 15 2022) doi:ARTN 116022 10.1016/j.desal.2022.116022.

- [8] P.T.P. Aryanti, et al., "Ultra low-pressure reverse osmosis (ULPRO) membrane for desalination: Current challenges and future directions," (in English), *Desalination* 560 (Aug 15 2023) doi:ARTN 116650 10.1016/j.desal.2023.116650.
- [9] J. Lubroth, "The new policy of the Food and Agriculture Organization of the United Nations and its Reference Centres for the Animal Production and Health Division," (in English), *Dev Biologicals* 128 (2007) 73–78 [Online]. Available: <Go to ISI>://WOS:000252030800011.
- [10] W. H. Organization, *Progress on Household Drinking Water, Sanitation and Hygiene 2000–2020: Five Years into the SDGs*, 2021.
- [11] N. Y. U. N. C. S. F. U. a. W. H. O. (WHO), *Progress on Household Drinking Water, Sanitation and Hygiene 2000–2022: Special Focus on Gender*, 2023.
- [12] A. Noy, H.G. Park, F. Fornasiero, J.K. Holt, C.P. Grigoropoulos, O. Bakajin, Nanofluidics in carbon nanotubes (in English), *Nano Today* 2 (6) (Dec 2007) 22–29, [https://doi.org/10.1016/S1748-0132\(07\)70170-6](https://doi.org/10.1016/S1748-0132(07)70170-6).
- [13] G.K. Ding, *Wastewater Treatment, Reused and Recycling—a Potential Source of Water Supply*, 2023.
- [14] F. Garcia-Avila, M. Guanoquiza-Suarez, J. Guzman-Galarza, R. Cabello-Torres, L. Valdiviezo-Gonzales, "Rainwater harvesting and storage systems for domestic supply: An overview of research for water scarcity management in rural areas," (in English), *Results Eng.* 18 (Jun 2023) doi:ARTN 101153 10.1016/j.rineng.2023.101153.
- [15] P. Vandome, et al., Making technological innovations accessible to agricultural water management: design of a low-cost wireless sensor network for drip irrigation monitoring in Tunisia, *Smart Agric. Technol.* 4 (2023) 100227.
- [16] M. Nakhaei, A. Ahmadi, M. Gheibi, B. Chahkandi, M. Hajiaghahi-Keshteli, K. Behzadian, A smart sustainable decision support system for water management of power plants in water stress regions, *Expert Syst. Applic.* (2023) 120752.
- [17] G.K. Ding, *Managing Water Scarcity—The Role of Sustainable Water Management*, 2023.
- [18] N. Ghaffour, T.M. Missimer, G.L. Amy, "technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability," (in English), *Desalination* 309 (Jan 15 2013) 197–207, <https://doi.org/10.1016/j.desal.2012.10.015>.
- [19] N. Voutchkov, *Desalination Project Cost Estimating and Management*, CRC Press, Boca Raton, FL, 2019 (in English).
- [20] N. W. G. C. L. L. C. F. L. U. S. A. Voutchkov, in: 1st ed. (Ed.), *Desalination Project Cost Estimating and Management*, CRC Press, 2018 (in English).
- [21] R.S. El-Emam, H. Ozcan, R. Bhattacharyya, L. Awerbuch, "Nuclear desalination: A sustainable route to water security," (in English), *Desalination* 542 (Nov 15 2022) doi:ARTN 116082 10.1016/j.desal.2022.116082.
- [22] I. Ihsanullah, J. Mustafa, A.M. Zafar, M. Obaid, M.A. Atieh, N. Ghaffour, "Waste to wealth: a critical analysis of resource recovery from desalination brine," (in English), *Desalination* 543 (Dec 1 2022) doi:ARTN 116093 10.1016/j.desal.2022.116093.
- [23] S.S. Ray, R.K. Verma, A. Singh, M. Ganesapillai, Y.N. Kwon, "A holistic review on how artificial intelligence has redefined water treatment and seawater desalination processes," (in English), *Desalination* 546 (Jan 15 2023) doi:ARTN 116221 10.1016/j.desal.2022.116221.
- [24] H. Liu, et al., "Recent advances in heat pump-coupled desalination systems: a systematic review," (in English), *Desalination* 543 (Dec 1 2022) doi:ARTN 116081 10.1016/j.desal.2022.116081.
- [25] H. Nassrullah, S.F. Anis, R. Hashaikeh, N. Hilal, "Energy for desalination: a state-of-the-art review," (in English), *Desalination* 491 (Oct 1 2020) doi:ARTN 114569 10.1016/j.desal.2020.114569.
- [26] K. Bourouni, M.T. Chaibi, L. Tadrast, "Water desalination by humidification and dehumidification of air: state of the art," (in English), *Desalination* 137 (1–3) (May 1 2001) 167–176, [https://doi.org/10.1016/S0011-9164\(01\)00215-6](https://doi.org/10.1016/S0011-9164(01)00215-6).
- [27] J.C. Farmer, D.V. Fix, G.V. Mack, R.W. Pekala, J.F. Poco, "Capacitive deionization of NaCl and NaNO<sub>3</sub> solutions with carbon aerogel electrodes," (in English), *J. Electrochem. Soc.* 143 (1) (Jan 1996) 159–169, <https://doi.org/10.1149/1.1836402>.
- [28] S. Burn, et al., "Desalination techniques - a review of the opportunities for desalination in agriculture," (in English), *Desalination* 364 (May 15 2015) 2–16, <https://doi.org/10.1016/j.desal.2015.01.041>.
- [29] C.J. Davey, et al., "Membrane distillation for concentrated blackwater: Influence of configuration (air gap, direct contact, vacuum) on selectivity and water productivity," (in English), *Sep. Purif. Technol.* 263 (May 15 2021) doi:ARTN 118390 10.1016/j.seppur.2021.118390.
- [30] P. Behnam, M. Faegh, M. Khadani, "A review on state-of-the-art applications of data-driven methods in desalination systems," (in English), *Desalination* 532 (Jun 15 2022) doi:ARTN 115744 10.1016/j.desal.2022.115744.
- [31] P.M. Williams, M. Ahmad, B.S. Connolly, D.L. Oatley-Radcliffe, "technology for freeze concentration in the desalination industry," (in English), *Desalination* 356 (Jan 15 2015) 314–327, <https://doi.org/10.1016/j.desal.2014.10.023>.
- [32] C.G. Xie, L.P. Zhang, Y.H. Liu, Q.C. Lv, G.L. Ruan, S.S. Hosseini, "a direct contact type ice generator for seawater freezing desalination using LNG cold energy," (in English), *Desalination* 435 (Jun 1 2018) 293–300, <https://doi.org/10.1016/j.desal.2017.04.002>.
- [33] C.W. Ong, C.L. Chen, "technical and economic evaluation of seawater freezing desalination using liquefied natural gas," (in English), *Energy* 181 (Aug 15 2019) 429–439, <https://doi.org/10.1016/j.energy.2019.05.193>.
- [34] J.N. Zheng, F.B. Cheng, Y.P. Li, X. Lu, M.J. Yang, "Progress and trends in hydrate based desalination (HBD) technology: a review," (in English), *Chinese J. Chem. Eng.* 27 (9) (Sep 2019) 2037–2043, <https://doi.org/10.1016/j.cjche.2019.02.017>.
- [35] M.N. Khan, C.J. Peters, C.A. Koh, "Desalination using gas hydrates: The role of crystal nucleation, growth and separation," (in English), *Desalination* 468 (Oct 15 2019) doi:ARTN 114049 10.1016/j.desal.2019.06.015.
- [36] D.U. Lawal, N.A.A. Qasem, "Humidification-dehumidification desalination systems driven by thermal-based renewable and low-grade energy sources: A critical review," (in English), *Renew. Sust. Energ. Rev.* 125 (Jun 2020) doi:ARTN 109817 10.1016/j.rser.2020.109817.
- [37] M.W. Shahzad, M. Burhan, L. Ang, K.C. Ng, "Energy-water-environment nexus underpinning future desalination sustainability," (in English), *Desalination* 413 (Jul 1 2017) 52–64, <https://doi.org/10.1016/j.desal.2017.03.009>.
- [38] D. Zarzo, D. Prats, "Desalination and energy consumption. What can we expect in the near future?," (in English), *Desalination* 427 (Feb 1 2018) 1–9, <https://doi.org/10.1016/j.desal.2017.10.046>.
- [39] J. Ayoub, R. Alward, "Water requirements and remote arid areas: the need for small-scale desalination," (in English), *Desalination* 107 (2) (Oct 1996) 131–147, [https://doi.org/10.1016/S0011-9164\(96\)00158-0](https://doi.org/10.1016/S0011-9164(96)00158-0).
- [40] H.D. Frederiksen, "The world water crisis and international security," (in English), *Middle East Policy* 16 (4) (2009) 76–89. Win, <https://doi.org/10.1111/j.1475-4967.2009.00416.x>.
- [41] A. Zandekis, L. Timma, D. Blumberga, C. Rochas, "Possibilities for utilization of solar thermal energy in multi-family buildings in Latvia," (in English), *Environ. Clim. Technol.* 6 (1) (Jun 2011) 138–146, <https://doi.org/10.2478/v10145-011-0020-4>.
- [42] K.M. Shah, et al., "Drivers, challenges, and emerging technologies for desalination of high-salinity brines: A critical review," (in English), *Desalination* 538 (Sep 15 2022) doi:ARTN 115827 10.1016/j.desal.2022.115827.
- [43] S. Prabhakar, R.N. Patra, B.M. Misra, M.P.S. Ramani, "Management and feasibility of reverse-osmosis schemes for rural water-supply in India," (in English), *Desalination* 73 (1–3) (Nov 1989) 37–46, [https://doi.org/10.1016/0011-9164\(89\)87003-1](https://doi.org/10.1016/0011-9164(89)87003-1).
- [44] F.G. Abbosh, I. Kamal, S. Chalchal, H. Gerke, "Design and performance of the worlds largest operating dual-purpose sea-water desalting plant," (in English), *Desalination* 45 (May) (1983) 223–230 [Online]. Available: [https://doi.org/10.1016/0011-9164\(83\)90003-1](https://doi.org/10.1016/0011-9164(83)90003-1).
- [45] M.A. Alkhadra, T. Gao, K.M. Conforti, H.H. Tian, M.Z. Bazant, "Small-scale desalination of seawater by shock electrodialysis," (in English), *Desalination* 476 (Feb 15 2020) doi:ARTN 114219 10.1016/j.desal.2019.114219.
- [46] S. Shoeibi, S.A.A. Mirjalili, H. Kargarsharifabad, M. Khadani, H. Panchal, "A comprehensive review on performance improvement of solar desalination with applications of heat pipes," (in English), *Desalination* 540 (Oct 15 2022) doi:ARTN 115983 10.1016/j.desal.2022.115983.
- [47] T. Mezher, H. Fath, Z. Abbas, A. Khaled, "Techno-economic assessment and environmental impacts of desalination technologies," (in English), *Desalination* 266 (1–3) (Jan 31 2011) 263–273, <https://doi.org/10.1016/j.desal.2010.08.035>.
- [48] A.K. Sharma, G. Tjandraatmadja, S. Cook, T. Gardner, "Decentralised systems - definition and drivers in the current context," (in English), *Water Sci. Technol.* 67 (9) (2013) 2091–2101, <https://doi.org/10.2166/wst.2013.093>.
- [49] K. Burashid, A.R. Hussain, "Seawater RO plant operation and maintenance experience: Addur desalination plant operation assessment," (in English), *Desalination* 165 (1–3) (Aug 15 2004) 11–22, <https://doi.org/10.1016/j.desal.2004.06.002>.
- [50] C. Tristan, M. Fallanza, R. Ibanez, I. Ortiz, "Reverse electrodialysis: potential reduction in energy and emissions of desalination," (in English), *Appl. Sci.-Basel* 10 (20) (Oct 2020) doi:ARTN 7317 10.3390/app10207317.
- [51] I. Al-Hayek, O.O. Badran, "The effect of using different designs of solar stills on water distillation," (in English), *Desalination* 169 (2) (Oct 1 2004) 121–127, <https://doi.org/10.1016/j.desal.2004.08.013>.
- [52] T. Hoepner, S. Lattemann, "Chemical impacts from seawater desalination plants - a case study of the northern Red Sea," (in English), *Desalination* 152 (1–3) (Feb 10 2003) 133–140, [https://doi.org/10.1016/S0011-9164\(02\)01056-1](https://doi.org/10.1016/S0011-9164(02)01056-1), doi:Pii S0011-9164(02)01056-1.
- [53] S.M. Montazeri, G. Kolliopoulos, "Hydrate based desalination for sustainable water treatment: a review," (in English), *Desalination* 537 (Sep 1 2022) doi:ARTN 115855 10.1016/j.desal.2022.115855.
- [54] N.P.B. Tan, P.M.L. Ucab, G.C. Dadol, L.M. Jabile, I.N. Talili, M.T.I. Cabaraban, "A review of desalination technologies and its impact in the Philippines," (in English), *Desalination* 534 (Jul 15 2022) doi:ARTN 115805 10.1016/j.desal.2022.115805.
- [55] N.A.T. Tran, T.M. Khoi, N.M. Phuoc, H. Bin Jung, Y.H. Cho, "A review of recent advances in electrode materials and applications for flow-electrode desalination systems," (in English), *Desalination* 541 (Nov 1 2022) doi:ARTN 116037 10.1016/j.desal.2022.116037.
- [56] A.S. Jatoti, et al., "A comprehensive review of microbial desalination cells for present and future challenges," (in English), *Desalination* 535 (Aug 1 2022) doi:ARTN 115808 10.1016/j.desal.2022.115808.
- [57] H.M. Ashraf, S.A. Al-Sobhi, M.H. El-Naas, "Mapping the desalination journal: A systematic bibliometric study over 54 years," (in English), *Desalination* 526 (Mar 15 2022) doi:ARTN 115535 10.1016/j.desal.2021.115535.
- [58] N. Sreedhar, N. Thomas, N. Ghaffour, H.A. Arafat, "The evolution of feed spacer role in membrane applications for desalination and water treatment: A critical review and future perspective," (in English), *Desalination* 554 (May 15 2023) doi:ARTN 116505 10.1016/j.desal.2023.116505.
- [59] Z.U. Khan, et al., "Electro-deionization (EDI) technology for enhanced water treatment and desalination: A review," (in English), *Desalination* 548 (Feb 15 2023) doi:ARTN 116254 10.1016/j.desal.2022.116254.

- [60] A. Raza, J.Z. Hassan, A. Mahmood, W. Nabgan, M. Ikram, "Recent advances in membrane-enabled water desalination by 2D frameworks: graphene and beyond," (in English), *Desalination* 531 (Jun 1 2022) doi:ARTN 115684 10.1016/j.desal.2022.115684.
- [61] A.W. Jeevadason, S. Padmini, C. Bharatiraja, A.E. Kabeel, "A review on diverse combinations and Energy-Exergy-Economics (3E) of hybrid solar still desalination," (in English), *Desalination* 527 (Apr 1 2022) doi:ARTN 115587 10.1016/j.desal.2022.115587.
- [62] J. Ma, C.X. Zhai, F. Yu, "Review of flow electrode capacitive deionization technology: research progress and future challenges," (in English), *Desalination* 564 (Oct 15 2023) doi:ARTN 116701 10.1016/j.desal.2023.116701.
- [63] A.M. Hamiche, A.B. Stambouli, S. Flazi, "A review of the water-energy nexus," (in English), *Renew. Sustain. Energy Rev.* 65 (Nov 2016) 319–331, <https://doi.org/10.1016/j.rser.2016.07.020>.
- [64] L. Dale, et al., "An integrated assessment of water-energy and climate change in Sacramento, California: how strong is the nexus?," (in English), *Clim. Change* 132 (2) (Sep 2015) 223–235, <https://doi.org/10.1007/s10584-015-1370-x>.
- [65] S.A. Kalogirou, "Seawater desalination using renewable energy sources," (in English), *Prog. Energ. Combust.* 31 (3) (2005) 242–281, <https://doi.org/10.1016/j.peccs.2005.03.001>.
- [66] A. Hanafi, "Desalination using renewable energy-sources," (in English), *Desalination* 97 (1–3) (Aug 1994) 339–352, [https://doi.org/10.1016/0011-9164\(94\)00098-0](https://doi.org/10.1016/0011-9164(94)00098-0).
- [67] D. Mentis, et al., "Desalination using renewable energy sources on the arid islands of South Aegean Sea," (in English), *Energy* 94 (Jan 1 2016) 262–272, <https://doi.org/10.1016/j.energy.2015.11.003>.
- [68] M. Goosen, H. Mahmoudi, N. Ghaffour, "Water desalination using geothermal energy," (in English), *Energies* 3 (8) (Aug 2010) 1423–1442, <https://doi.org/10.3390/en3081423>.
- [69] T. Woto, Experience with Small-Scale Desalinators for Remote Area Dwellers of the Kalahari Botswana, 1987.
- [70] B. Naghdj, et al., "Salt precipitation challenge in floating interfacial solar water desalination systems," (in English), *Desalination* 565 (Nov 1 2023) doi:ARTN 116868 10.1016/j.desal.2023.116868.
- [71] M.M. Zubair, H. Saleem, S.J. Zaidi, "Recent progress in reverse osmosis modeling: an overview," (in English), *Desalination* 564 (Oct 15 2023) doi:ARTN 116705 10.1016/j.desal.2023.116705.
- [72] W.L. Bai, et al., "Quantifying and reducing concentration polarization in reverse osmosis systems," (in English), *Desalination* 554 (May 15 2023) doi:ARTN 116480 10.1016/j.desal.2023.116480.
- [73] L.X. Li, J.H. Dong, T.M. Nenoff, R. Lee, "Reverse osmosis of ionic aqueous solutions on a MFI zeolite membrane," (in English), *Desalination* 170 (3) (Nov 5 2004) 309–316, <https://doi.org/10.1016/j.desal.2004.02.102>.
- [74] L.X. Li, J.H. Dong, T.M. Nenoff, R. Lee, "Desalination by reverse osmosis using MFI zeolite membranes," (in English), *J. Membr. Sci.* 243 (1–2) (Nov 1 2004) 401–404, <https://doi.org/10.1016/j.memsci.2004.06.045>.
- [75] M. Kazemimoghadam, T. Mohammadi, "Synthesis of MFI zeolite membranes for water desalination," (in English), *Desalination* 206 (1–3) (Feb 5 2007) 547–553, <https://doi.org/10.1016/j.desal.2006.04.063>.
- [76] A. Garofalo, et al., Scale-up of MFI zeolite membranes for desalination by vacuum membrane distillation, *Desalination* 397 (2016) 205–212.
- [77] H. Elfil, A. Hamed, A. Hannachi, "Technical evaluation of a small-scale reverse osmosis desalination unit for domestic water," (in English), *Desalination* 203 (1–3) (Feb 5 2007) 319–326, <https://doi.org/10.1016/j.desal.2006.03.530>.
- [78] E.S. Mohamed, G. Papadakis, E. Mathioulakis, V. Belessiotis, "The effect of hydraulic energy recovery in a small sea water reverse osmosis desalination system: experimental and economical evaluation," (in English), *Desalination* 184 (1–3) (Nov 1 2005) 241–246, <https://doi.org/10.1016/j.desal.2005.02.066>.
- [79] I. Katz, C.G. Dosoretz, "Desalination of domestic wastewater effluents: phosphate removal as pretreatment," (in English), *Desalination* 222 (1–3) (Mar 1 2008) 230–242, <https://doi.org/10.1016/j.desal.2007.01.160>.
- [80] Y. Cohen, UCLA develops 'smart'water desalination system, *Membr. Technol.* 2009 (11) (2009) 8.
- [81] L.X. Gao, A. Rahardianto, H. Gu, P.D. Christofides, Y. Cohen, "Novel design and operational control of integrated ultrafiltration - reverse osmosis system with RO concentrate backwash," (in English), *Desalination* 382 (Mar 15 2016) 43–52, <https://doi.org/10.1016/j.desal.2015.12.022>.
- [82] Q.Y. Li, et al., "development of a mobile groundwater desalination system for communities in rural India," (in English), *Water Res.* 144 (Nov 1 2018) 642–655, <https://doi.org/10.1016/j.watres.2018.08.001>.
- [83] T. Lee, A. Rahardianto, Y. Cohen, "Flexible reverse osmosis (FLERO) desalination," (in English), *Desalination* 452 (Feb 15 2019) 123–131, <https://doi.org/10.1016/j.desal.2018.10.022>.
- [84] T. Lee, A. Rahardianto, Y. Cohen, "Multi-cycle operation of semi-batch reverse osmosis (SBRO) desalination," (in English), *J. Membr. Sci.* 588 (Oct 15 2019) doi:ARTN 117090 10.1016/j.memsci.2019.05.015.
- [85] J.Y. Choi, et al., "On the feasibility of small communities wellhead RO treatment for nitrate removal and salinity reduction," (in English), *J. Environ. Manage.* 250 (Nov 15 2019) doi:ARTN 109487 10.1016/j.jenvman.2019.109487.
- [86] K. Walha, R. Ben Amar, L. Firdaus, F. Quemeneure, P. Jaouen, "Brackish groundwater treatment by nanofiltration, reverse osmosis and electrodialysis in Tunisia: performance and cost comparison," (in English), *Desalination* 207 (1–3) (Mar 10 2007) 95–106, <https://doi.org/10.1016/j.desal.2006.03.583>.
- [87] S. Thampy, G.R. Desale, V.K. Shahi, B.S. Makwana, P.K. Ghosh, "development of hybrid electrodialysis-reverse osmosis domestic desalination unit for high recovery of product water," (in English), *Desalination* 282 (Nov 1 2011) 104–108, <https://doi.org/10.1016/j.desal.2011.08.060>.
- [88] T.M. Mansour, T.M. Ismail, K. Ramzy, M. Abd El-Salam, "Energy recovery system in small reverse osmosis desalination plant: experimental and theoretical investigations," (in English), *Alex Eng. J.* 59 (5) (Oct 2020) 3741–3753, <https://doi.org/10.1016/j.aej.2020.06.030>.
- [89] D.W. Song, et al., "Performance investigation and evaluation of a new three-piston pump energy recovery device for small scale desalination system," (in English), *Energy. Convers. Manage.* 260 (May 15 2022) doi:ARTN 115576 10.1016/j.enconman.2022.115576.
- [90] S. Al-Amshawee, M.Y.B. Yunus, A.A.M. Azoddein, D.G. Hassell, I.H. Dakhil, H. Abu Hasan, "Electrodialysis desalination for water and wastewater: a review," (in English), *Chem. Eng. J.* 380 (Jan 15 2020) doi:ARTN 122231 10.1016/j.cej.2019.122231.
- [91] V.K. Shahi, B.S. Makwana, S.K. Thampy, R. Rangarajan, "A novel electrodialyzer for the production of demineralized water by electrodialysis," (in English), *Desalination* 151 (1) (Jan 2 2003) 33–42, [https://doi.org/10.1016/S0011-9164\(02\)00970-0](https://doi.org/10.1016/S0011-9164(02)00970-0), doi:Pii S0011-9164(02)00970-0.
- [92] T. Sirivedhin, J. McCue, L. Dallbauman, "Reclaiming produced water for beneficial use: salt removal by electrodialysis," (in English), *J. Membr. Sci.* 243 (1–2) (Nov 1 2004) 335–343, <https://doi.org/10.1016/j.memsci.2004.06.038>.
- [93] M. Sedighi, M.M.B. Usefi, A.F. Ismail, M. Ghasemi, "Environmental sustainability and ions removal through electrodialysis desalination: Operating conditions and process parameters," (in English), *Desalination* 549 (Mar 1 2023) doi:ARTN 116319 10.1016/j.desal.2022.116319.
- [94] R. Mohammadi, W. Tang, M. Sillanpaa, "A systematic review and statistical analysis of nutrient recovery from municipal wastewater by electrodialysis," (in English), *Desalination* 498 (Jan 15 2021) doi:ARTN 114626 10.1016/j.desal.2020.114626.
- [95] S.R. Shah, N.C. Wright, P.A. Nepsky, A.G. Winter, "Cost-optimal design of a batch electrodialysis system for domestic desalination of brackish groundwater," (in English), *Desalination* 443 (Oct 1 2018) 198–211, <https://doi.org/10.1016/j.desal.2018.05.010>.
- [96] K.G. Nayar, et al., "Feasibility study of an electrodialysis system for in-home water desalination and purification in urban india," (in English), in: *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2015 Vol 2a, 2016 [Online]. Available: <https://doi.org/10.1016/j.procs.2016.03.004>.
- [97] B. Pilat, "Practice of water desalination by electrodialysis," (in English), *Desalination* 139 (1–3) (Sep 20 2001) 385–392, [https://doi.org/10.1016/S0011-9164\(01\)00338-1](https://doi.org/10.1016/S0011-9164(01)00338-1).
- [98] B. Pilat, "Water of high quality for household conditions," (in English), *Desalination* 153 (1–3) (Feb 10 2003) 405–407, [https://doi.org/10.1016/S0011-9164\(02\)01135-9](https://doi.org/10.1016/S0011-9164(02)01135-9), doi:Pii S0011-9164(02)01135-9.
- [99] J.M. Ortiz, et al., "Brackish water desalination by electrodialysis: batch recirculation operation modeling," (in English), *J. Membr. Sci.* 252 (1–2) (Apr 15 2005) 65–75, <https://doi.org/10.1016/j.memsci.2004.11.021>.
- [100] L.J. Banasiak, T.W. Kruttschnitt, A.I. Schafer, "Desalination using electrodialysis as a function of voltage and salt concentration," (in English), *Desalination* 205 (1–3) (Feb 5 2007) 38–46, <https://doi.org/10.1016/j.desal.2006.04.038>.
- [101] M. Sadrzadeh, T. Mohammadi, "Sea water desalination using electrodialysis," (in English), *Desalination* 221 (1–3) (Mar 1 2008) 440–447, <https://doi.org/10.1016/j.desal.2007.01.103>.
- [102] L.J. Banasiak, A.I. Schafer, "Removal of inorganic trace contaminants by electrodialysis in a remote Australian community," (in English), *Desalination* 248 (1–3) (Nov 15 2009) 48–57, <https://doi.org/10.1016/j.desal.2008.05.037>.
- [103] J.C. Farmer, D.V. Fix, G.V. Mack, R.W. Pekala, J.F. Poco, "Capacitive deionization of NH<sub>4</sub>ClO<sub>4</sub> solutions with carbon aerogel electrodes," (in English), *J. Appl. Electrochem.* 26 (10) (Oct 1996) 1007–1018 [Online]. Available: <https://doi.org/10.1016/j.jelechem.2006.03.003>.
- [104] K.T. McSweeney, D. Morris, B. Rettle, S.E. Kelley, Capacitive Deionization of NH<sub>4</sub>ClO<sub>4</sub> Solutions with Carbon Aerogel Electrodes, Lawrence Livermore National Lab Ca Chemistry and Materials Science Dept, 1996.
- [105] A. Thamilselvan, A.S. Nesaraj, M. Noel, "Review on carbon-based electrode materials for application in capacitive deionization process," (in English), *Int. J. Environ Sci Technol.* 13 (12) (Dec 2016) 2961–2976, <https://doi.org/10.1007/s13762-016-1061-9>.
- [106] Q. Liu, J. Liu, Z. Wang, K.Z. Huang, Progress in study of electrode materials and application on capacitive deionization, in: *Letter from the Editor* 104, 2015.
- [107] Y. Oren, Capacitive deionization (CDI) for desalination and water treatment—past, present and future (a review), *Desalination* 228 (1–3) (2008) 10–29.
- [108] S. Porada, R. Zhao, A. van der Wal, V. Presser, P.M. Biesheuvel, "Review on the science and technology of water desalination by capacitive deionization," (in English), *Prog. Mater. Sci.* 58 (8) (Oct 2013) 1388–1442, <https://doi.org/10.1016/j.pmatsci.2013.03.005>.
- [109] L. Wang, et al., "Capacitive deionization of NaCl solutions using carbon nanotube sponge electrodes," (in English), *J. Mater. Chem.* 21 (45) (2011) 18295–18299, <https://doi.org/10.1039/c1jm13105b>.
- [110] S. Porada, et al., "Water desalination using capacitive deionization with microporous carbon electrodes," (in English), *ACS Appl. Mater. Inter.* 4 (3) (Mar 2012) 1194–1199, <https://doi.org/10.1021/am201683j>.
- [111] P. Liang, L.L. Yuan, X.F. Yang, S.J. Zhou, X. Huang, "Coupling ion-exchangers with inexpensive activated carbon fiber electrodes to enhance the performance of capacitive deionization cells for domestic wastewater desalination," (in English),

- Water Res. 47 (7) (May 1 2013) 2523–2530, <https://doi.org/10.1016/j.watres.2013.02.037>.
- [112] C. Tsouris, et al., "Mesoporous carbon for capacitive deionization of saline water," (in English), *Environ. Sci. Technol.* 45 (23) (Dec 1 2011) 10243–10249, <https://doi.org/10.1021/es201551e>.
- [113] L.M. Chang, X.Y. Duan, W. Liu, "Preparation and electrosorption desalination performance of activated carbon electrode with titania," (in English), *Desalination* 270 (1–3) (Apr 1 2011) 285–290, <https://doi.org/10.1016/j.desal.2011.01.008>.
- [114] M. Haro, G. Rasines, C. Macias, C.O. Ania, "Stability of a carbon gel electrode when used for the electro-assisted removal of ions from brackish water," (in English), *Carbon* 49 (12) (Oct 2011) 3723–3730, <https://doi.org/10.1016/j.carbon.2011.05.001>.
- [115] H.H. Jung, S.W. Hwang, S.H. Hyun, L. Kang-Ho, G.T. Kim, "Capacitive deionization characteristics of nanostructured carbon aerogel electrodes synthesized via ambient drying," (in English), *Desalination* 216 (1–3) (Oct 5 2007) 377–385, <https://doi.org/10.1016/j.desal.2006.11.023>.
- [116] M.S. Lee, C.S. Fan, Y.W. Chen, K.C. Chang, P.T. Chiueh, C.H. Hou, "Membrane capacitive deionization for low-salinity desalination in the reclamation of domestic wastewater effluents," (in English), *Chemosphere* 235 (Nov 2019) 413–422, <https://doi.org/10.1016/j.chemosphere.2019.06.190>.
- [117] Metcalf, et al., *Wastewater Engineering: Treatment and Resource Recovery*, McGraw Hill Education, 2014.
- [118] J.C. Farmer, et al., "Electrosorption of chromium ions on carbon aerogel electrodes as a means of remediating ground water," (in English), *Energy Fuel* 11 (2) (Mar-Apr 1997) 337–347, <https://doi.org/10.1021/ef9601374>.
- [119] T. Welgemoed, C.F. Schutte, *Capacitive deionization technologyTM: an alternative desalination solution*, *Desalination* 183 (1–3) (2005) 327–340.
- [120] E. Garcia-Quismondo, C. Santos, J. Palma, M.A. Anderson, "On the challenge of developing wastewater treatment processes: capacitive deionization," (in English), *Desalin. Water Treat.* 57 (5) (Jan 26 2016) 2315–2324, <https://doi.org/10.1080/19443994.2014.984929>.
- [121] T.H. Yu, H.Y. Shiu, M. Lee, P.T. Chiueh, C.H. Hou, "Life cycle assessment of environmental impacts and energy demand for capacitive deionization technology," (in English), *Desalination* 399 (Dec 1 2016) 53–60, <https://doi.org/10.1016/j.desal.2016.08.007>.
- [122] P. Dlugolecki, A. van der Wal, "Energy recovery in membrane capacitive deionization," (in English), *Environ. Sci. Technol.* 47 (9) (May 7 2013) 4904–4910, <https://doi.org/10.1021/es3053202>.
- [123] Y.S. Li, et al., "Desalination by membrane pervaporation: a review," (in English), *Desalination* 547 (Feb 1 2023) doi:ARTN 116223 10.1016/j.desal.2022.116223.
- [124] N.A. Shahrim, N.M. Abounahia, A.M.A. El-Sayed, H. Saleem, S.J. Zaidi, "An overview on the progress in produced water desalination by membrane-based technology," (in English), *J. Water Process. Eng.* 51 (Feb 2023) doi:ARTN 103479 10.1016/j.jwpe.2022.103479.
- [125] P. Behnam, A. Shafieian, M. Zargar, M. Khiadani, "Development of machine learning and stepwise mechanistic models for performance prediction of direct contact membrane distillation module- a comparative study," (in English), *Chem. Eng. Process.* 173 (Mar 2022) doi:ARTN 108857 10.1016/j.ccep.2022.108857.
- [126] K. Ali, A.A. Alwan, S. Bahayan, E. Alhseinat, M.I.H. Ali, "A numerical analysis of the electromagnetic field effect on direct contact membrane distillation performance," (in English), *Energy Convers. Manag.* 292 (Sep 15 2023) doi:ARTN 117328 10.1016/j.enconman.2023.117328.
- [127] M.A. Azeem, D.U. Lawal, H. Al Abdulgader, T.N. Baroud, "Enhanced performance of superhydrophobic polyvinylidene fluoride membrane with sandpaper texture for highly saline water desalination in air-gap membrane distillation," (in English), *Desalination* 528 (Apr 15 2022) doi:ARTN 115603 10.1016/j.desal.2022.115603.
- [128] M.A. Abu-Zeid, Y.Q. Zhang, H. Dong, L. Zhang, H.L. Chen, L. Hou, "A comprehensive review of vacuum membrane distillation technique," (in English), *Desalination* 356 (Jan 15 2015) 1–14, <https://doi.org/10.1016/j.desal.2014.10.033>.
- [129] Z. Li, et al., "An experimental study on recovering and concentrating ammonia by sweep gas membrane distillation," (in English), *Process. Saf. Environ.* 171 (Mar 2023) 555–560, <https://doi.org/10.1016/j.psep.2023.01.053>.
- [130] H. Chamani, J. Woloszyn, T. Matsuura, D. Rana, C.Q. Lan, "Pore wetting in membrane distillation: a comprehensive review," (in English), *Prog. Mater. Sci.* 122 (Oct 2021) doi:ARTN 100843 10.1016/j.pmatsci.2021.100843.
- [131] A. Alkhudhiri, N. Darwish, N. Hilal, "Membrane distillation: a comprehensive review," (in English), *Desalination* 287 (Feb 15 2012) 2–18, <https://doi.org/10.1016/j.desal.2011.08.027>.
- [132] A.F.S. Foureux, V.R. Moreira, Y.A.R. Lebron, L.V.S. Santos, M.C.S. Amaral, "Direct contact membrane distillation as an alternative to the conventional methods for value-added compounds recovery from acidic effluents: a review," (in English), *Sep. Purif. Technol.* 236 (Apr 1 2020) doi:ARTN 116251 10.1016/j.seppur.2019.116251.
- [133] A. Samadi, T.L. Ni, E. Fontananova, G. Tang, H. Shon, S.F. Zhao, "Engineering antiwetting hydrophobic surfaces for membrane distillation: a review," (in English), *Desalination* 563 (Oct 1 2023) doi:ARTN 116722 10.1016/j.desal.2023.116722.
- [134] M.R. Elmarghany, A.H. El-Shazly, M.S. Salem, M.N. Sabry, N. Nady, "Thermal analysis evaluation of direct contact membrane distillation system," (in English), *Case Stud. Therm. Eng.* 13 (Mar 2019) doi:ARTN 100377 10.1016/j.csite.2018.100377.
- [135] K. Zhao, et al., "Experimental study of the memsys vacuum-multi-effect-membrane-distillation (V-MEMD) module," (in English), *Desalination* 323 (Aug 15 2013) 150–160, <https://doi.org/10.1016/j.desal.2012.12.003>.
- [136] A. Criscuoli, P. Bafaro, E. Drioli, "Vacuum membrane distillation for purifying waters containing arsenic," (in English), *Desalination* 323 (Aug 15 2013) 17–21, <https://doi.org/10.1016/j.desal.2012.08.004>.
- [137] A. Criscuoli, M.C. Carnevale, E. Drioli, "Modeling the performance of flat and capillary membrane modules in vacuum membrane distillation," (in English), *J. Membr. Sci.* 447 (Nov 15 2013) 369–375, <https://doi.org/10.1016/j.memsci.2013.07.044>.
- [138] G. Naidu, Y. Choi, S. Jeong, T.M. Hwang, S. Vigneswaran, "Experiments and modeling of a vacuum membrane distillation for high saline water," (in English), *J. Ind. Eng. Chem.* 20 (4) (Jul 25 2014) 2174–2183, <https://doi.org/10.1016/j.jiec.2013.09.048>.
- [139] E.S. Mohamed, P. Boutikos, E. Mathioulakis, V. Belessiotis, "Experimental evaluation of the performance and energy efficiency of a vacuum multi-effect membrane distillation system," (in English), *Desalination* 408 (Apr 15 2017) 70–80, <https://doi.org/10.1016/j.desal.2016.12.020>.
- [140] X.X. Jia, et al., "Pilot-scale vacuum membrane distillation for decontamination of simulated radioactive wastewater: System design and performance evaluation," (in English), *Sep. Purif. Technol.* 275 (Nov 15 2021) doi:ARTN 119129 10.1016/j.seppur.2021.119129.
- [141] M.B. Elsheniti, A. Ibrahim, O. Elsamni, M. Elewa, "Experimental and economic investigation of sweeping gas membrane distillation/pervaporation modules using novel pilot scale device," (in English), *Sep. Purif. Technol.* 310 (Apr 1 2023) doi:ARTN 123165 10.1016/j.seppur.2023.123165.
- [142] L.M. Song, Z.D. Ma, X.H. Liao, P.B. Kosaraju, J.R. Irish, K.K. Sirkar, "Pilot plant studies of novel membranes and devices for direct contact membrane distillation-based desalination," (in English), *J. Membr. Sci.* 323 (2) (Oct 15 2008) 257–270, <https://doi.org/10.1016/j.memsci.2008.05.079>.
- [143] H.C. Duong, P. Cooper, B. Nelemans, T.Y. Cath, L.D. Nghiem, "Optimising thermal efficiency of direct contact membrane distillation by brine recycling for small-scale seawater desalination," (in English), *Desalination* 374 (Oct 15 2015) 1–9, <https://doi.org/10.1016/j.desal.2015.07.009>.
- [144] A. Mabrouk, Y. Elhenawy, G. Moustafa, "Experimental evaluation of corrugated feed channel of direct contact membrane distillation," *J. Membr. Sci. Technol.* 6 (151) (2016) 2.
- [145] D. Woldemariam, A. Kullab, U. Fortkamp, J. Magner, H. Royen, A. Martin, "Membrane distillation pilot plant trials with pharmaceutical residues and energy demand analysis," (in English), *Chem. Eng. J.* 306 (Dec 15 2016) 471–483, <https://doi.org/10.1016/j.ccej.2016.07.082>.
- [146] A.E. Khalifa, S.M. Alawad, "Air gap and water gap multistage membrane distillation for water desalination," (in English), *Desalination* 437 (Jul 1 2018) 175–183, <https://doi.org/10.1016/j.desal.2018.03.012>.
- [147] C.K. Lee, C. Park, Y.C. Woo, J.S. Choi, J.O. Kim, "A pilot study of spiral-wound air gap membrane distillation process and its energy efficiency analysis," (in English), *Chemosphere* 239 (Jan 2020) doi:ARTN 124696 10.1016/j.chemosphere.2019.124696.
- [148] R. Pawar, Z. Zhang, R.D. Vidic, "Laboratory and pilot-scale studies of membrane distillation for desalination of produced water from Permian Basin," (in English), *Desalination* 537 (Sep 1 2022) doi:ARTN 115853 10.1016/j.desal.2022.115853.
- [149] E. Korngold, E. Korin, I. Ladizhensky, "Water desalination by pervaporation with hollow fiber membranes," (in English), *Desalination* 107 (2) (Oct 1996) 121–129, [https://doi.org/10.1016/S0011-9164\(96\)00157-9](https://doi.org/10.1016/S0011-9164(96)00157-9).
- [150] S.M. Soufari, M. Zamen, M. Amidpour, "Performance optimization of the humidification-dehumidification desalination process using mathematical programming," (in English), *Desalination* 237 (1–3) (Feb 2009) 305–317, <https://doi.org/10.1016/j.desal.2008.01.024>.
- [151] J.A. Miller, J.H. Lienhard, "Impact of extraction on a humidification-dehumidification desalination system," (in English), *Desalination* 313 (Mar 15 2013) 87–96, <https://doi.org/10.1016/j.desal.2012.12.005>.
- [152] S.A. El-Abouz, M. Abugderah, "Experimental analysis of humidification process by air passing through seawater," (in English), *Energy Convers. Manag.* 49 (12) (Dec 2008) 3698–3703, <https://doi.org/10.1016/j.enconman.2008.06.033>.
- [153] K.H. Mistry, A. Mitsos, J.H. Lienhard, "Optimal operating conditions and configurations for humidification-dehumidification desalination cycles," (in English), *Int. J. Therm. Sci.* 50 (5) (May 2011) 779–789, <https://doi.org/10.1016/j.ijthermalsci.2010.12.013>.
- [154] M. Mehrgoo, M. Amidpour, "Constructal design of humidification-dehumidification desalination unit architecture," (in English), *Desalination* 271 (1–3) (Apr 15 2011) 62–71, <https://doi.org/10.1016/j.desal.2010.12.011>.
- [155] H. Xu, S. Jiang, M.X. Xie, T. Jia, Y.J. Dai, "Technical improvements and perspectives on humidification-dehumidification desalination - a review," (in English), *Desalination* 541 (Nov 1 2022), <https://doi.org/10.1016/j.desal.2022.116029>.
- [156] P. Behnam, M. Faegh, I. Fakhari, P. Ahmadi, E. Faegh, M.A. Rosen, et al., *J. Therm. Eng.* 8 (1) (Jan 2022) 52–66, <https://doi.org/10.18186/thermal.1067015>.
- [157] M. Faegh, P. Behnam, M.B. Shafii, M. Khiadani, "Development of artificial neural networks for performance prediction of a heat pump assisted humidification-dehumidification desalination system," (in English), *Desalination* 508 (Jul 15 2021) doi:ARTN 115052 10.1016/j.desal.2021.115052.
- [158] A. Eslamianesh, M.S. Hatamipour, "Economic study of a small-scale direct contact humidification-dehumidification desalination plant," (in English), *Desalination* 250 (1) (Jan 1 2010) 203–207, <https://doi.org/10.1016/j.desal.2008.11.015>.

- [159] E.H. Amer, H. Kotb, G.H. Mostafa, A.R. El-Ghalban, "Theoretical and experimental investigation of humidification-dehumidification desalination unit," (in English), *Desalination* 249 (3) (Dec 25 2009) 949–959, <https://doi.org/10.1016/j.desal.2009.06.063>.
- [160] S.A. El-Agouz, "Desalination based on humidification-dehumidification by air bubbles passing through brackish water," (in English), *Chem. Eng. J.* 165 (2) (Dec 1 2010) 413–419, <https://doi.org/10.1016/j.cej.2010.09.008>.
- [161] G.P. Narayan, M.G. St John, S.M. Zubair, V.J.H. Lienhard, "Thermal design of the humidification dehumidification desalination system: an experimental investigation," (in English), *Int. J. Heat Mass Transf.* 58 (1–2) (Mar 2013) 740–748, <https://doi.org/10.1016/j.jheatmasstransfer.2012.11.035>.
- [162] M.H. Sharqawy, M.A. Antar, S.M. Zubair, A.M. Elbasher, "Optimum thermal design of humidification dehumidification desalination systems," (in English), *Desalination* 349 (Sep 15 2014) 10–21, <https://doi.org/10.1016/j.desal.2014.06.016>.
- [163] M.H. Sharqawy, I. Al-Shalawi, M.A. Antar, S.M. Zubair, "Experimental investigation of packed-bed cross-flow humidifier," (in English), *Appl. Therm. Eng.* 117 (May 5 2017) 584–590, <https://doi.org/10.1016/j.applthermaleng.2017.02.061>.
- [164] S.H. Soomro, R. Santosh, C.U. Bak, C.H. Yoo, W.S. Kim, Y.D. Kim, "Effect of humidifier characteristics on performance of a small-scale humidification-dehumidification desalination system," (in English), *Appl. Therm. Eng.* 210 (Jun 25 2022) doi:ARTN 118400 10.1016/j.applthermaleng.2022.118400.
- [165] E.W. Tow, J.H. Lienhard, "Experiments and modeling of bubble column dehumidifier performance," (in English), *Int. J. Therm. Sci.* 80 (Jun 2014) 65–75, <https://doi.org/10.1016/j.jthermalsci.2014.01.018>.
- [166] M. Khan, M.A. Antar, A.E. Khalifa, S.M. Zubair, "Experimental investigation of air heated bubble column humidification dehumidification desalination system," (in English), *Int. J. Energy Res.* 45 (2) (Feb 2021) 2610–2628, <https://doi.org/10.1002/er.5951>.
- [167] H. Kariman, S. Hoseinzadeh, A. Shirkhani, P.S. Heyns, J. Wannenburger, "Energy and economic analysis of evaporative vacuum easy desalination system with brine tank," (in English), *J. Therm. Anal. Calorim.* 140 (4) (May 2020) 1935–1944, <https://doi.org/10.1007/s10973-019-08945-8>.
- [168] S. Aly, H. Manzoor, S. Simson, A. Abotaleb, J. Lawler, A.N. Mabrouk, "Pilot testing of a novel Multi Effect Distillation (MED) technology for seawater desalination," (in English), *Desalination* 519 (Dec 1 2021) doi:ARTN 115221 10.1016/j.desal.2021.115221.
- [169] H.S. Son, M.W. Shahzad, N. Ghaffour, K.C. Ng, "Pilot studies on synergetic impacts of energy utilization in hybrid desalination system: multi-effect distillation and adsorption cycle (MED-AD)," (in English), *Desalination* 477 (Mar 1 2020) doi:ARTN 114266 10.1016/j.desal.2019.114266.
- [170] F. Hesari, F. Salimnezhad, M.H.K. Manesh, M.R. Morad, "A novel configuration for low-grade heat-driven desalination based on cascade MED," (in English), *Energy* 229 (Aug 15 2021) doi:ARTN 120657 10.1016/j.energy.2021.120657.
- [171] F. Kafi, V. Renaudin, D. Alonso, J.M. Hornut, "New MED plate desalination process: thermal performances," (in English), *Desalination* 166 (1–3) (Aug 15 2004) 53–62, <https://doi.org/10.1016/j.desal.2004.06.058>.
- [172] V. Renaudin, F. Kafi, D. Alonso, A. Andreoli, "Performances of a three-effect plate desalination process," (in English), *Desalination* 182 (1–3) (Nov 1 2005) 165–173, <https://doi.org/10.1016/j.desal.2005.03.017>.
- [173] H. Kariman, S. Hoseinzadeh, S. Heyns, A. Sohani, "Modeling and exergy analysis of domestic MED desalination with brine tank," (in English), *Desalin. Water Treat.* 197 (Sep 2020) 1–13, <https://doi.org/10.5004/dwt.2020.26105>.
- [174] H. Kariman, S. Hoseinzadeh, P.S. Heyns, "Energetic and exergetic analysis of evaporation desalination system integrated with mechanical vapor recompression circulation," (in English), *Case Stud. Therm. Eng.* 16 (Dec 2019) doi:ARTN 100548 10.1016/j.csite.2019.100548.
- [175] B.M. Karambati, M. Ghodrati, G. Ghorbani, A. Lalbakhsh, M. Behnia, "Design methodology and multi-objective optimization of small-scale power-water production based on integration of Stirling engine and multi-effect evaporation desalination system," (in English), *Desalination* 526 (Mar 15 2022) doi:ARTN 115542 10.1016/j.desal.2021.115542.
- [176] S. Aly, J. Jawad, H. Manzoor, S. Simson, J. Lawler, A.N. Mabrouk, "Pilot testing of a novel integrated Multi Effect Distillation-Absorber compressor (MED-AB) technology for high performance seawater desalination," (in English), *Desalination* 521 (Jan 1 2022) doi:ARTN 115388 10.1016/j.desal.2021.115388.
- [177] S. Lattemann, T. Hopner, "Environmental impact and impact assessment of seawater desalination," (in English), *Desalination* 220 (1–3) (Mar 1 2008) 1–15, <https://doi.org/10.1016/j.desal.2007.03.009>.
- [178] D. Voivontas, K. Misirlis, E. Manoli, G. Arampatzis, D. Assimacopoulos, A. Zervos, "A tool for the design of desalination plants powered by renewable energies," (in English), *Desalination* 133 (2) (Mar 10 2001) 175–198, [https://doi.org/10.1016/S0011-9164\(01\)00096-0](https://doi.org/10.1016/S0011-9164(01)00096-0).
- [179] U. Seibert, G. Vogt, C. Brenning, R. Gebhard, F. Holz, "Autonomous desalination system concepts for seawater and brackish water in rural areas with renewable energies - potentials, technologies, field experience, socio-technical and socio-economic impacts - ADIRA," (in English), *Desalination* 168 (Aug 15 2004) 29–37, <https://doi.org/10.1016/j.desal.2004.06.166>.
- [180] A.M. Bilton, L.C. Kelley, S. Dubowsky, "Photovoltaic reverse osmosis - feasibility and a pathway to develop technology," (in English), *Desalin. Water Treat.* 31 (1–3) (Jul 2011) 24–34, <https://doi.org/10.5004/dwt.2011.2398>.
- [181] D. Herold, V. Horstmann, A. Neskakis, J. Plettner-Marliani, G. Piernavieja, R. Calero, "Small scale photovoltaic desalination for rural water supply - demonstration plant in Gran Canaria," (in English), *Renew. Energy* 14 (1–4) (May–Aug 1998) 293–298, [https://doi.org/10.1016/S0960-1481\(98\)00080-9](https://doi.org/10.1016/S0960-1481(98)00080-9).
- [182] E. Tzen, K. Perrakis, P. Baltas, "Design of a stand alone PV - desalination system for rural areas," (in English), *Desalination* 119 (1–3) (Sep 20 1998) 327–333, [https://doi.org/10.1016/S0011-9164\(98\)00177-5](https://doi.org/10.1016/S0011-9164(98)00177-5).
- [183] D. Herold, A. Neskakis, "A small PV-driven reverse osmosis desalination plant on the island of Gran Canaria," (in English), *Desalination* 137 (1–3) (May 1 2001) 285–292, [https://doi.org/10.1016/S0011-9164\(01\)00230-2](https://doi.org/10.1016/S0011-9164(01)00230-2).
- [184] Z. Al Suleimani, V.R. Nair, "Desalination by solar-powered reverse osmosis in a remote area of the Sultanate of Oman," (in English), *Appl. Energy* 65 (1–4) (Jan–Apr 2000) 367–380, [https://doi.org/10.1016/S0306-2619\(99\)00100-2](https://doi.org/10.1016/S0306-2619(99)00100-2).
- [185] A. Joyce, D. Loureiro, C. Rodrigues, S. Castro, "Small reverse osmosis units using PV systems for water purification in rural places," (in English), *Desalination* 137 (1–3) (May 1 2001) 39–44, [https://doi.org/10.1016/S0011-9164\(01\)00202-8](https://doi.org/10.1016/S0011-9164(01)00202-8).
- [186] G.E. Ahmad, J. Schmid, "Feasibility study of brackish water desalination in the Egyptian deserts and rural regions using PV systems," (in English), *Energy Convers. Manag.* 43 (18) (Dec 2002) 2641–2649, doi:Pii S0196-8904(01)00189-3 10.1016/S0196-8904(01)00189-3.
- [187] M. Thomson, D. Infield, "A photovoltaic-powered seawater reverse-osmosis system without batteries," (in English), *Desalination* 153 (1–3) (Feb 10 2003) 1–8, doi:Pii S0011-9164(02)01087-1 10.1016/S0011-9164(03)80004-8.
- [188] B.S. Richards, A.I. Schafer, "Design considerations for a solar-powered desalination system for remote communities in Australia," (in English), *Desalination* 144 (1–3) (Sep 10 2002) 193–199, doi:Pii S0011-9164(02)00311-9 10.1016/S0011-9164(02)00311-9.
- [189] M. Thomson, M.S. Miranda, D. Infield, "A small-scale seawater reverse-osmosis system with excellent energy efficiency over a wide operating range," (in English), *Desalination* 153 (1–3) (Feb 10 2003) 229–236, doi:Pii S0011-9164(02)01141-4 10.1016/S0011-9164(02)01141-4.
- [190] E. Tzen, D. Theofiloyianakos, M. Sigalas, K. Karamanis, "Design and development of a hybrid autonomous system for seawater desalination," (in English), *Desalination* 166 (1–3) (Aug 15 2004) 267–274, <https://doi.org/10.1016/j.desal.2004.06.081>.
- [191] J. Joseph, R. Saravanan, S. Renganarayanan, "Studies on a single-stage solar desalination system for domestic applications," (in English), *Desalination* 173 (1) (Mar 1 2005) 77–82, <https://doi.org/10.1016/j.desal.2004.06.210>.
- [192] E.S. Mohamed, G. Papadakis, E. Mathioulakis, V. Belessiotis, "An experimental comparative study of the technical and economic performance of a small reverse osmosis desalination system equipped with an hydraulic energy recovery unit," (in English), *Desalination* 194 (1–3) (Jun 10 2006) 239–250, <https://doi.org/10.1016/j.desal.2005.10.031>.
- [193] S. Bougoucha, B. Hamrouni, M. Dhahbi, "Small scale desalination pilots powered by renewable energy sources: case studies," (in English), *Desalination* 183 (1–3) (Nov 1 2005) 151–165, <https://doi.org/10.1016/j.desal.2005.03.032>.
- [194] E.S. Mohamed, G. Papadakis, E. Mathioulakis, V. Belessiotis, "A direct coupled photovoltaic seawater reverse osmosis desalination system toward battery based systems - a technical and economical experimental comparative study," (in English), *Desalination* 221 (1–3) (Mar 1 2008) 17–22, <https://doi.org/10.1016/j.desal.2007.01.065>.
- [195] S. Dallas, N. Sumiyoshi, J. Kirk, K. Mathew, N. Wilmot, "Efficiency analysis of the Solarflow - an innovative solar-powered desalination unit for treating brackish water," (in English), *Renew. Energy* 34 (2) (Feb 2009) 397–400, <https://doi.org/10.1016/j.renene.2008.05.016>.
- [196] F. Banat, A. Dhahi, "Design and operation of small-scale photovoltaic-driven reverse osmosis (PV-RO) desalination plant for water supply in rural areas," *Comput. Water Energy Environ. Eng.* 1 (03) (2012) 31.
- [197] B. Penate, V.J. Subiela, F. Vega, F. Castellano, F.J. Dominguez, V. Millan, "Uninterrupted eight-year operation of the autonomous solar photovoltaic reverse osmosis system in Ksar Ghilene (Tunisia)," (in English), *Desalin. Water Treat.* 55 (11) (Sep 11 2015) 3141–3148, <https://doi.org/10.1080/19443994.2014.940643>.
- [198] N.C. Wright, G. Van de Zande, A.G. Winter, "Justification, design, and analysis of a village-scale photovoltaic-powered electro dialysis reversal system for rural India," (in English), in: *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2015 Vol 2a, 2016 [Online]. Available: <http://WOS:000379883700043>.
- [199] M.A. Alghoul, et al., "design and experimental performance of brackish water reverse osmosis desalination unit powered by 2 kW photovoltaic system," (in English), *Renew. Energy* 93 (Aug 2016) 101–114, <https://doi.org/10.1016/j.renene.2016.02.015>.
- [200] D.S. Ayoub, H.M. Ega, A. Coronas, "A feasibility study of a small-scale photovoltaic-powered reverse osmosis desalination plant for potable water and salt production in Madura Island: a techno-economic evaluation," (in English), *Therm. Sci. Eng. Prog.* 35 (Oct 1 2022) doi:ARTN 101450 10.1016/j.tsep.2022.101450.
- [201] N. Ishimaru, "Solar photovoltaic desalination of brackish-water in remote areas by electro dialysis," (in English), *Desalination* 98 (1–3) (Sep 1994) 485–493, [https://doi.org/10.1016/0011-9164\(94\)00175-8](https://doi.org/10.1016/0011-9164(94)00175-8).
- [202] R.P. Allison, "Electro dialysis reversal in water reuse applications," (in English), *Desalination* 103 (1–2) (Nov 1995) 11–18, [https://doi.org/10.1016/0011-9164\(95\)00082-8](https://doi.org/10.1016/0011-9164(95)00082-8).
- [203] J.E. Lundstrom, "Water desalting by solar powered electro dialysis," *Desalination* 31 (1–3) (1979) 469–488.
- [204] H. Hamdan, M. Saidy, I. Alameddine, M. Al-Hindi, "The feasibility of solar-powered small-scale brackish water desalination units in a coastal aquifer prone to saltwater intrusion: a comparison between electro dialysis reversal and reverse osmosis," (in English), *J. Environ. Manage.* 290 (Jul 15 2021) doi:ARTN 112604 10.1016/j.jenvman.2021.112604.

- [205] H.M.N. AlMadani, "Water desalination by solar powered electrodialysis process," (in English), *Renew. Energy* 28 (12) (Oct 2003) 1915–1924, [https://doi.org/10.1016/S0960-1481\(03\)00014-4](https://doi.org/10.1016/S0960-1481(03)00014-4).
- [206] H.Y. Xu, X. Ji, L.L. Wang, J.X. Huang, J.Y. Han, Y. Wang, "Performance study on a small-scale photovoltaic electrodialysis system for desalination," (in English), *Renew. Energy* 154 (Jul 2020) 1008–1013, <https://doi.org/10.1016/j.renene.2020.03.066>.
- [207] J.M. Ortiz, E. Exposito, F. Gallud, V. Garcia-Garcia, V. Montiel, A. Aldaz, "Desalination of underground brackish waters using an electrodialysis system powered directly by photovoltaic energy," (in English), *Sol. Energy Mater. Sol. Cells* 92 (12) (Dec 2008) 1677–1688, <https://doi.org/10.1016/j.solmat.2008.07.020>.
- [208] M.R. Elmarghany, A. Radwan, Y. Abdelhay, N. Samir, M. Samir, E. Hares, "Experimental study of a standalone membrane water desalination unit fully powered by solar energy," (in English), *Desalination* 553 (May 1 2023) doi:ARTN 116476 10.1016/j.desal.2023.116476.
- [209] P.A. Hogan, A. Sudjito, G. Fane, G.L. Morrison, "Desalination by solar heated membrane distillation," (in English), *Desalination* 81 (1–3) (Jul 1991) 81–90, [https://doi.org/10.1016/0011-9164\(91\)85047-X](https://doi.org/10.1016/0011-9164(91)85047-X).
- [210] F. Banat, N. Jwaied, M. Rommel, J. Koschikowski, M. Wiegand, *Desalination by a "compact SMADES" autonomous solarpowered membrane distillation unit*, *Desalination* 217 (1–3) (2007) 29–37.
- [211] F. Banat, N. Jwaied, "Economic evaluation of desalination by small-scale autonomous solar-powered membrane distillation units," (in English), *Desalination* 220 (1–3) (Mar 1 2008) 566–573, <https://doi.org/10.1016/j.desal.2007.01.057>.
- [212] A. Chafidz, S. Al-Zahrani, M.N. Al-Otaibi, C.F. Hoong, T.F. Lai, M. Prabu, "Portable and integrated solar-driven desalination system using membrane distillation for arid remote areas in Saudi Arabia," (in English), *Desalination* 345 (Jul 15 2014) 36–49, <https://doi.org/10.1016/j.desal.2014.04.017>.
- [213] Q.M. Ma, A. Ahmadi, C. Cabassud, "Direct integration of a vacuum membrane distillation module within a solar collector for small-scale units adapted to seawater desalination in remote places: design, modeling & evaluation of a flat-plate equipment," (in English), *J. Membr. Sci.* 564 (Oct 15 2018) 617–633, <https://doi.org/10.1016/j.memsci.2018.07.067>.
- [214] J.A. Andres-Manas, A. Ruiz-Aguirre, F.G. Acien, G. Zaragoza, "Assessment of a pilot system for seawater desalination based on vacuum multi-effect membrane distillation with enhanced heat recovery," (in English), *Desalination* 443 (Oct 1 2018) 110–121, <https://doi.org/10.1016/j.desal.2018.05.025>.
- [215] J.A. Andres-Manas, L. Roca, A. Ruiz-Aguirre, F.G. Acien, J.D. Gil, G. Zaragoza, "Application of solar energy to seawater desalination in a pilot system based on vacuum multi-effect membrane distillation," (in English), *Appl. Energy* 258 (Jan 15 2020) doi:ARTN 114068 10.1016/j.apenergy.2019.114068.
- [216] A. Shafieian, M. Khiadani, M.R. Azhar, "A solar membrane-based wastewater treatment system for high-quality water production," (in English), *Energy* 206 (Sep 1 2020) doi:ARTN 118233 10.1016/j.energy.2020.118233.
- [217] Y.S. Chang, A.L. Ahmad, C.P. Leo, C.J.C. Derek, B.S. Ooi, "Air bubbling assisted solar-driven submerged vacuum membrane distillation for aquaculture seawater desalination," (in English), *J. Environ. Chem. Eng.* 10 (1) (Feb 2022) doi:ARTN 107088 10.1016/j.jece.2021.107088.
- [218] J. Choi, J. Cho, J. Shin, H. Cha, J. Jung, K.G. Song, "Performance and economic analysis of a solar membrane distillation pilot plant under various operating conditions," (in English), *Energy Convers. Manag.* 268 (Sep 15 2022) doi:ARTN 115991 10.1016/j.enconman.2022.115991.
- [219] M.M. ElKasaby, M.A. Hassan, A. Khalil, "Energy and economic performance assessment of a solar-assisted regenerative vacuum membrane desalination system," (in English), *Appl. Therm. Eng.* 225 (May 5 2023) doi:ARTN 120181 10.1016/j.applthermaleng.2023.120181.
- [220] H. Baqeeel, F. Abdelhady, A.S. Alghamdi, M.M. El-Halwagi, "Optimal design and scheduling of a solar-assisted domestic desalination systems," (in English), *Comput. Chem. Eng.* 132 (Jan 4 2020) doi:ARTN 106605 10.1016/j.compchemeng.2019.106605.
- [221] A.S. Nafey, H.E.S. Fath, S.O. El-Helaby, A.M. Soliman, "Solar desalination using humidification dehumidification processes. Part I. A numerical investigation," (in English), *Energy Convers. Manag.* 45 (7–8) (May 2004) 1243–1261, [https://doi.org/10.1016/S0196-8904\(03\)00151-1](https://doi.org/10.1016/S0196-8904(03)00151-1).
- [222] N.K. Nawayseh, M.M. Farid, S. Al-Hallaj, A.R. Al-Timimi, "Solar desalination based on humidification process - I. Evaluating the heat and mass transfer coefficients," (in English), *Energy Convers. Manag.* 40 (13) (Sep 1999) 1423–1439, [https://doi.org/10.1016/S0196-8904\(99\)00018-7](https://doi.org/10.1016/S0196-8904(99)00018-7).
- [223] M. Shatat, M. Worall, S. Riffat, "Economic study for an affordable small scale solar water desalination system in remote and semi-arid region," (in English), *Renew. Sustain. Energy Rev.* 25 (Sep 2013) 543–551, <https://doi.org/10.1016/j.rser.2013.05.026>.
- [224] M.A. Younis, M.A. Darwish, F. Juwayhel, "Experimental and theoretical study of a humidification-dehumidification desalting system," (in English), *Desalination* 94 (1) (Sep 1993) 11–24, [https://doi.org/10.1016/0011-9164\(93\)80151-C](https://doi.org/10.1016/0011-9164(93)80151-C).
- [225] S. Al-Hallaj, M.M. Farid, A.R. Tamimi, "Solar desalination with a humidification-dehumidification cycle: performance of the unit," (in English), *Desalination* 120 (3) (Dec 22 1998) 273–280, [https://doi.org/10.1016/S0011-9164\(98\)00224-0](https://doi.org/10.1016/S0011-9164(98)00224-0).
- [226] M. Vlachogiannis, V. Bontozoglou, C. Georgalas, G. Litinas, "Desalination by mechanical compression of humid air," (in English), *Desalination* 122 (1) (May 25 1999) 35–42, [https://doi.org/10.1016/S0011-9164\(99\)00025-9](https://doi.org/10.1016/S0011-9164(99)00025-9).
- [227] H. Muller-Holst, M. Engelhardt, W. Scholkopf, "Small-scale thermal seawater desalination simulation and optimization of system design," (in English), *Desalination* 122 (2–3) (Jul 7 1999) 255–262, [https://doi.org/10.1016/S0011-9164\(99\)00046-6](https://doi.org/10.1016/S0011-9164(99)00046-6).
- [228] Y.J. Dai, H.F. Zhang, "Experimental investigation of a solar desalination unit with humidification and dehumidification," (in English), *Desalination* 130 (2) (Nov 1 2000) 169–175, [https://doi.org/10.1016/S0011-9164\(00\)00084-9](https://doi.org/10.1016/S0011-9164(00)00084-9).
- [229] H.E.S. Fath, A. Ghazy, "Solar desalination using humidification-dehumidification technology," (in English), *Desalination* 142 (2) (Feb 1 2002) 119–133, [https://doi.org/10.1016/S0011-9164\(01\)00431-3](https://doi.org/10.1016/S0011-9164(01)00431-3).
- [230] A. Nafey, H.E. Fath, S. El-Helaby, A. Soliman, *Solar desalination using humidification-dehumidification processes. Part II. An experimental investigation*, *Energy Convers. Manag.* 45 (7–8) (2004) 1263–1277.
- [231] G. Al-Enezi, H. Ettouney, N. Fawzy, "Low temperature humidification dehumidification desalination process," (in English), *Energy Convers. Manag.* 47 (4) (Mar 2006) 470–484, <https://doi.org/10.1016/j.enconman.2005.04.010>.
- [232] C. Yamali, I. Solmus, "Theoretical investigation of a humidification-dehumidification desalination system configured by a double-pass flat plate solar air heater," (in English), *Desalination* 205 (1–3) (Feb 5 2007) 163–177, <https://doi.org/10.1016/j.desal.2006.02.053>.
- [233] G.F. Yuan, H.F. Zhang, "Mathematical modeling of a closed circulation solar desalination unit with humidification-dehumidification," (in English), *Desalination* 205 (1–3) (Feb 5 2007) 156–162, <https://doi.org/10.1016/j.desal.2006.03.550>.
- [234] J. Orfi, N. Galanis, M. Laplante, "Air humidification-dehumidification for a water desalination system using solar energy," (in English), *Desalination* 203 (1–3) (Feb 5 2007) 471–481, <https://doi.org/10.1016/j.desal.2006.04.022>.
- [235] H. Muller-Holst, "Solar thermal desalination using the Multiple Effect Humidification (MEH)-method," (in English), *Nato Sci. Peace Secur.* (2007) 215–225, [https://doi.org/10.1007/978-1-4020-5508-9\\_16](https://doi.org/10.1007/978-1-4020-5508-9_16).
- [236] C. Yamali, I. Solmus, "A solar desalination system using humidification-dehumidification process: experimental study and comparison with the theoretical results," (in English), *Desalination* 220 (1–3) (Mar 1 2008) 538–551, <https://doi.org/10.1016/j.desal.2007.01.054>.
- [237] K. Zhani, H. Ben Bacha, "Experimental investigation of a new solar desalination prototype using the humidification dehumidification principle," (in English), *Renew. Energy* 35 (11) (Nov 2010) 2610–2617, <https://doi.org/10.1016/j.renene.2010.03.033>.
- [238] J.J. Hermosillo, C.A. Arancibia-Bulnes, C.A. Estrada, "Water desalination by air humidification: mathematical model and experimental study," (in English), *Sol. Energy* 86 (4) (Apr 2012) 1070–1076, <https://doi.org/10.1016/j.solener.2011.09.016>.
- [239] G.F. Yuan, Z.F. Wang, H.Y. Li, X. Li, "Experimental study of a solar desalination system based on humidification-dehumidification process," (in English), *Desalination* 277 (1–3) (Aug 15 2011) 92–98, <https://doi.org/10.1016/j.desal.2011.04.002>.
- [240] M.A. Antar, M.H. Sharqawy, "Experimental investigations on the performance of an air heated humidification-dehumidification desalination system," (in English), *Desalin. Water Treat.* 51 (4–6) (Jan 2013) 837–843, <https://doi.org/10.1080/19443994.2012.714598>.
- [241] Z.H. Chang, H.F. Zheng, Y.J. Yang, Y.H. Su, Z.C. Duan, "Experimental investigation of a novel multi-effect solar desalination system based on humidification-dehumidification process," (in English), *Renew. Energy* 69 (Sep 2014) 253–259, <https://doi.org/10.1016/j.renene.2014.03.048>.
- [242] M.T. Ghazal, U. Atikol, F. Egelioglu, "An experimental study of a solar humidifier for HDD systems," (in English), *Energy Convers. Manag.* 82 (Jun 2014) 250–258, <https://doi.org/10.1016/j.enconman.2014.03.019>.
- [243] C. Yildirim, I. Solmus, "A parametric study on a humidification-dehumidification (HDH) desalination unit powered by solar air and water heaters," (in English), *Energy Convers. Manag.* 86 (Oct 2014) 568–575, <https://doi.org/10.1016/j.enconman.2014.06.016>.
- [244] P. Behnam, M.B. Shafii, "Examination of a solar desalination system equipped with an air bubble column humidifier, evacuated tube collectors and thermosyphon heat pipes," (in English), *Desalination* 397 (Nov 1 2016) 30–37, <https://doi.org/10.1016/j.desal.2016.06.016>.
- [245] M.I. Zubair, F.A. Al-Sulaiman, M.A. Antar, S.A. Al-Dini, N.I. Ibrahim, "Performance and cost assessment of solar driven humidification dehumidification desalination system," (in English), *Energy Convers. Manag.* 132 (Jan 15 2017) 28–39, <https://doi.org/10.1016/j.enconman.2016.10.005>.
- [246] A. Aburub, M. Aliyu, D. Lawal, M.A. Antar, *Experimental investigations of a cross-flow humidification dehumidification desalination system*, *Int. Water Technol. J. IWTJ* 7 (2017) 198–208.
- [247] A. Mahmoud, H. Fath, S. Ookwara, M. Ahmed, "Influence of partial solar energy storage and solar concentration ratio on the productivity of integrated solar still/humidification-dehumidification desalination systems," (in English), *Desalination* 467 (Oct 1 2019) 29–42, <https://doi.org/10.1016/j.desal.2019.04.033>.
- [248] V. Patel, R. Patel, J. Patel, "Theoretical and experimental investigation of bubble column humidification and thermoelectric cooler dehumidification water desalination system," (in English), *Int. J. Energy Res.* 44 (2) (Feb 2020) 890–901, <https://doi.org/10.1002/er.4931>.
- [249] B.W. Tleimat, E.D. Howe, *Nocturnal production of solar distillers*, *Sol. Energy* 10 (2) (1966) 61–66.
- [250] A. Bohner, "Solar desalination with a high-efficiency multi effect process offers new facilities," (in English), *Desalination* 73 (1–3) (Nov 1989) 197–203, [https://doi.org/10.1016/0011-9164\(89\)87014-6](https://doi.org/10.1016/0011-9164(89)87014-6).
- [251] S.M. Moustafa, G.H. Brusewitz, D.M. Farmer, *Direct use of solar energy for water desalination*, *Sol. Energy* 22 (2) (1979) 141–148.

- [252] F. Al-Juwayhel, H. El-Dessouky, H. Ettouney, "Analysis of single-effect evaporator desalination systems combined with vapor compression heat pumps," (in English), *Desalination* 114 (3) (Dec 30 1997) 253–275, [https://doi.org/10.1016/S0011-9164\(98\)00017-4](https://doi.org/10.1016/S0011-9164(98)00017-4).
- [253] N.A. Rahim, "High-performance domestic solar desalination system," (in English), *Renew. Energy* 4 (7) (Oct 1994) 855–862, [https://doi.org/10.1016/0960-1481\(94\)90238-0](https://doi.org/10.1016/0960-1481(94)90238-0).
- [254] N.A. Rahim, E. Taqi, Comparison of free and forced condensing systems in solar desalination units, *Renew. Energy* 2 (4–5) (1992) 405–410.
- [255] H. Müller-Holst, M. Engelhardt, M. Herve, W. Schölkopf, Solarthermal seawater desalination systems for decentralised use, *Renew. Energy* 14 (1–4) (1998) 311–318.
- [256] B. Boučekima, B. Gros, R. Ouahes, M. Diboun, "The performance of the capillary film solar still installed in South Algeria," (in English), *Desalination* 137 (1–3) (May 1 2001) 31–38, [https://doi.org/10.1016/S0011-9164\(01\)00201-6](https://doi.org/10.1016/S0011-9164(01)00201-6).
- [257] H.E.S. Fath, F.M. El-Shall, F. Vogt, U. Seibert, "A stand alone complex for the production of water, food, electrical power and salts for the sustainable development of small communities in remote areas," (in English), *Desalination* 183 (1–3) (Nov 1 2005) 13–22, <https://doi.org/10.1016/j.desal.2005.03.028>.
- [258] M. Ben Amara, I. Houcine, A. Guizani, M. Maalej, "Comparison of indoor and outdoor experiments on a newly designed air solar plate collector used with the operating conditions of a solar desalination process," (in English), *Desalination* 168 (Aug 15 2004) 81–88, <https://doi.org/10.1016/j.desal.2004.06.171>.
- [259] K. Schwarzer, M.E. Vieira, C. Müller, H. Lehmann, L. Coutinho, Modular solar thermal desalination system with flat plate collector, in: *RIO 3–World Climate & Energy Event*, 2003, pp. 281–286.
- [260] A.B. Auti, "domestic solar water desalination system," (in English), *Energy Proc.* 14 (2012) 1774–1779, <https://doi.org/10.1016/j.egypro.2011.12.1166>.
- [261] M.S. Sapre, A.B. Auti, T.P. Singh, "Design and manufacturing of absorber for solar desalination system," (in English), *Appl. Mech. Mater.* 446–447 (2014) 716–720, <https://doi.org/10.4028/www.scientific.net/AMM.446-447.716>.
- [262] A.B. Auti, D.R. Pangavane, T.P. Singh, M. Sapre, "Estimation of time of tracking for designed absorber used in domestic solar desalination system using experimental and Finite Element analysis (ANSYS)," (in English), *Mater Today-Proc* 4 (2) (2017) 2516–2524 [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2214388217300290>.
- [263] A.I. Schafer, C. Remy, B.S. Richards, "Performance of a small solar-powered hybrid membrane system for remote communities under varying feedwater salinities," (in English), *Wa Sci. Technol.* 4 (5–6) (2004) 233–243, <https://doi.org/10.2166/ws.2004.0113>.
- [264] A.I. Schafer, B.S. Richards, "Testing of a hybrid membrane system for groundwater desalination in an Australian national park," (in English), *Desalination* 183 (1–3) (Nov 1 2005) 55–62, <https://doi.org/10.1016/j.desal.2005.05.007>.
- [265] A.I. Schafer, A. Broeckmann, B.S. Richards, "Renewable energy powered membrane technology. 1. Development and characterization of a photovoltaic hybrid membrane system," (in English), *Environ. Sci. Technol.* 41 (3) (Feb 1 2007) 998–1003, <https://doi.org/10.1021/es061166o>.
- [266] C. Bales, et al., Photovoltaic powered operational scale membrane capacitive deionization (MCDI) desalination with energy recovery for treated domestic wastewater reuse, *Desalination* 559 (2023) 116647.
- [267] C.T. Kiranoudis, N.G. Voros, Z.B. Maroulis, "Wind energy exploitation for reverse osmosis desalination plants," (in English), *Desalination* 109 (2) (May 1997) 195–209, [https://doi.org/10.1016/S0011-9164\(97\)00065-9](https://doi.org/10.1016/S0011-9164(97)00065-9).
- [268] Q.F. Ma, H. Lu, "Wind energy technologies integrated with desalination systems: Review and state-of-the-art," (in English), *Desalination* 277 (1–3) (Aug 15 2011) 274–280, <https://doi.org/10.1016/j.desal.2011.04.041>.
- [269] Y. Nakatake, H. Tanaka, "A new maritime lifesaving distiller driven by wind," (in English), *Desalination* 177 (1–3) (Jun 20 2005) 31–42, <https://doi.org/10.1016/j.desal.2004.10.031>.
- [270] G. Petersen, S. Fries, J. Mohn, A. Müller, Wind and solar-powered reverse osmosis desalination units-description of two demonstration projects, *Desalination* 31 (1–3) (1979) 501–509.
- [271] G. Petersen, S. Fries, J. Mohn, A. Muller, "Wind and solar powered reverse-osmosis desalination units - design, start up, operating experience," (in English), *Desalination* 39 (1–3) (1981) 125–135, [https://doi.org/10.1016/S0011-9164\(00\)86115-9](https://doi.org/10.1016/S0011-9164(00)86115-9).
- [272] R. Robinson, G. Ho, K. Mathew, "Development of a reliable low-cost reverse-osmosis desalination unit for remote communities," (in English), *Desalination* 86 (1) (Apr 1992) 9–26, [https://doi.org/10.1016/0011-9164\(92\)80020-A](https://doi.org/10.1016/0011-9164(92)80020-A).
- [273] A. Maurel, Desalination by reverse osmosis using renewable energies (solar-wind) cadarche centre experiment, in: *Seminar on New Technologies for the Use of Renewable Energies in Water Desalination*, Athens, 1991, pp. 26–28.
- [274] S.M. Habali, I.A. Saleh, "Design of stand-alone brackish-water desalination wind energy system for Jordan," (in English), *Sol. Energy* 52 (6) (Jun 1994) 525–532, [https://doi.org/10.1016/0038-092x\(94\)90660-2](https://doi.org/10.1016/0038-092x(94)90660-2).
- [275] A. Neris, G. Giannakopoulos, N. Vovos, Autonomous wind turbine supplying a reverse osmosis desalination unit, *Wind Eng.* (1995) 325–347.
- [276] D. Infield, "Performance analysis of a small wind powered reverse osmosis plant," (in English), *Sol Energy* 61 (6) (Dec 1997) 415–421, [https://doi.org/10.1016/S0038-092x\(97\)00082-0](https://doi.org/10.1016/S0038-092x(97)00082-0).
- [277] C.C.K. Liu, J.W. Park, R. Migita, G. Qin, "Experiments of a prototype wind-driven reverse osmosis desalination system with feedback control," (in English), *Desalination* 150 (3) (Nov 10 2002) 277–287, doi: Pii S0011-9164(02)00984-0 Doi 10.1016/S0011-9164(02)00984-0.
- [278] M.S. Miranda, D. Infield, "A wind-powered seawater reverse-osmosis system without batteries," (in English), *Desalination* 153 (1–3) (Feb 10 2003) 9–16, [https://doi.org/10.1016/S0011-9164\(02\)01088-3](https://doi.org/10.1016/S0011-9164(02)01088-3), doi:Pii S0011-9164(02)01088-3.
- [279] M. Gokcek, O.B. Gokcek, "Technical and economic evaluation of freshwater production from a wind-powered small-scale seawater reverse osmosis system (WP-SWRO)," (in English), *Desalination* 381 (Mar 1 2016) 47–57, <https://doi.org/10.1016/j.desal.2015.12.004>.
- [280] N. Ghaffour, J. Bundschuh, H. Mahmoudi, M.F.A. Goosen, "Renewable energy-driven desalination technologies: a comprehensive review on challenges and potential applications of integrated systems," (in English), *Desalination* 356 (Jan 15 2015) 94–114, <https://doi.org/10.1016/j.desal.2014.10.024>.
- [281] S. Bouguecha, M. Dhahbi, "Fluidised bed crystalliser and air gap membrane distillation as a solution to geothermal water desalination," (in English), *Desalination* 152 (1–3) (Feb 10 2003) 237–244, [https://doi.org/10.1016/S0011-9164\(02\)01069-X](https://doi.org/10.1016/S0011-9164(02)01069-X), doi:Pii S0011-9164(02)01069-X.
- [282] B. Tomaszewska, et al., "Use of low-enthalpy and waste geothermal energy sources to solve arsenic problems in freshwater production in selected regions of Latin America using a process membrane distillation - research into model solutions," (in English), *Sci Total Environ* 714 (Apr 20 2020) doi:ARTN 136853 10.1016/j.scitotenv.2020.136853.
- [283] J. Bundschuh, N. Ghaffour, H. Mahmoudi, M. Goosen, S. Mushtaq, J. Hoinkis, "Low-cost low-enthalpy geothermal heat for freshwater production: innovative applications using thermal desalination processes," (in English), *Renew. Sustain. Energy Rev.* 43 (Mar 2015) 196–206, <https://doi.org/10.1016/j.rser.2014.10.102>.
- [284] H. Gurgenci, Fresh water using geothermal heat, *Australas. Sci.* 31 (5) (2010) 35–37.
- [285] P. Behnam, A. Arefi, M.B. Shafii, "Energetic and thermoeconomic analysis of a trigeneration system producing electricity, hot water, and fresh water driven by low-temperature geothermal sources," (in English), *Energy Convers. Manag.* 157 (Feb 1 2018) 266–276, <https://doi.org/10.1016/j.enconman.2017.12.014>.
- [286] K. Bourouni, R. Martin, L. Tadrist, M.T. Chaibi, "Heat transfer and evaporation in geothermal desalination units," (in English), *Appl. Energy* 64 (1–4) (Sep-Dec 1999) 129–147, [https://doi.org/10.1016/S0306-2619\(99\)00071-9](https://doi.org/10.1016/S0306-2619(99)00071-9).
- [287] A.M.I. Mohamed, N.A.S. El-Minshawy, "Humidification-dehumidification desalination system driven by geothermal energy," (in English), *Desalination* 249 (2) (Dec 15 2009) 602–608, <https://doi.org/10.1016/j.desal.2008.12.053>.
- [288] H. Gutiérrez, S. Espíndola, Using low enthalpy geothermal resources to desalinate sea water and electricity production on desert areas in Mexico, *GHC Bull.* 29 (2010) 19–24.
- [289] D.C. Hicks, C.M. Pleass, G.R. Mitcheson, J.F. Salevan, "Delboub - ocean wave-powered seawater reverse-osmosis desalination system," (in English), *Desalination* 73 (1–3) (Nov 1989) 81–94, [https://doi.org/10.1016/0011-9164\(89\)87006-7](https://doi.org/10.1016/0011-9164(89)87006-7).
- [290] M. Folley, T. Whittaker, "The cost of water from an autonomous wave-powered desalination plant," (in English), *Renew. Energy* 34 (1) (Jan 2009) 75–81, <https://doi.org/10.1016/j.renene.2008.03.009>.
- [291] A. Corsini, E. Tortora, E. Cima, "Preliminary assessment of wave energy use in an off-grid minor island desalination plant," (in English), in: *70th Conference of the Italian Thermal Machines Engineering Association*, Ati2015 82, 2015, pp. 789–796, <https://doi.org/10.1016/j.egypro.2015.11.813>.
- [292] P.A. Davies, "Wave-powered desalination: resource assessment and review of technology," (in English), *Desalination* 186 (1–3) (Dec 30 2005) 97–109, <https://doi.org/10.1016/j.desal.2005.03.093>.
- [293] L.F. Prieto, G.R. Rodriguez, J.S. Rodriguez, "Wave energy to power a desalination plant in the north of Gran Canaria Island: wave resource, socioeconomic and environmental assessment," (in English), *J. Environ. Manage.* 231 (Feb 1 2019) 546–551, <https://doi.org/10.1016/j.jenvman.2018.10.071>.
- [294] N. Sharmila, P. Jaliha, A.K. Swamy, M. Ravindran, "Wave powered desalination system," (in English), *Energy* 29 (11) (Sep 2004) 1659–1672, <https://doi.org/10.1016/j.energy.2004.03.099>.
- [295] C.M. Ling, Y.F. Wang, C.H. Min, Y.W. Zhang, "Economic evaluation of reverse osmosis desalination system coupled with tidal energy," (in English), *Front. Energy* 12 (2) (Jun 2018) 297–304, <https://doi.org/10.1007/s11708-017-0478-2>.
- [296] R. Suchithra, et al., "Numerical modelling and design of a small-scale wave-powered desalination system," (in English), *Ocean Eng.* 256 (Jul 15 2022) doi: ARTN 111419 10.1016/j.oceaneng.2022.111419.
- [297] R.S. Kumar, A. Mani, S. Kumaraswamy, "Experimental studies on desalination system for ocean thermal energy utilisation," (in English), *Desalination* 207 (1–3) (Mar 10 2007) 1–8, <https://doi.org/10.1016/j.desal.2006.08.001>.
- [298] C. Koroneos, A. Dompros, G. Roubas, "Renewable energy driven desalination systems modelling," (in English), *J. Clean Prod.* 15 (5) (2007) 449–464, <https://doi.org/10.1016/j.jclepro.2005.07.017>.
- [299] T.M. Missimer, Y.D. Kim, R. Rachman, K.C. Ng, "Sustainable renewable energy seawater desalination using combined-cycle solar and geothermal heat sources," (in English), *Desalin. Water Treat.* 51 (4–6) (Jan 2013) 1161–1170, <https://doi.org/10.1080/19443994.2012.704685>.
- [300] M.A. Eltaawil, Z. Zhengming, L.Q. Yuan, "A review of renewable energy technologies integrated with desalination systems," (in English), *Renew. Sustain. Energy Rev.* 13 (9) (Dec 2009) 2245–2262, <https://doi.org/10.1016/j.rser.2009.06.011>.
- [301] H. Cherif, J. Belhadj, "Large-scale time evaluation for energy estimation of stand-alone hybrid photovoltaic-wind system feeding a reverse osmosis desalination unit," (in English), *Energy* 36 (10) (Oct 2011) 6058–6067, <https://doi.org/10.1016/j.energy.2011.08.010>.

- [302] M. Prajapati, et al., "Geothermal-solar integrated groundwater desalination system: current status and future perspective," (in English), *Groundw. Sustain. Dev.* 12 (Feb 2021) doi: ARTN 100506 10.1016/j.gsd.2020.100506.
- [303] D. Weiner, D. Fisher, E.J. Moses, B. Katz, G. Meron, "Operation experience of a solar- and wind-powered desalination demonstration plant," (in English), *Desalination* 137 (1–3) (May 1 2001) 7–13, [https://doi.org/10.1016/S0011-9164\(01\)00198-9](https://doi.org/10.1016/S0011-9164(01)00198-9).
- [304] A.A. Setiawan, Y. Zhao, C.V. Nayar, "Design, economic analysis and environmental considerations of mini-grid hybrid power system with reverse osmosis desalination plant for remote areas," (in English), *Renew. Energy* 34 (2) (Feb 2009) 374–383, <https://doi.org/10.1016/j.renene.2008.05.014>.
- [305] E.S. Mohamed, G. Papadakis, "Design, simulation and economic analysis of a stand-alone reverse osmosis desalination unit powered by wind turbines and photovoltaics," (in English), *Desalination* 164 (1) (Mar 25 2004) 87–97, [https://doi.org/10.1016/S0011-9164\(04\)00159-6](https://doi.org/10.1016/S0011-9164(04)00159-6), doi:Pii S0011-9164(04)00159-6.
- [306] E.M.A. Mokheimer, A.Z. Sahin, A. Al-Sharafi, A.I. Ali, "Modeling and optimization of hybrid wind-solar-powered reverse osmosis water desalination system in Saudi Arabia," (in English), *Energy Convers. Manag.* 75 (Nov 2013) 86–97, <https://doi.org/10.1016/j.enconman.2013.06.002>.
- [307] K. Mousa, A. Diabat, H. Fath, "Optimal design of a hybrid solar-wind power to drive a small-size reverse osmosis desalination plant," (in English), *Desalin. Water Treat.* 51 (16–18) (Apr 2013) 3417–3427, <https://doi.org/10.1080/19443994.2012.749199>.
- [308] M. Gokcek, "integration of hybrid power (wind-photovoltaic-diesel-battery) and seawater reverse osmosis systems for small-scale desalination applications," (in English), *Desalination* 435 (Jun 1 2018) 210–220, <https://doi.org/10.1016/j.desal.2017.07.006>.
- [309] N. Voutchkov, "Energy use for membrane seawater desalination - current status and trends," (in English), *Desalination* 431 (Apr 1 2018) 2–14, <https://doi.org/10.1016/j.desal.2017.10.033>.
- [310] M.A. Abdelkareem, M.E. Assad, E.T. Sayed, B. Soudan, "Recent progress in the use of renewable energy sources to power water desalination plants," (in English), *Desalination* 435 (Jun 1 2018) 97–113, <https://doi.org/10.1016/j.desal.2017.11.018>.
- [311] A. Shafieian, A. Roostaei, P. Behnam, M. Khiadani, "Performance analysis of a solar-driven integrated direct-contact membrane distillation and humidification-dehumidification system," (in English), *Energy Convers. Manag.* 274 (Dec 15 2022) doi: ARTN 116479 10.1016/j.enconman.2022.116479.
- [312] J.N. Easley, S. Talazi, A.G. Winter, "Feasibility and design of solar-powered electrodialysis reversal desalination systems for agricultural applications in the Middle East and North Africa," (in English), *Desalination* 561 (Sep 1 2023) doi: ARTN 116628 10.1016/j.desal.2023.116628.
- [313] Q.B. Chen, et al., "An emerging pilot-scale electrodialysis system for desalination of SWNF permeate: evaluating the role of typical factors," (in English), *Desalination* 542 (Nov 15 2022) doi: ARTN 116064 10.1016/j.desal.2022.116064.
- [314] M. Lehmann, F. Karimpour, C.A. Goudey, P.T. Jacobson, M.R. Alam, "ocean wave energy in the United States: current status and future perspectives," (in English), *Renew. Sustain. Energy Rev.* 74 (Jul 2017) 1300–1313, <https://doi.org/10.1016/j.rser.2016.11.101>.
- [315] A. Al-Karaghoul, D. Renne, L.L. Kazmerski, "Technical and economic assessment of photovoltaic-driven desalination systems," (in English), *Renew. Energy* 35 (2) (Feb 2010) 323–328, <https://doi.org/10.1016/j.renene.2009.05.018>.
- [316] C.V. Nayar, S.J. Phillips, W.L. James, T.L. Pryor, D. Remmer, "Novel wind diesel battery hybrid energy system," (in English), *Sol Energy* 51 (1) (Jul 1993) 65–78, [https://doi.org/10.1016/0038-092x\(93\)90043-N](https://doi.org/10.1016/0038-092x(93)90043-N).
- [317] M.M. Generous, N.A.A. Qasem, U.A. Akbar, S.M. Zubair, "Techno-economic assessment of electrodialysis and reverse osmosis desalination plants," (in English), *Sep. Purif. Technol.* 272 (Oct 1 2021) doi:ARTN 118875 10.1016/j.seppur.2021.118875.
- [318] L. Saleh, T. Mezher, "Techno-economic analysis of sustainability and externality costs of water desalination production," (in English), *Renew. Sustain. Energy Rev.* 150 (Oct 2021) doi: ARTN 111465 10.1016/j.rser.2021.111465.