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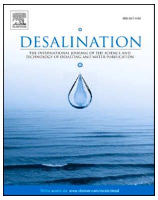

Engineering advance

Utilization of renewable energy sources in desalination of geothermal water for agriculture

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HIGHLIGHTS

- RE use in desalination of geothermal water for irrigation is reviewed.
- A novel approach that integrates RESs into agri-food chain is presented.
- Specific cases of geothermal water desalination from Turkey and Poland are given.
- Possible new generation RESs in desalination by capacitive deionization are explored.
- Advantages/disadvantages of RE use in geothermal water desalination are discussed.

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ABSTRACT

The agricultural sector, which is highly dependent on water, is urged to build on improved water management practices and explore available options to match supply and demand because of the water scarcity risks and a sustainable and productive agri-food chain. Geothermal water is an energy source used to generate electricity and/or heat. After harnessing its energy, the remaining water can be used as a water source for irrigation following treatment because of its high ionic content. Geothermal fields are mostly located in rural areas where agricultural activities exist. This would be a good match to decrease the transportation cost of irrigation water. The energy demand of the desalination process for agriculture is higher, requiring additional post-treatment processes. Fossil fuels to fulfill the energy requirements are becoming expensive, and greenhouse gas emissions are harmful to the environment. Thus, efforts should be directed towards integrating renewable energy resources into desalination process. This work focuses on presenting a comprehensive review of geothermal water desalination which is powered by renewable energy and provides specific cases from Turkey and Poland. Furthermore, possible new generation renewable energy systems in desalination are introduced, considering their potential application in the desalination of geothermal water for agricultural irrigation.

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1. Introduction

Climate change, pollution, increased human demand, and overuse of water is the main cause for water scarcity. The freshwater problem is harshly experienced in some parts of the world, while more regions are experiencing drought conditions because of global warming [1].

Turkey is one of the countries that periodically struggle with a deficit of drinking water. Moreover, projections show a significantly increased need for water soon, mostly due to irrigation [2]. Poland has modest water resources, one of the lowest in Europe [3–5]. With the current and forecasted high freshwater demand, it is increasingly difficult to sustain freshwater supply security without producing freshwater from contaminated, brackish, or saline water and reusing agricultural, industrial, and municipal wastewater after proper treatment.

Water is a crucial input for agricultural output and plays a significant role in ensuring food security. Worldwide, the agri-food sector contributes 80–90% of the overall global use of fresh water, with 70% for irrigation only [6]. Irrigation is the method where regulated quantities of water are given to plants at the appropriate intervals and helps to cultivate crops, sustain the landscape, and re-vegetation of soil in dry areas and during periods of less than normal rainfall. The intensity, rate, volume, and time of irrigation are different for different crops and differ by soil and season.

The agricultural sector heavily relies on fossil fuels and contributes to the largest emissions of NH_3 (92%), CH_4 (54%), and NMVOCs (16%) in the EU [7]. For example, Poland has been struggling with exceeding the permissible levels of air pollution for several years. The Polish agricultural sector's electricity consumption for production purposes-without farmer households- was 1633 GWh, and heat consumption was 900 TJ in 2016 [8]. The most commonly used energy carrier in Polish agriculture is hard coal [9,10], whereas the utilization rate of renewable energy sources (RES) is low. In Turkey, the agricultural sector's contribution to CH_4 and N_2O emissions are 55% and 77%, respectively [11].

Renewable energy use in agriculture is not quite common in many countries. However, increasing the share of RES would contribute to improving the environmental impact of the agricultural sector, including the reduction of greenhouse gas emissions. Desalination is commonly used to obtain freshwater removing minerals, contaminants, and salts from brackish waters [12]. Energy consumption has been one of the main obstacles to desalination. Desalination requires considerably higher energy than traditional (conventional) water treatment methods. Thus, the cost and greenhouse gas emissions of the desalination process are higher. For instance; energy consumption of seawater desalination has a share in total operating cost of 50–70%.

There are two mature technological methods used in desalination as thermal (e.g., distillation) and membrane-based (e.g., reverse osmosis) desalination. Thermal-based methods are categorized as much higher energy-intensive than membrane-based ones. According to the review conducted by Ahmed et al. [13], membrane-based desalination methods dominate installed and online desalination capacity across the globe by about 73% while thermal-based methods accounted for only 27% at the end of the year 2016. Membrane-based desalination methods need high pressure and the required pressure for the seawater desalination varies from 55 to 70 bar, while typical operating pressure for the brackish water desalination changes from 15 to 30 bar [14]. However, Tomaszewska and Bodzek [15,16] pointed effective geothermal brackish water desalination using RO with 10–11 bar. Specific energy consumption of low and high-pressure pumps alone accounts for about 60–80% of the total energy use in brackish or seawater desalination processes [17]. Unfortunately, the use of fossil fuel to power desalination of either brackish water or seawater accounts for about 99% worldwide [18]. For example, the electrical energy need to produce fresh water from seawater is 3–5 kWh/m^3 for membrane-based technology and 1.5–2 kWh/m^3 for thermal methods. Furthermore, thermal methods require additional heat energy as high as 60–70 kWh/m^3 [18]. From both economic and environmental perspectives, the use of fossil fuel-powered desalination plants is not considered since many countries have to import fossil fuels to meet their demand, which will harm their economy. Furthermore, the use of fossil fuels is threatened by the emission of CO_2, which contributes to the greenhouse effect [19–21]. For that reason, it is of paramount importance to explore the potential of RESs such as wind, geothermal, and solar for desalination of brackish water before its use, especially in agricultural irrigation.

Previous studies revealed that there are cases where geothermal resources are close to agricultural areas. Hence geothermal resources could be a source of irrigation water as well as a source of energy [22,23]. However, due to high ionic content, geothermal water should be treated before use in irrigation.

The aim of this study is to provide a general overview of geothermal water desalination powered by renewable energy systems such as geothermal, solar, wind, and integrated systems. Besides, specific cases of geothermal water desalination from Turkey and Poland are mentioned. Furthermore, possible new generation renewable energy systems in desalination are introduced.

2. Desalination of geothermal waters

Following heat extraction, geothermal water is generally directed to reinjection wells, yet there are cases where it is rejected directly to the environment. Given the scarcity of freshwater resources for worldwide consumption and agriculture, geothermal water could be evaluated as an unexploited waste stream and considered to be used in agricultural activities. However, due to the increased salinity of geothermal waters, their use for irrigation often requires the application of desalination processes, which can be supported by different sources of renewable energy.

The Balçova-Narlıdere Geothermal Field (BNGF) in Turkey is located in a densely populated area, which makes direct heat applications efficient and economical. The heat produced from the BNGF is used for greenhouse heating, balneology, and residential heating, which is the largest in Turkey with a heating capacity of 160 MWt. However, geothermal waters of the BNGF contain high boron (11–18 mg/L) and arsenic (150–300 μg/L) concentrations [24–26]. Unfortunately, the geothermal water was reported to intrude freshwater wells located in the north of the field, having detrimental effects on citrus orchards [27].

Boron is one of the harmful elements present in geothermal waters. Boron is a micronutrient for some plants, but tolerance limits of plants for boron are varied, and the excess amount of boron in irrigation water causes toxic effects on the growth of some plants [28–32]. The permissible limits of boron concentration for drinking and irrigation waters are set by the World Health Organisation (WHO) as 2.4 mg/L and < 1.0 mg/L, respectively [33].

Arsenic in groundwaters is mostly due to mining activities, inputs from geothermal sources, uncontrolled anthropogenic activities, and the use of some pesticides [29,32,34–37]. Although geothermal water can be an alternative source for water supply, it may contain potentially toxic elements including boron and arsenic. Therefore, a suitable treatment process should be employed before using and discharging the geothermal waters containing boron and arsenic into the environment.

The use of boron-selective chelating ion exchange resins is the most common method for boron removal. According to the literature, the boron-selective ion exchange resins having *N*-methyl-D-glucamine groups are the best sorbents for removal of boron due to their high selectivity [29,38–68].

Selecting a treatment method for arsenic removal from water depends on some factors such as the initial arsenic concentration, arsenic speciation in the feed water, and the target level of treatment. Adsorption using inorganic adsorbent materials like zerovalent iron, hydroxyapatite-based ceramics, and magnetite, is a highly used method for arsenic removal since it is more convenient than chemical precipitation/coprecipitation that produces large volumes of sludge. Ion exchange resins are more expensive than inorganic adsorbents [32].

The chelating ion exchange resins have poor kinetics due to the diffusion-controlled rate-limiting processes. High efficiency in the ion exchange process could be obtained with the resin beads having small particle sizes due to the large surface area and improved kinetics. Application of the adsorption-membrane filtration hybrid method was successful on boron removal application from geothermal water using boron selective resins having small particle size [45–47,59,62,69–72]. Recently, novel boron selective gel-like chelating resins and epidermal-activated chelating resins were applied for boron and arsenic removal concurrently from the geothermal water by adsorption-membrane filtration hybrid method. The performance of newly synthesized resins was highly comparable with the commercial boron selective ion exchange resins [73,74]. The experimental set-up of the adsorption-membrane filtration system was depicted in Fig. 1. In this method, boron selective ion exchange resins having a small particle size (about 10 μm) and a hollow-fiber type ultrafiltration membrane module were used. By this method, boron concentration in the geothermal water could be lowered below 1.0 mg/L.

The pressure-driven RO membranes were also employed to reclaim spent geothermal water for further use as irrigation water [75], Yavuz et al. [76] conducted tests by a grid-powered mini-pilot scale RO system to determine the effect of membrane configuration. The system was fed by the spent geothermal water of the BNGF and the water temperature decreased to room temperature before the membrane treatment. Sand and cartridge filters were used for pre-treatment, as shown in Fig. 2. The RO membrane used in the study was FilmTechTM B30-2540 which had an active area of 2.6 m^2.

The qualities of geothermal water of the BNGF pre- and post-treatment with RO membrane were compared to the agricultural irrigation standards in Table 1. As can be seen from Table 1, the boron concentration in the geothermal water (8.8–11.4 mg/L) was much higher than the permissible level ($<$1 mg/L) for irrigation water. Meeting the irrigation water standard for boron is not possible using a RO membrane at the natural groundwater pH of the geothermal water. Since boron removal is highly affected by pH, the authors further investigated the removal of boron from geothermal water at different pH values [77]. The boron concentration below the allowable levels (for irrigation water) could be achieved by increasing the pH of geothermal water before the RO membrane process when the treated water is intended to be used as irrigation water. On the other hand, increasing pH of the geothermal water before the membrane treatment caused a flux decline due to the scaling of membranes by the insoluble precipitates of Ca^{2+} and Mg^{2+} ions in the geothermal water [4].

Poland has a significantly high potential of low-enthalpy geothermal waters [79] and most of them are extracted in the central part of Poland (Polish Lowland) and the southern part of the country (Podhale Geothermal System). The research presented by [16], Tomaszewska [80] and Tomaszewska et al. [4] demonstrated that geothermal wastewater (cooled down in heat exchangers) could be purified using membrane processes and subsequently reused as potable water and after remineralization as water suitable for irrigation purposes. The best solution of treated water has been obtained for relatively low mineralized geothermal water exploited from the Podhale Geothermal Basin [81]. The geothermal waters with a temperature of 30 °C, contain total dissolved solids (TDS) as 2.6 g/L, boron as high as 9.0 mg/L, iron as 4.0 mg/L, arsenic as 0.03 mg/L, fluoride as 2.6 mg/L and silica as 43 mg/L. A schematic diagram of the desalination plant which has a capacity of 1 m^3/h, is shown in Fig. 3. The preliminary treatment contained an iron removal system and two ultrafiltration (UF) membrane modules (UFC M5, X-Flow). Two steps of RO processes connected in series were equipped with spiral wound Dow FILMTEC BW30HR-440i polyamide thin-film composite membranes. The first step of RO had two filtration modules while the second step had one. The final treatment included remineralization and disinfection of the permeate (Fig. 3).

During the pilot tests, no antiscalants, biocides, or other chemicals were used. Before RO-1, the feed reaction was lowered to about 5.5 by dosing minuscule amounts of hydrochloric acid, which effectively prevented membrane scaling. The permeate pH at the exit of RO-1 was increased to 10–10.5 and directed to RO-2. The pressure of 1.1 ± 0.1 MPa was used in both stages of RO. The results of the pilot tests showed the electrical power consumption of the pumps in the UF pre-treatment process may be reduced to 5.9 kW due to the artesian pressure of the production wells [4]. The overpressure of the geothermal system during water production from the boreholes was ca. 1.2 MPa and was additionally corrected by the use of a water turbine, located between the heat exchanger and the treatment station, which generated about 3 kW of energy (Fig. 4). The usage of reservoir artesian overpressure during

Fig. 1. Experimental set-up for adsorption-membrane filtration study.

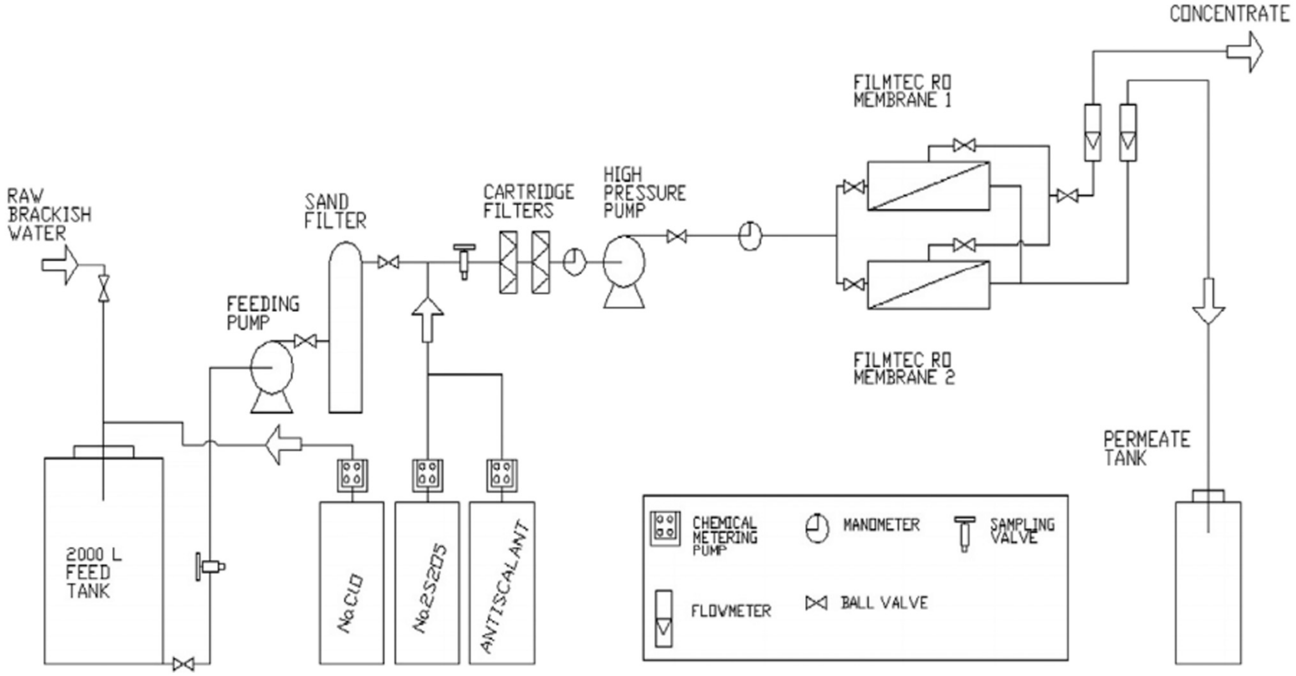

Fig. 2. A schematic diagram of the mini-pilot scale RO system (Reproduced with permission from [75]).

Table 1
The quality parameters of geothermal water pre- and post-treatment process (Adapted from [75,77,78]).

Parameter		Irrigation water standard	Geothermal water (pH 7.3)	Product water (pH 7.3)	Product water (pH 10.5)
Conductivity	(μS/cm)	1000–2250	1679–1772	23.3	75.3
TDS	(mg/L)	500–5000	840–887	19.9	37.7
Na^+	(mg/L)	50–250	324–363	0.00	BDL
K^+	(mg/L)	No guideline	27–45	0.61	0.38
Ca^{2+}	(mg/L)	40–100	20–22	0.12	0.02
Mg^{2+}	(mg/L)	30–50	2.3–5.8	0.02	BDL
Cl^-	(mg/L)	0–400	160–169	2.60	3.06
SO_4^{2-}	(mg/L)	200–575	153–174	0.14	0.48
B	(mg/L)	<1	8.80–11.4	4.67	0.50

BDL: below the detection limit.

the geothermal water desalination was the advantage of the system. Furthermore, low water mineralization and increased water temperature to 30 °C in the RO desalination, lead to a decrease in water viscosity. Generally, in the presented system, the net energy consumption of the water desalination per unit of freshwater produced was 1.40 kWh/m^3 [4]. An additional benefit can be achieved by using photovoltaic panels to supply the installation with electricity. Such activities are planned for the near future.

3. Geothermal energy powered desalination

The general idea of using geothermal resources due to the possibility of generating electricity and heat is presented in Fig. 5. The diagram has been divided into three cycles, where 1 means the use of geothermal steam to generate electricity. In the next stage (2), they can be used (after condensation) to generate electricity in the Organic Rankine Cycle (ORC) or the Kalina Cycle (KC), like geothermal water separated from geothermal vapors in a separator (stage 1). Likewise, with lower enthalpy resources, geothermal waters can be diverted directly from the production well into the ORC or KC. Stage 3 is the use of energy accumulated in geothermal waters after the electricity generation to generate heat. In such a complementary system, it is possible to supply water desalination processes that require both electricity and heat. In each case, however, it will depend on the local geothermal conditions.

The thermal energy capacity of geothermal resources can be converted into electricity or used as direct geothermal heat. In both cases, the technologies that are used to generate electricity and direct heat should be considered mature and possible to use for desalination processes. The key barriers that may limit the use of geothermal water are the temperature and the efficiency of the energy generation system. However, as it was mentioned, this depends on the locally prevailing geothermal conditions. Based on the geothermal resource temperature, desalination technologies differ. If the temperature of geothermal sources is in the range of 40–70 °C, low-temperature desalination technologies such as membrane distillation, multi-effect distillation units, and simple evaporation basins, can be used. Multi-effect evaporation and multi-stage flash desalination processes can be run by geothermal resources at a temperature of higher than 70 °C. Higher geothermal resource temperatures (120 and 200 °C) may be considered for cogeneration schemes [82]. As suggested by Gude [82], cogeneration schemes could include thermal and membrane-based desalination processes. The main advantages of such systems are fewer maintenance requirements than RO membranes and low environmental impact since energy input comes from geothermal resource. Furthermore, since geothermal resources have constant temperature and flowrate with continuous flow, thermal energy storage is not required. Thus, geothermal resources appeared to be an ideal choice for thermal desalination processes [83].

Currently, there are several desalination plants based on geothermal energy in the world, but these are usually small installations [84–86]. They are located in Mexico (Baja, California), Greece (Kimolos), Tunisia (two installations in Tunisia), and the USA (two installations in the

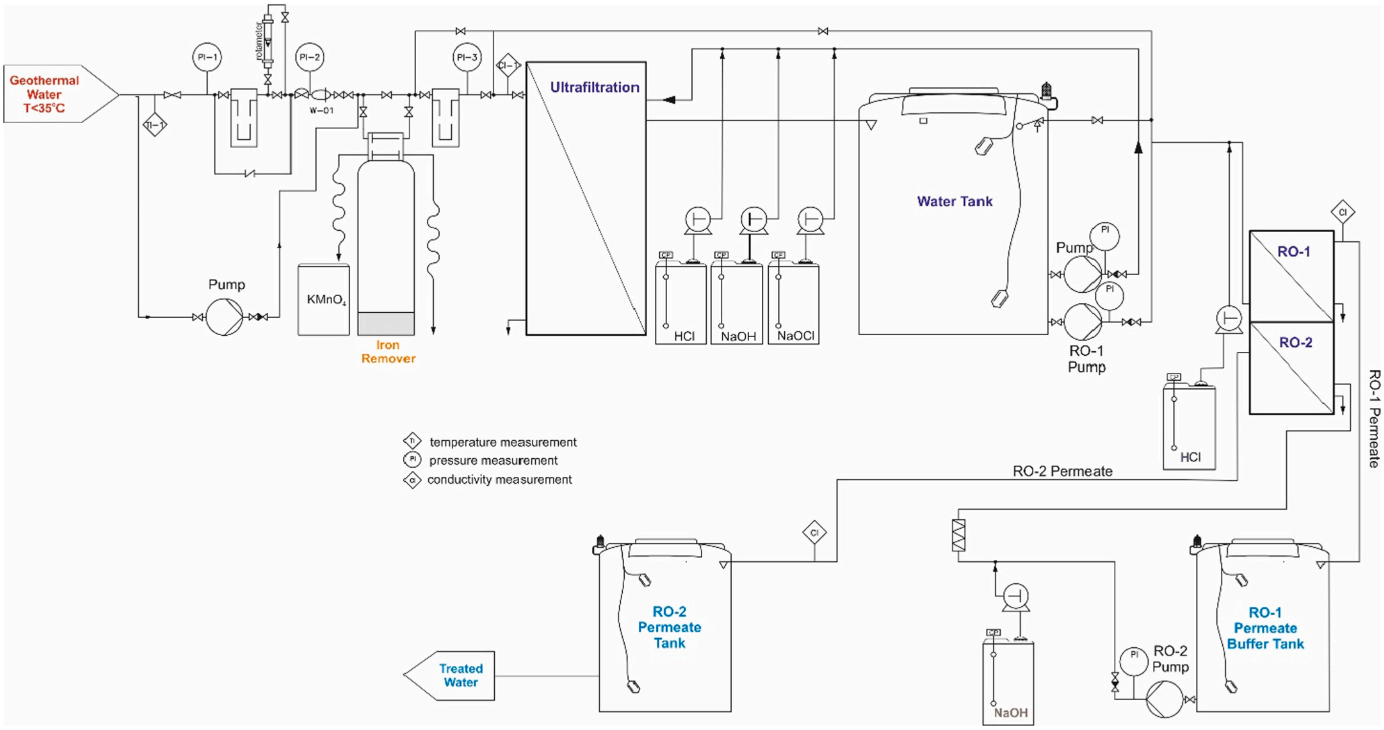

Fig. 3. A schematic diagram of the pilot-scale membrane desalination plant for treatment of the geothermal water in Poland (*Reproduced with permission from* [15]).

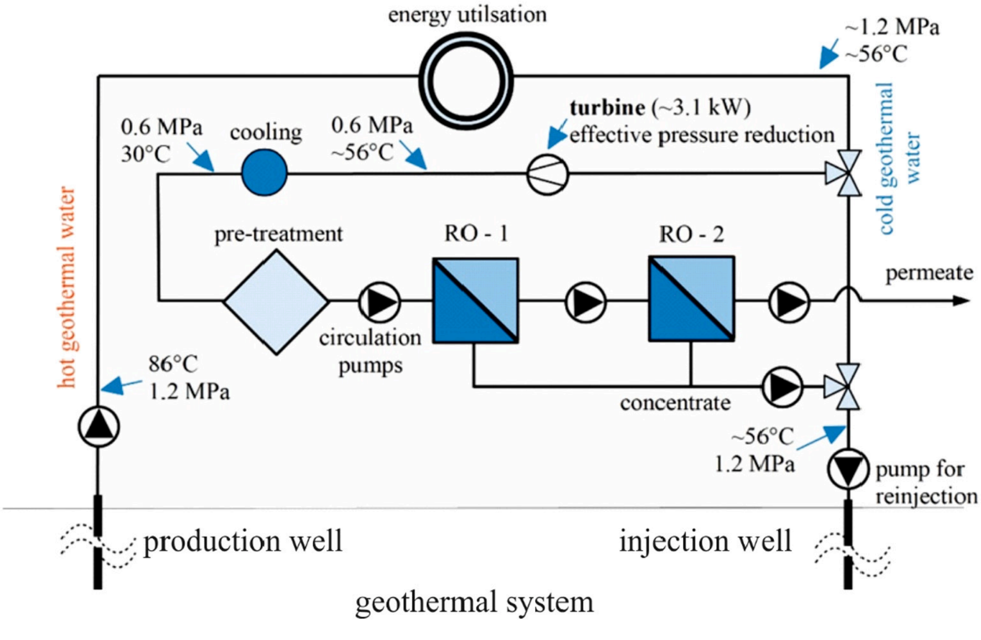

Fig. 4. The conception of geothermal water circulation and use (*Reproduced with permission from* [4]).

Salton Sea) and are used for desalting, mainly seawater. An exception is an installation located in Greece, which desalts brackish water. The highest water desalination efficiency is characteristic for the installation based on membrane distillation and multi-effect distillation technologies located in Tunisia, for which the capacity is 1382 m^3/day [87]. The second installation in Tunisia uses the humidification-dehumidification process (HDH), but the details are not known for it. The second-largest value is characterized by the installation based on multi-effect distillation technology in Greece. This pilot installation based on the multi-effect distillation is operating on the island of Kimolos. It uses geothermal water at a temperature of 60–61 °C extracted from a depth of 188 m. The installation allows desalinating with a capacity of 80 m^3/day by a geothermal water demand of 1440 m^3/day [88–90].

Both plants operating in the USA (Salton Sea) are based on the MED/VTE process. In the case of the MED/VTE (2-effects) installation, the production capacity is 18.9 m^3/day, while in the case of MED/VTE (15-effects), it is more than 4 times higher and amounts to 79.5 m^3/day. In both cases, geothermal steam with a temperature of 100 °C is used. In the first case, it is 454 kg/h, while in the second 3402 kg/h [91,92].

It seems reasonable to search for the use of low enthalpy geothermal waters in desalination processes. In the past, such research was conducted, among others by Rodriguez et al. [93], who indicated that for desalting 1 m^3 of seawater in multi-effect distillation and multi-stage flash technology, it is necessary to use 14 m^3 of geothermal water at

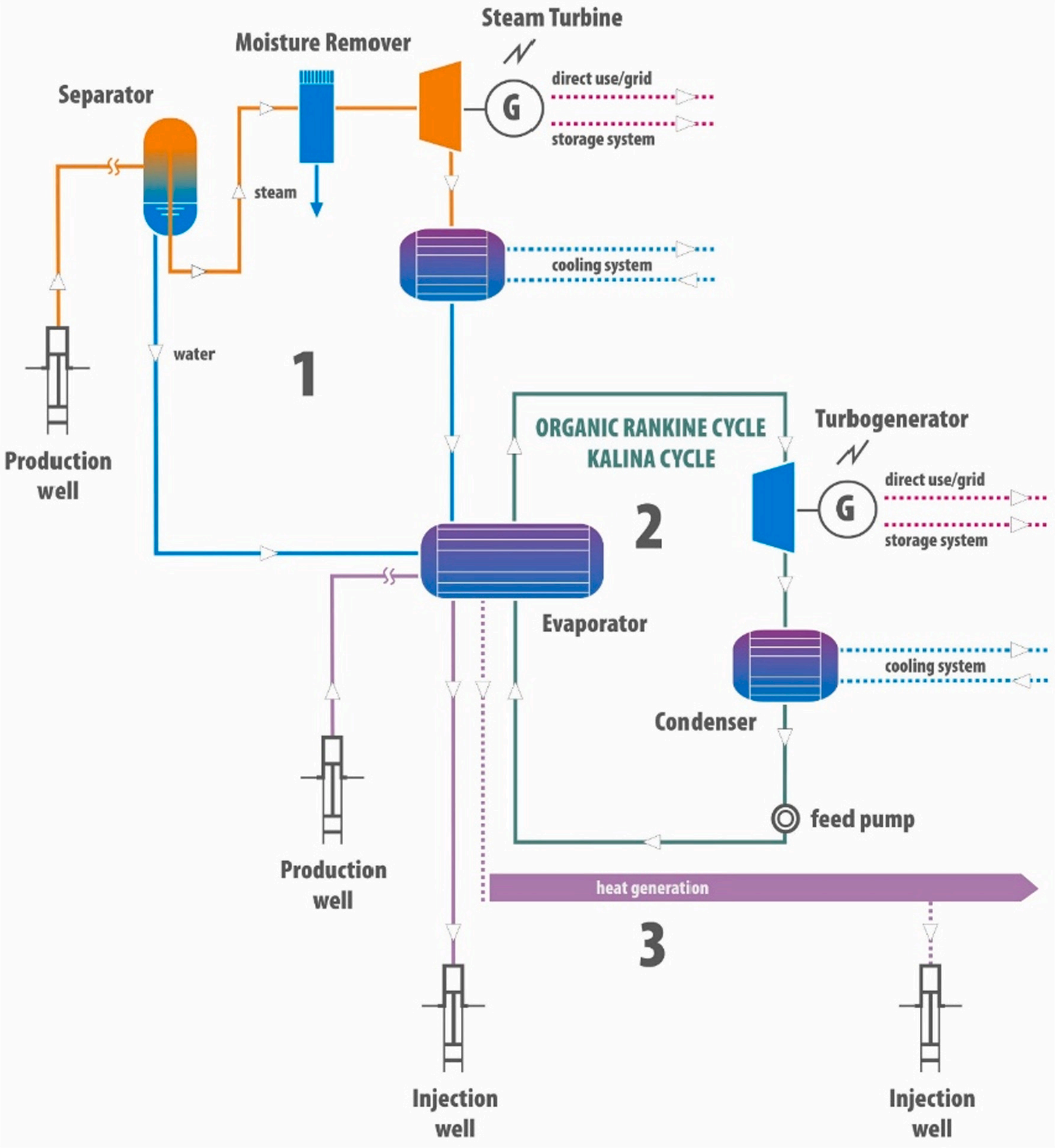

Fig. 5. General diagram of using geothermal resources.

80 °C. It should be added that at such a temperature of geothermal water, it is possible to generate electricity by binary cycles, while the flow rate with which geothermal water is extracted should be at a higher level [94,95]. In turn, Gutiérrez and Espíndola [96] designed and tested a prototype unit in the laboratory, obtaining 20 m^3/day of desalinated water with geothermal water consumption of 118 m^3. The research was also conducted on the islands of Milos and Nysyros, indicating the potential for desalting water at 75–80 m^3/day using geothermal water extracted from a depth of 85–184 m with a capacity of 12,840 m^3/day [89,97]. For the island of Nisyros, the potential was estimated as 225 m^3/day of freshwater production [98].

Until now, geothermal energy has not been used in commercial-scale desalination processes. The stability of the generation of thermal energy from geothermal resources makes them very attractive to be used in desalination processes successfully in the future. In addition, according to Ghaffour et al. [88], supplying heat to desalination plants using geothermal resources can generally be considered more economically viable than solar energy. An important issue that should be noted is the possibility of using geothermal waters also for its treatment, provided that its chemical composition allows it.

4. Review of other renewable energy powered desalination

Between the years 2010–2020, water desalination by different technologies, including membrane processes, has been the subject of many scientific studies. Many of them focused on the problem of the high energy demand of the desalination process and progressing water scarcity crisis because energy costs represent as much as half of the production cost of desalination plants [99]. Khan et al. [100] also conducted an economic evaluation of systems based on renewable energy as a potential energy source for water desalination. They concluded that currently used desalination systems based on a different source of energy vary in a wide range: a) photovoltaic (PV) energy ranging from 0.8 m^3/d to 60,000 m^3/d with an approximate cost of US$ 34.21/m^3 to 0.825/m^3, b) wind energy ranging from 1 m^3/d to 250,000 m^3/d with an approximate cost of US$ 15.75/m^3 to 0.66/m^3, and c) wind-PV integrated energy ranging from 3 m^3/d to 83,000 m^3/d with a water production cost varies from US$ 6.12/m^3 to 1.4 US$/$m^3$.

As can be seen, the presented values apply to two types of renewable energy sources: photovoltaics and wind energy separately, as well as in a hybrid system. This is due to the high popularity of these technologies in combination with water desalination processes. This, in turn, is the result of the relatively easier implementation of this type of solution in the context of electricity generation, especially in the case of photovoltaics. The situation is different in the case of the use of a geothermal source to generate electricity, which is determined by the available temperature of geothermal water and its amount that can be extracted. For this reason, in the context of desalination of geothermal waters, especially in locations with low enthalpy geothermal waters, the inclusion of solar or wind energy in the meaning of a hybrid system and cooperation with a heat production system from geothermal waters, for their subsequent desalination, can be considered as justified and desirable. For this reason, in the further part of this article, some references are given not only to geothermal energy but also to other renewable energy sources as mutually compensating.

4.1. *Solar energy powered desalination*

Among renewable energy sources used for the desalination of either brackish water or seawater, solar energy is the most common source worldwide [18]. A large part of the literature has investigated the potential of small-scale RO systems driven by PV in different locations such as Greece, Italy, Spain, Saudi Arabia, or Egypt either as part of the theoretical studies or pilot experiments [101].

Solar energy can be used for desalination directly or indirectly, depending on which technology is used to harness the energy. Indirect solar desalination systems known as solar stills, freshwater is generated directly mostly in the solar collector, while in indirect solar desalination systems, solar energy is collected as thermal or electrical energy, which, in effect, is being used for desalination [13]. Commercial-scale solar desalination research concentrated on two major categories of systems as concentrated solar energy (CSP) in conjunction with thermal or RO desalination processes and PV in conjunction with RO systems [102]. The PV module generates DC and, if the PV is to supply electricity to the grid, it needs to be converted to AC using an inverter, as most are AC grids [13]. In general, PV systems require batteries to store energy [103], particularly if the current needs to be supplied irrespective of solar radiation. When neither the inverter nor the batteries are in operation, a variable-flow pump is also used to compensate for seasonal variations in solar radiation [104].

Desalination of brackish and seawater using direct or indirect solar energy was investigated by Wazed et al. [105], Ruiz-García and Nuez [106], El-Awady et al. [107], Tong et al. [108], Pouyfaucon and García-Rodríguez [109], and Delgado-Torres et al. [110]. El-Awady et al. [107] investigated small-scale irrigation water production for greenhouses using direct solar energy in remote and arid areas in Egypt. The humidification–dehumidification (HDH) system was equipped with evaporators and distilled water condensers. They were able to produce 0.104 m^3/day of irrigation water. Peterson and Gray [111] installed a brackish water RO-PV powered desalination system to supply irrigation water to Mt. Coot-tha Botanic Gardens, Australia. The desalination system operated with a capacity of 10 m^3/day. The PV-powered system was expensive, which was about 50 US$/$m^3$ of product water. However, the authors claimed that the cost could be lowered by scale-up and long-term operation. Ruiz-García and Nuez [106] investigated a full-scale long-term intermittent PV-powered brackish water RO desalination system over 14 years. The system was equipped with 2-staged Filmtec™BW30–400 RO membrane elements operated at 12 bar. The plant was designed to produce irrigation water at a capacity of 416 m^3/day and a water recovery of 65%. The product water has an electrical conductivity of 250–700 μS/cm, while the specific energy consumption (SEC) was 1.82–2.21 kWh/m^3.

Filippini et al. [112] investigated the possibility of adding a PV system to a hybrid desalination plant (membrane desalination and RO). The authors conducted an economic analysis as well and estimated that the cost of electricity generation of the PV system was in a range of 0.06–0.15 €/kWh, depending on solar radiation and the duration of daylight. Calise et al. [113] also presented an economic assessment of complex renewable energy systems integrating PV panels, seawater desalination, and water storage. They underlined that increase in PV area leads to significant cost savings (even from 67% to 94%). Moreover, they indicated that the volume of the water storage basin does not significantly affect the economic efficiency of the plant when appropriate photovoltaic capacity is selected.

In a geothermal heat center at Izmir city, Turkey, solar energy is being used to power a mini-pilot scale NF/RO desalination system installed for the treatment of the spent geothermal water. The installed solar energy system consists of 12 solar panels as depicted in Fig. 6, and each panel has a power capacity of 320 We. The panels generate electricity from solar radiation in the form of DC. Attached to the PV module, there is an inverter that converts generated DC by the panels to AC, which can be used to power our installed NF/RO membrane treatment system. The PV module does not have batteries; for that reason, the energy generated by the panels is directly utilized for the treatment of the spent geothermal water in the NF/RO treatment system. The NF/RO membrane system powered by a PV module is shown in Fig. 6. The energy produced by solar panels and energy consumed by NF/RO membrane system is monitored by a software.

Fig. 7 exhibits an example of power generation by the PV system and power consumption by RO membrane system on September 3rd, 2020, at 12:20–16:20. The membrane system consists of 2 pumps (high and low pressure), BW30 model (Dow FilmTech) RO membrane. A 15 bar of applied pressure was maintained constant during the study. Water recovery from the system was kept constant at 60% and the duration of the experiment was 240 min. Fig. 7 illustrates that at the beginning of the study, the energy produced by the PV system was almost twice the energy consumed by the membrane treatment system (2701 W produced by PV module, 1370 W consumed by the membrane treatment system). This study was conducted during mid-day (12:20–4:20 pm) when the solar radiation to the solar panels was at its peak. However, towards the end (150th min) of the study, there was a notable drop in the energy produced by the PV module (2035 W) compared to the first 15th min (2701 W) since the sun changes direction towards the sunset, the amount of solar radiation coming to the solar panels decreases.

As already mentioned, the consideration of PV installations in the context of desalination of geothermal water or supporting desalination processes with the use of geothermal heat may be justified, as indicated by examples cited above. It should be remembered that when considering the possibility of using geothermal heat in desalination processes, electricity is still necessary, which results from the specificity of the desalination processes themselves, or even in terms of auxiliary energy for such processes. In summary, by the dominant type of energy for desalination processes such as MSF (multi-stage flash), MED (multiple effect distillation), TVC (thermal vapor compression), AD (adsorption desalination), MD (membrane distillation), HDH (humidification-dehumidification), it is mainly thermal energy. However, it must not be forgotten that electricity is also essential [23,35].

4.2. *Wind energy powered desalination*

Wind energy, like solar energy, is considered to supply water desalination processes rather in integrated systems, which allows these RESs to complement each other. The complementarity of power and generated energy decides that there are relatively few autonomous installations using wind energy in desalination processes, mostly in coastal areas. Abdelkareem et al. [114] listed installations located in France (Ile de Planner), Australia (Debenham), Spain (Fuerteventura, Gran Canaria), Greece (Thersasia Island), Great Britain (Loughborough University), and Germany (Enercon SW, Enercon BW). The amount of permeate produced varies from 500 to 104,000 L/h, with the SEC coefficient from

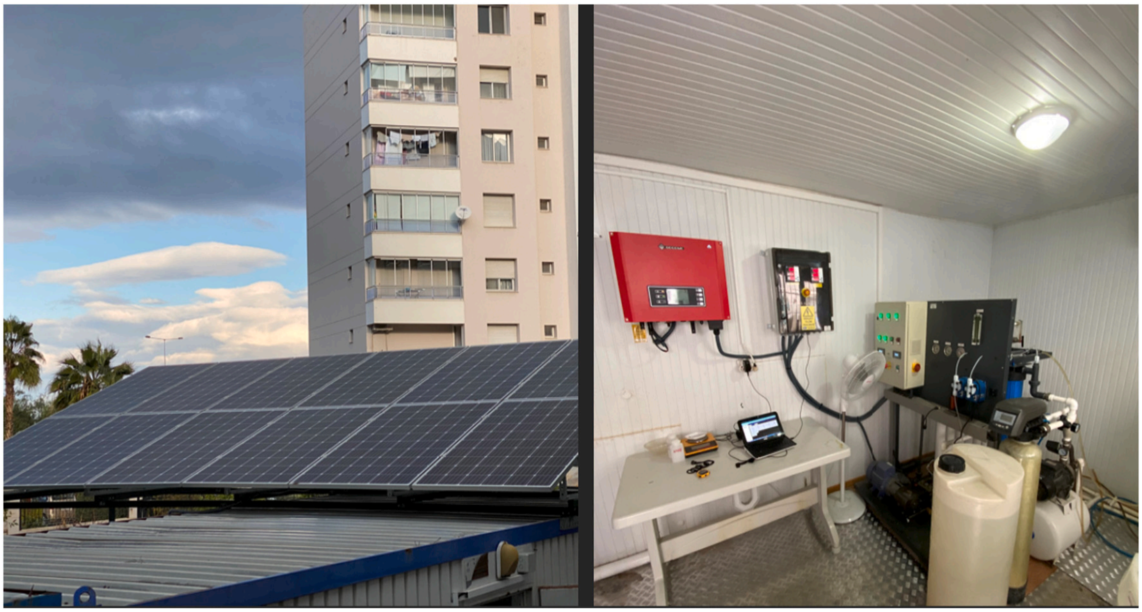

Fig. 6. Solar panels (left), RO system powered by PV module (right).

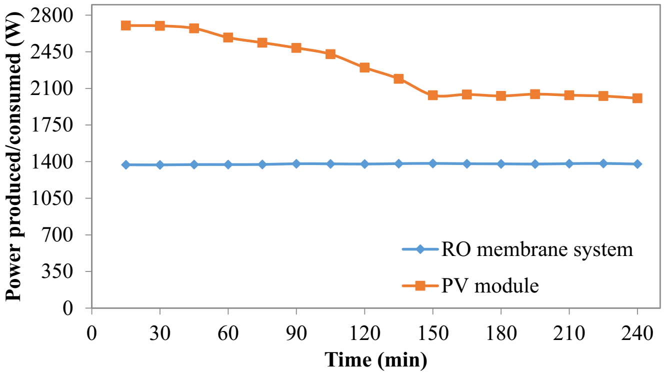

Fig. 7. The power produced by PV module/power consumed by RO membrane system on September 3rd, 2020 at 12:20–16:20.

2.5 to 200 kW/m^3. The highest operating parameters characterized the Enercon installation using brackish water, for which the amount of permeate varies from 14,600 to 104,000 L/h with SEC coefficients of 200 kW/m^3 [114]. It should also be noted that the seawater desalination plants dominate (this applies to 5 out of 8 listed above), which probably results from favorable wind conditions of the coastal areas. However, such examples can be easily adapted for geothermal water treatment. Nevertheless, in recent years several studies have appeared that relate only to wind energy in desalination processes. Among the latest research by Loutatidou et al. [115] in the United Arab Emirates should be mentioned. In that study, the possibilities of industrial use of wind turbines operating at low wind speeds to feed RO processes were analyzed. They obtained the Levelized cost of water (LCWO) as 1.57–1.63 US$/m^3 for 7000 m^3/day, 1.83–1.96 US$/m^3 for 10,500 m^3/day and 2.09–2.11 US$/m^3 for 14,000 m^3/day for water production. Gökçek and Gökçek [116] were carried out a technical and economic analysis on the possibility of using small wind turbines in the desalination process. They analyzed 6–30 kWe turbines for use in RO on Gökceada Island in Turkey. The economic results they obtained indicate that the cost of water desalination ranges from 2.962 to 6.457 US$/m^3, which is very promising by several wind power plants and high wind potential in Turkey. Among older studies, attention should be paid to those carried out by Miranda and Infield [117]. They also relocated a small 2.2 kWe wind turbine, cooperating with the RO desalination unit, focusing on analyzing the impact of changing wind speed to optimize the rate of freshwater production. Whereas Dehmas et al. [118] presented a model enabling the analysis of the economic profitability of using wind energy in desalination processes based on the seawater RO plant, taking into account the reduction of CO_2 emissions for Ténès in Algeria.

Wind energy, adequately to solar energy, can complement the geothermal desalination plant. The potential of this renewable energy source may be of particular interest in agricultural areas. Due to their specificity, these are less urbanized areas, which may facilitate investments in high-capacity units. Additionally, it can be concluded that this type of RES does not interfere with farming, which results from the lack of necessity to exclude significant land areas from use. It should be emphasized once again, however, that in the case of desalination of geothermal water, considerations on the inclusion of wind energy in the system should primarily concern areas where geothermal resources do not allow for the generation of electricity, or its amount is inadequate to the needs resulting from the required amount of water for desalination.

4.3. *Desalination using integrated systems*

Due to the complementarity of available power and energy from individual renewable energy technologies, the vast majority of research is currently focused on integrated systems. This should be considered as the right direction for the increase in the use of renewable energy technologies in desalination processes. Most research focuses on analyzing the potential of RESs in a given area and determining the amount of water that can be desalinated using them. Among the most frequently studied combinations of RESs, solar and wind energy cooperation should be mentioned first of all.

General studies on the possibilities of using renewable energy to run desalination processes without focusing on specific types of renewable energy had conducted by Aminfard et al. [119] and Padrón et al. [120]. In both works cited, the technical and economic feasibility analysis of renewable energy use was evaluated. Aminfard et al. [119] based their analysis on a multi-layered spatial model taking into account the potential of locally occurring RESs, availability, and depth of water resources as well as the level of their salinity and very importantly the price of water in the studied area. In total, 1445 locations were analyzed. Among all renewable energy technologies, 145 out of the studied locations were indicated as the optimal use of geothermal energy while in 28 locations solar energy was the most cost-effective technology.

Padrón et al. [120] researched renewable energy use potential for the islands-Lanzarote and Fuerteventura. For this purpose, assuming that the RO production capacity will be up to 50 m^3/day, the optimal system for Lanzarote was defined as the cooperation of a 30 kWe wind turbine, a 5 kWe PV installation, and a conventional 10 kWe generator. The system was completed by 160 batteries with a capacity of 360 Ah, and the whole allows to cover 96% of electricity demand at 0.404 US $/kWh. In the case of Fuerteventura, the system also consists of a 30 kWe wind turbine, a 5 kWe PV system, but with a conventional 15 kW generator and 200 batteries, which translated into 92% of energy demand coverage at a unit cost of 0.478 US$/kWh.

Technical and economic models on integrated use of solar PV and wind energy in the process of RO has been developed by Maleki et al. [121], Fornarelli et al. [122], Aminfard et al. [119], Mito et al. [123] as well as Mollahosseini et al. [124], while in the last work, the possibility of using geothermal energy was additionally analyzed. Particularly interesting conclusions were formulated by Mito et al. [123]. They are concerned with optimization in the management of energy production processes using wind energy and solar PV. The authors focused on identifying technical challenges and potential solutions to implement this analyzed technology on a commercial scale. They pointed out that the technical challenge is to avoid shortening the life of membranes used in the RO process, proposing as a solution modulation of work owing to the renewable energy sources available at commercial plants at a given moment. Also, the results of research carried out by Fornarelli et al. [122] are interesting, mainly because they refer to rural Australia by proposing an integrated 2.8 MWe of solar system and a 2.4 MWe of wind farm. The total amount of energy that could be produced was 15.2 GWh, of which only 1.2 GWh would be used in desalination processes, and the remaining part of the energy would serve the residents' living needs, making them independent of conventional energy sources. The energy cost was estimated at 0.077 US$/kWh, which is 47% less than the one applicable in the analyzed region.

Bitaw et al. [125] presented the results of research oriented towards energy optimizations and cost analysis of integrated systems of seawater desalination LREE (low recovery, energy consumption, emission). For total recovery ratios of 7.% and 25.3%, they achieved an SEC as 1.3 kWh/m^3. They established that the integrated NF-electrodialysis (ED)-RO system possessed the highest reduction in the concentrated brine discharge (even 40%), lower energy use, 1.731 kWh/m^3, and the lowest cost increase rate (around 28%) in comparison with the state-of-the-art stand-alone RO system.

Despite the integration of various renewable energy systems, one should be aware that, e.g., in the case of integration between solar and wind energy, problems with power and energy shortage may appear, and thus the stability of the water desalination process will be disturbed. Research in this direction was carried out by Atallah et al. [126], in addition to the integration of wind and solar energy systems, analyzed their cooperation with a conventional unit, which was a diesel generator. Returning to the research of Atallah et al. [126], they were conducted in the city of Nakhl in Egypt. The desalinated water production level was assumed by the authors at 100 m^3/day, which, according to calculations, would require a 160 kWe of photovoltaic installation and a 50 kWe of diesel generator. The analysis of many models ultimately indicated the abandonment of wind energy in this system. However, the installation has been supplemented with an electricity storage system in 190 lead-acid batteries (19 chains) with a capacity of 3.11 kWh.

Among integrated renewable energy technologies, geothermal energy should play an increasingly important role in the future as a stable source that can be used continuously regardless of weather conditions. This direction of research, and thus supplementing solar and wind energy systems using geothermal energy, has been analyzed in recent years by Azhar et al. [127], Okati et al. [128], Mollahosseini et al. [124] as well as Colmenar-Santos et al. [129]. Azhar et al. [127] analyzed the possibility of integrated use of solar, geothermal, and ocean thermal energy. The total power output was estimated as approximately 55 MWe, and the proposed integrated system was able to produce 18.54 kg/s of high-quality water. Although Mollahosseini et al. [124] analyzed the potential of all RESs that can be used in Iran for desalination processes, estimating them at 140.2 MWe. Wind and solar energy were indicated as the most optimal technologies. This proves that, although geothermal energy is a stable source of energy, it strongly depends on locally prevailing hydrogeological conditions, which directly affects the economic profitability of its use. From the latest research, the integrated geothermal and solar energy system was analyzed by Colmenar-Santos et al. [129] in Spain. From the perspective of geothermal energy, the possibility of using geothermal water at 41.8 °C was initially analyzed. However, it allowed covering energy demand only 76% of the time during the year. Calculations made by the authors indicated that to increase this ratio to 100%, it would be necessary to extract water at a temperature of at least 70 °C.

4.4. Desalination using capacitive deionization

Some desalination methods belong to the group of electrochemical processes. According to the definition given by Biesheuvel and Dykstra [130], such processes appear when freely moving ions in the electrolyte phase meet another phase/material and can interact with it. That 'other' phase can be either a charged interface or an electrode. The authors extended the definition to such desalination processes as RO and NF and included them in the electrochemical group. However, the core electrochemical processes are still ED and capacitive deionization (CDI). The first one is well recognized and applied on the industrial scale, while the second one is just in its emerging state and is still developed. The CDI is a water desalination method implementing a pair of porous conductive electrodes that can attract anions and cations when they are charged positively and negatively. In the classical CDI stack, water flows along the electrodes, but sometimes it is directed through the electrodes. The last design uses highly permeable electrodes prepared, usually from nano/microfibrous math. When the electrode is formed by the conductive slurry, such design is defined as flow electrode CDI (FCDI). The ordinary design with two stationary electrodes can be wrapped by ion-exchange membranes. Formed in such a way, membrane enhanced CDI (MCDI) is characterized by increased efficiency as well as salt adsorption capacity [131]. Hence, in the CDI electrochemical process, three various configurations appear: classical CDI, membrane CDI and flow CDI. Each of them has its profits and drawbacks, and these methods were discussed in many publications. What is interesting, most of these papers show that CDI can be applied as a source of energy. Brogioli [132] developed that way of thinking and invented the capacitive mixing method (CAPMIX) for harvesting salinity gradient energy. Later on, that method appeared as the third option for getting renewable energy from mixing saline fluids [133–135]. Siekierka et al. [136] proved that by coating electrodes with ion-exchange membranes, one can increase power production of the CAPMIX system by 100 times. The authors were able to obtain 200 mW/m^2-electrode. That effect can be multiplied for a multi-compartment stack [137].

The above-presented evidence is well-reflected in theory. Kong et al. [138], using molecular modeling found that there is an optimal charging potential to maximize the net electrical charge output and that potential depends on the pore diameter of the electrode. Once the pore size is doubled in ion diameter, the best results are obtained. For the classical CDI, with two flat conductive electrodes, the process of desalination is composed of two steps: electro-sorption and electro-desorption. Each of them needs energy. However, they are some different metrics used by various authors to describe the electro-membrane systems. To make any comparison relevant, the definition of common metrics for the capacitive desalination process was needed. That was done by Hawks et al. [139]. They suggested using volumetric energy consumption calculated per m^3 of dilating (E_v) to show energy consumption. When the product of voltage and current is positive, the system is charged (E_{in}), in the

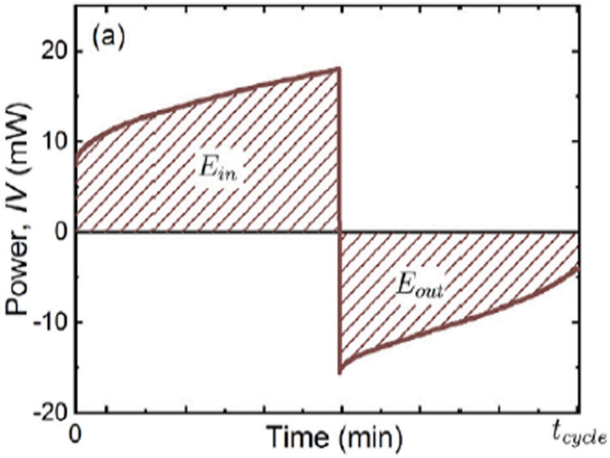

Fig. 8. Energy variation in the case of CDI system (after [139]).

opposite case, the system is discharged (E_{out}). The change of power for a CDI cell is exhibited in Fig. 8.

Hence, the net portion of E_{out} can be used for charging the second CDI system. That idea was used by Omosebi et al. [140] and is shown in Fig. 9.

The system for energy recovery was analyzed by Oyarzun et al. [141]. Their studies showed that energy storage and utilization efficiency were at the level of 90% for the initial voltage of 1 V. In the studies of FCDI connected to storage devices [142], the authors were able to recover about 10% of energy. A better result was noted by Lim et al. [143] as 25% recovery of energy for their FCDI system.

The described discrepancy in the evaluation of energy recovery shows that the CDI systems still need more advanced studies. The best example of the divergent view on the system can be found in papers comparing RO with CDI. Qin et al. [144] concluded that the energy efficiency of RO is higher than CDI. The development of more efficient electrodes, according to the authors, can marginally improve the desalination cost of brackish water. The opposite point of view has been presented by Porada et al. [145]. They showed that water recovery for the MCDI system is 95% and the energy consumption is remarkably lower than RO. They stated that the use of different process metrics enables comparison of different technics and makes controversial any attempt. They appeal for the unification of used parameters to not confuse the potential readers.

Generally, the CDI system can be used in double-action: for water demineralization and the generation of energy. The graphical abstract taken from the paper of Kang et al. [146] well picture that case (Fig. 10).

Comparing various processes for gathering energy from salinity gradient, it is a cheaper and non-toxic method [147]. The authors concluded that efficiencies of electro-dialytic, osmotic, and capacitive storage systems are alike. The most important constrain of the wide use of these systems is their membrane price.

The presented examples prove that there is a continuous development of technologies for both electricity and heat generation. In many respects, renewable energy technologies are still treated as a separate energy sector, separate from conventional energy. It is justified for some reasons, but the integration of energy systems considered as a whole requires the inclusion of renewable energy technologies in the electricity or thermal energy sectors as equivalent and mature solutions. With this approach, RES should no longer be considered as an alternative to conventional fuels, but widely used, provided that energy, economic and environmental criteria are met. This is extremely important in the case of high-energy-consuming desalination processes. Therefore, the challenge to be met is the development of renewable energy sources that can

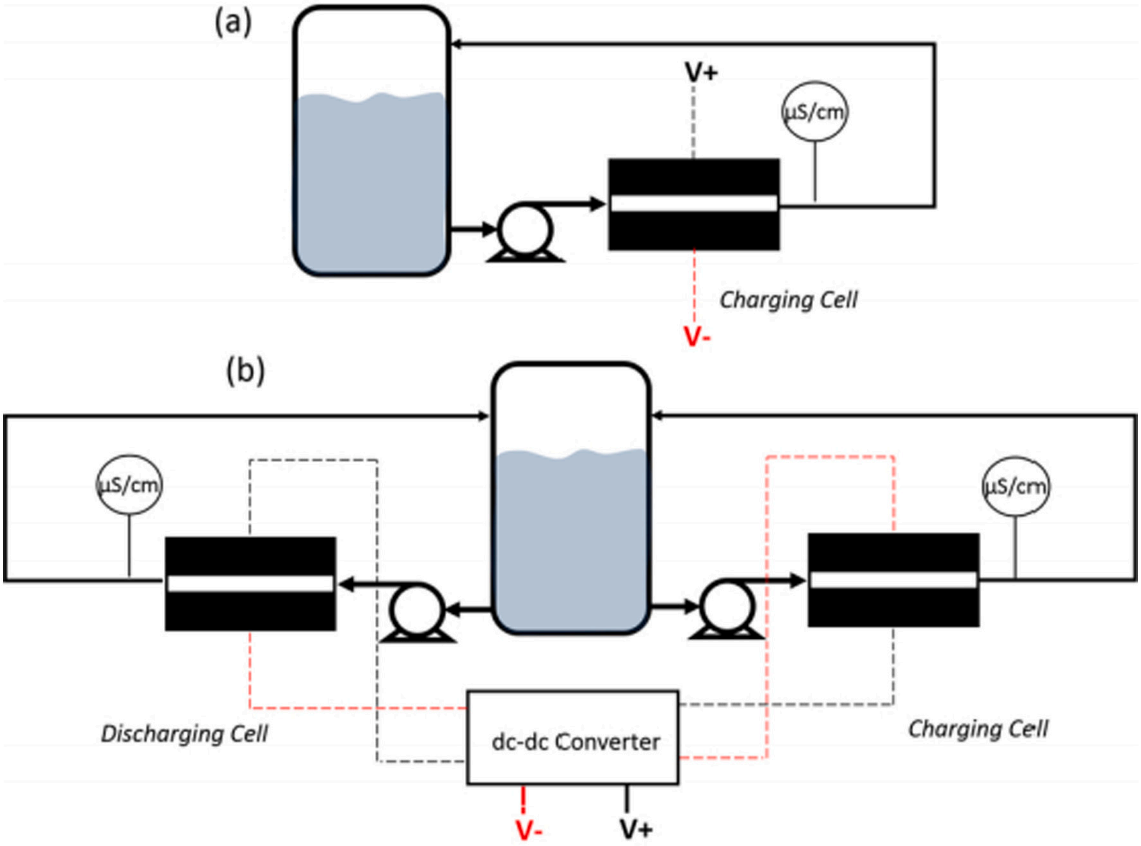

Fig. 9. Sketch of a) single CDI system and b) doubled CDI system with energy recovery (after [140]).

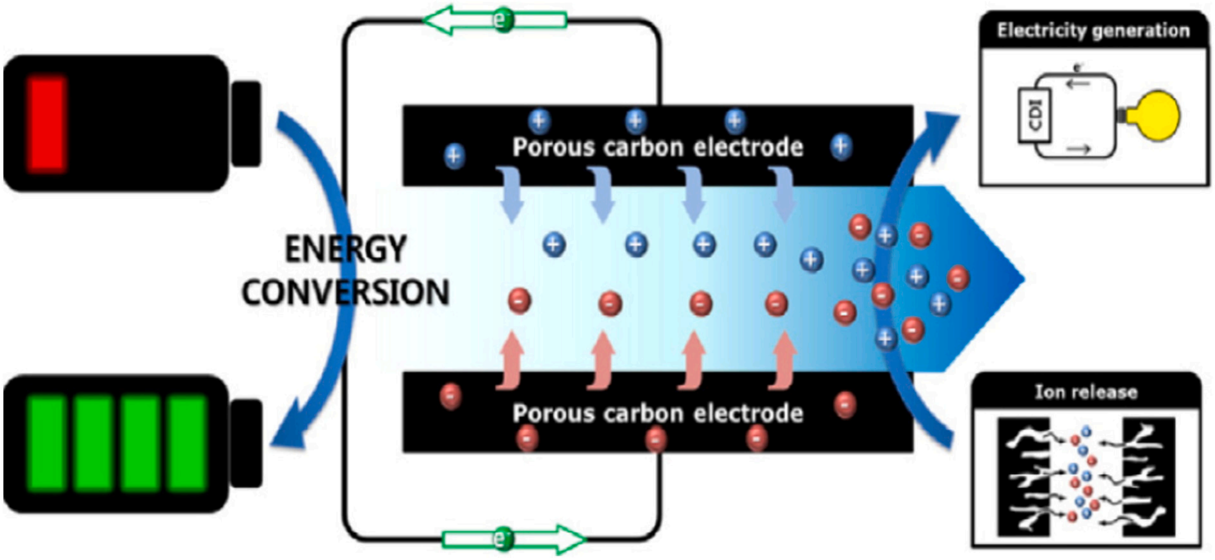

Fig. 10. Energy recovery in CDI system (after [146]).

be considered as alternatives, such as the use of a salinity gradient.

5. Advantages and disadvantages of using RES in geothermal water treatment processes

Considering the use of RES in the context of water treatment processes, especially in geothermal water desalination, as well as their general role in power engineering, one should refer to their advantages and disadvantages. Referring to ecological issues, it should be stated that the use of RES does not, first of all, emit pollutants into the environment at the stage of their functioning. A completely different situation occurs when conventional energy sources are used. In addition, there is negligible noise emission or even lack of it in the case of technologies as e.g., PV. The situation is similar in the case of light emission. An important aspect in favor of RESs is also the lack of the need to use significant amounts of water in cooling processes, typical for conventional energy generation.

Apart from the ecological issue, the positive impact of diversification of energy sources on a local and global scale should be considered. It impacts independence from the supply and prices of fossil fuels, followed by greater stability and predictability of energy prices on the market. The development of the region in which renewable energy is used is also significant, which is particularly visible in the case of geothermal energy and its recreational values. However, it should be noted that the downside to the use of RESs is their dependence on local meteorological, topographic, and geological conditions. In many cases, it causes the inability to use one renewable energy source and the need to look for integrated solutions to achieve the required power and the amount of energy generated.

In many cases, positive economic effects resulting from the use of RESs compared to conventional energy sources should be considered as an advantage, which was also often confirmed by the previously cited results of published research in water treatment processes. Considering the use of geothermal water and energy for driving membrane systems, a detailed cost analysis of the produced water from the geothermal water by an integrated UF-RO process, has been presented by Tomaszewska et al. [4,148]. As it was pointed out, the implementation of the mentioned process for geothermal water desalination taking into consideration 120 m^3/h water intake and electricity cost of EUR 0.117/kWh, required 2.0 kWh/m^3 of energy consumption by the integrated UF-RO system and finally 0.6 EUR/m^3 of the total cost of the water, which can be used for irrigation.

Generally and maybe the popular opinion is that RO process is considered expensive and should not be considered for desalination of geothermal water due to the high quality of product water. But as it was pointed out, if the membrane combinations were selected properly (e.g. by reducing concentrate as it was presented by Tomaszewska et al. [4,148] and/or by applying pyramidal design of RO system and/or mixing RO permeate with well water at a certain ratio may reduce the cost and consumption of large volume of well water.

Once again, however, it should be noted that this phenomenon is strongly dependent on local conditions, including prices of electricity and heat generated from conventional sources, for which RESs are to be an alternative.

6. Conclusions

The agriculture sector in the world mostly relies on fossil fuels. Increasing the share of RES contribute to improving the environmental impact of the agriculture sector, including the reduction of greenhouse gas emissions. Therefore, decreasing the dependency of agriculture and the agri-food chain on fossil fuels will contribute to global food security and climate protection. Apart from energetic aspects, water scarcity is an imminent problem for agriculture and the agri-food chain. Since water is essential for the proper growth of the crops and the sustainability of the agri-food chain, using the spent geothermal brine for agricultural activities should be considered. As an unexploited waste stream with high ionic content, the spent geothermal brine should be desalinated before use in irrigation. High specific energy consumption is the main barrier for the desalination process, However, if the proper technology solution to be used (e.g. reducing concentrate, applying pyramidal design of RO system, mixing RO permeate with well water at a certain ratio) may reduce the cost of adequate water production for irrigation.

Using fossil fuels accompanies greenhouse gas emissions, which harm the environment. Considering the water-food-energy nexus, use of RESs for safe agriculture and agri-food chain contributes to environmental protection and decreases the climate change effects of fossil fuel use. The challenge of providing drinking water in the required quantities means that desalination techniques not only look for technological opportunities to cooperate with RESs sustainably and stably but also the desalination technologies themselves are developed. An example of this is the aforementioned CDI method, which shows the potential to be modified to increase efficiency and become competitive with more established desalination technologies in cooperation with RES, such as

RO.

CRediT authorship contribution statement

Barbara Tomaszewska: Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Gulden Gokcen Akkurt:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision. **Michał Kaczmarczyk:** Writing – original draft. **Wiesław Bujakowski:** Writing – original draft. **Nazli Keles:** Writing – original draft. **Yakubu A. Jarma:** Writing – original draft. **Alper Baba:** Supervision, Project administration, Funding acquisition. **Marek Bryjak:** Conceptualization, Writing – original draft, Writing – review & editing. **Nalan Kabay:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no established conflicting financial interests or personal relations that may have affected the work stated in this paper.

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References

[1] T.M. Missimer, K.C. Ng, K. Thuw, M.W. Shahzad, Geothermal electricity generation and desalination: an integrated process design to conserve latent heat with operational improvements, Desalin. Water Treat. 57 (2016) 23110–23118.

[2] EEA, European Environment Agency. "Actual Turkish water use and projection for 2023". https://www.eea.europa.eu/data-and-maps/figures/actual-turkish-water-use- (2018).

[3] Tomaszewska, B., Dendys, M., Tyszer, M., Comparison of the availability of groundwater information sources in Poland with other European countries: knowledge inventory for hydrogeology research – project KINDRA. E3S Web of Conferences 22 (2017) art. no. 00178, 1–8.

[4] B. Tomaszewska, L. Pająk, J. Bundschuh, W. Bujakowski, Low-enthalpy geothermal energy as a source of energy and integrated freshwater production in inland areas: technological and economic feasibility, Desalination 435 (2018) 35–44.

[5] B. Tomaszewska, M. Tyszer, M. Dendys, The availability of groundwater information sources in relations to the transposition of the WFD into Polish law, in: Project KINDRA, Thermal Science and Engineering Process 5, 2018, pp. 437–443.

[6] J. Bundschuh, G. Chen, B. Tomaszewska, N. Ghaffour, S. Mushtaq, I. Hamawand, K. Reardon-Smith, T. Maraseni, T. Banhazi, H. Mahmoudi, M. Goosen, L. D. Antille, Solar, wind and geothermal energy applications in agriculture: back to the future? in: J. Bundschuh, G. Chen, D. Chandrasekharam, J. Piechocki (Eds.), Geothermal, Wind and Solar Energy Applications in Agriculture and Aquaculture London: CRC Press; Taylor & Francis Group, cop. (Sustainable Energy Developments; ISSN 2164-0645), 2017, pp. 1–32 (ISBN: 978-1-138-02970-5; e-ISBN: 978-1-315-15896-9).

[7] EEA-European Environment Agency. Air quality in Europe-2019 report, No 10/2019, https://www.eea.europa.eu/publications/air-quality-in-europe- (2019).

[8] CSO, Consumption of fuels and energy carriers in 2016, Central Statistical Office, 2017, pp. 12–19.

[9] CSO, Energy Statistics in 2013 and 2015, Central Statistical Office, 2015, pp. 217–220.

[10] CSO, Energy Statistics in 2015 and 2016, Central Statistical Office, 2017, pp. 217–220.

[11] TSI, Turkish greenhouse gas inventory 1990-2016, in: National Inventory Report for submission under the United Nations Framework Convention on Climate Change, Turkish Statistical Institute, 2018, pp. 244–288.

[12] M. Thimmaraju, D. Sreepada, G.S. Babu, B.K. Dasari, S.K. Velpula, N. Vallepu, Desalination of Water, Desalination Fact Sheet, Australian Water Association, What Is Water Scarcity?, 2018. Oct 6,2017, https://www.fluencecorp.com/what-is-water-scarcity/.

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

[14] R. Dashtpour, S.N. Al-Zubaidy, Energy efficient reverse osmosis desalination process, Int. J. Environ. Sci. Dev. 3 (4) (2012) 339.

[15] B. Tomaszewska, M. Bodzek, Desalination of geothermal waters using a hybrid UF-RO process. Part I. Boron removal in pilot-scale tests, Desalination 319 (2013) 99–106.

[16] B. Tomaszewska, M. Bodzek, The removal of radionuclides during desalination of geothermal waters containing boron using the BWRO system, Desalination 309 (2013) 284–290.

[17] A.J. Karabelas, C.P. Koutsou, M. Kostoglou, D.C. Sioutopoulos, Analysis of specific energy consumption in reverse osmosis desalination processes, Desalination 431 (2018) 15–21.

[18] M. Kettani, P. Bandelier, Techno-economic assessment of solar energy coupling with large-scale desalination plant: the case of Morocco, Desalination 494 (2020), 114627.

[19] C. Chen, Y. Jiang, Z. Ye, Y. Yang, L. Hou, Sustainably integrating desalination with solar power to overcome future freshwater scarcity in China, Glob. Energy Interconnection 2 (2019) 098–113.

[20] P. Gładysz, A. Sowiżdżał, M. Miecznik, L. Pająk, Carbon dioxide-enhanced geothermal systems for heat and electricity production: energy and economic analyses for central Poland, Energy Convers. Manag. 220 (2020), 113142, https://doi.org/10.1016/j.enconman.2020.113142.

[21] A. Sowiżdżał, P. Gładysz, L. Pająk, Sustainable use of petrothermal resources—a review of the geological conditions in Poland, Resources 10 (1) (2021) 1–18 (Article number 8).

[22] J. Bundschuh, B. Tomaszewska, N. Ghaffour, I. Hamawand, H. Mahmoudi, M. Goosen, Coupling geothermal direct heat with agriculture, in: J. Bundschuh, B. Tomaszewska (Eds.), Geothermal Water Management 2, CRC Press. Taylor & Francis Group, cop. 2018, (Sustainable Water Developments: Resources, Management, Treatment, Efficiency and Reuse); ISSN 2373-7506; vol, 2018, pp. 77–300 (ISBN: 978-1-138-02721-3; e-ISBN: 978-1-315-73497-2).

[23] J. Bundschuh, M. Kaczmarczyk, N. Ghaffour, B. Tomaszewska, State-of-the-art of renewable energy sources used in water desalination: present and future prospects, Desalination 508 (2021) 115035.

[24] A. Baba, H. Sözbilir, Source of arsenic based on geological and hydrogeochemical properties of geothermal systems in Western Turkey, Chem. Geol. 334 (2012) 364–377.

[25] A. Cakın, G. Gokcen, A.E. Eroğlu, A. Baba, Hydrogeochemistry and environmental properties of geothermal fields. Case study: Balçova, Izmir-Turkey, energy sources, part A: recovery, Util. Environ. Eff. 34 (8) (2012) 732–745.

[26] Y.A. Jarma, A. Karaoglu, O. Tekin, A. Baba, H.E. Okten, B. Tomaszewska, K. Bostancı, M. Arda, N. Kabay, Assessment of different nanofiltration and reverse osmosis membranes for simultaneous removal of arsenic and boron from spent geothermal water, J. Hazard. Mater. (2020), https://doi.org/10.1016/j.jhazmat.2020.124129.

[27] G. Gökçen, Evaluation of Geothermal Energy Projects Applied in Turkey Based on Clean Energy: Balçova Geothermal District Heating System-Izmir and Kizildere Geothermal Power Plant-Denizli, Turkish Scientific and Technological Research Council of Turkey, Project No: 104M301, 2008 (In Turkish).

[28] N. Hilal, G.J. Kim, C. Somerfield, Boron removal from saline water: a comprehensive review, Desalination 273 (2011) 23–35.

[29] N. Kabay, J. Bundschuh, B. Hendry, M. Bryjak, K. Yoshizuka, P. Bhattacharya, S. Anac (Eds.), The Global Arsenic Problem: Challenges for Safe Water Production, CRC Press, Boca Raton, FL, 2010.

[30] N. Kabay, E. Guler, M. Bryjak, Boron in seawater and methods for its separation: a review, Desalination 261 (3) (2010) 212–217.

[31] U. Roessner, J. Patterson, M. Forbes, G. Fincher, P. Langridge, A. Bacic, An investigation of boron toxicity in barley using metabolomics, Plant Physiol. 142 (2006) 1087–1101.

[32] K. Yoshizuka, N. Kabay, M. Bryjak, Arsenic and boron in geothermal water and their removal, in: N. Kabay, J. Bundschuh, B. Hendry, M. Bryjak, K. Yoshizuka, P. Bhattacharya, S. Anac (Eds.), The Global Arsenic Problem: Challenges for Safe Water Production, CRC Press, Boca Raton, FL, 2010, pp. 103–120.

[33] WHO, Guidelines for Drinking-water Quality. 4th edition, Geneva, Switzerland, 2011.

[34] J. Bundschuh, M. Aurora Armienta, N. Morales-Simfors, M. Ayaz Alam, D. L. López, V. Delgado Quezada, S. Dietrich, J. Schneider, J. Tapia, O. Sracek, E. Castillo, L.M. Marco Parra, M. Altamirano Espinoza, L.R. Guimarães Guilherme, N. Nahuel Sosa, N. Khan Niazi, B. Tomaszewska, K. Lizama Allende, K. Bieger, D.L. Alonso, P.F.B. Brandão, P. Bhattacharya, M.I. Litter, A. Ahmad, Arsenic in Latin America: New findings on source, mobilization and mobility in human environments in 20 countries based on decadal research 2010–2020, Crit. Rev. Environ. Sci. Technol. (2020), https://doi.org/10.1080/10643389.2020.1770527.

[35] J. Bundschuh, J. Schneider, M.A. Alamc, N.K. Niazi, I. Herath, F. Parvez, B. Tomaszewska, L.R. Guimaraes Guilherme, J.P. Maity, D.L. López, A. Fernández Cirelli, A. Pérez-Carrera, N. Morales-Simfors, M.T. Alarcón-Herrera, P. Baisch, D. Mohan, A. Mukherjee, Seven potential sources of arsenic pollution in Latin America and their environmental and health impacts, Sci. Total Environ. 780 (2021) 146274.

[36] T.S.Y. Choong, T.G. Chuah, Y. Robiah, F.L. Gregory Koay, I. Azni, Arsenic toxicity, health hazards and removal techniques from water: an overview, Desalination 217 (2007) 139–166.

[37] K. Yoshizuka, S. Nishihama, H. Sato, Analytical survey of arsenic in geothermal waters from sites in Kyushu, Japan, and a method for removing arsenic using magnetite, Environ. Geochem. Health 32 (2010) 297–302.

[38] M. Badruk, N. Kabay, M. Demircioglu, H. Mordogan, U. Ipekoglu, Removal of boron from wastewater of geothermal power plant by selective ion-exchange resins. I. Batch-sorption-elution studies, Sep. Sci. Technol. 34 (13) (1999) 2553–2569.

[39] M. Badruk, N. Kabay, M. Demircioglu, H. Mordogan, U. Ipekoglu, Removal of boron from wastewater of geothermal power plant by selective ion-exchange resins. I. Column-mode sorption-elution studies, Sep. Sci. Technol. 34 (15) (1999) 2981–2995.

[40] N. Bicak, N. Bulutcu, B.F. Senkal, M. Gazi, Modification of crosslinked glycidyl methacrylate-based polymers for boron-specific column extraction, React. Funct. Polym. 47 (2001) 175–184.

[41] M. Bryjak, J. Wolska, N. Kabay, Removal of boron from seawater by adsorption-membrane hybrid process: implementation and challenges, Desalination 223 (2008) 57–62.

[42] Y. Inukai, Y. Tanaka, T. Matsuda, N. Mihara, K. Yamada, N. Nambu, D. Itoh, Y. Kaida, S. Yasuda, Removal of boron (III) by N-methylglucamine-type cellulose derivatives with higher adsorption rate, Anal. Chim. Acta 511 (2004) 261–265.

[43] N. Kabay, I. Yilmaz, S. Yamac, S. Samatya, M. Yuksel, U. Yuksel, M. Arda, M. Saglam, T. Iwanaga, K. Hirowatari, Removal and recovery of boron from geothermal wastewater by selective ion exchange resins. I. Laboratory tests, React. Funct. Polym. 60 (2004) 163–170.

[44] N. Kabay, I. Yılmaz, S. Yamac, M. Yuksel, U. Yuksel, N. Yildirim, O. Aydogdu, T. Iwanaga, K. Hirowatari, Removal and recovery of boron from geothermal wastewater by selective ion-exchange resins. II. Field tests, Desalination 167 (2004) 427–438.

[45] N. Kabay, I. Yilmaz, M. Bryjak, M. Yuksel, Removal of boron from from aqueous solutions by ion exchange-membrane hybrid process, Desalination 198 (2006) 74–81.

[46] N. Kabay, S. Sarp, M. Yuksel, M. Kitis, H. Koseoğlu, Ö. Arar, M. Bryjak, R. Semiat, Removal of boron from SWRO permeate by boron selective ion exchange resins containing N-methylglucamine groups, Desalination 223 (2008) 49–56.

[47] N. Kabay, M. Bryjak, S. Schlosser, M. Kitis, S. Avlonitis, Z. Matejka, I. Al-Mutaz, M. Yuksel, Adsorption-membrane filtration (AMF) hybrid process for boron removal from seawater – an overview, Desalination 223 (2008) 38–48.

[48] R. Kunin, A.F. Preuss, Characterization of boron-specific ion exchange resins, Ind. Eng. Chem. Prod. Res. Dev. 3 (4) (1964) 304–306.

[49] C. Marston, M. Busch, S. Prabhakaran, A boron selective resin for seawater desalination, in: Presented Data During European Desalination Society Conference on Desalination and Environment, Santa Margherita Liqure (Italy), 2005.

[50] O. Okay, H. Guclu, E. Soner, T. Balkas, Boron pollution in Simav River, Turkey and various methods for boron removal, Water Res. 19 (1985) 857–862.

[51] H. Parshova, E. Mistova, Z. Matejka, L. Jelinek, N. Kabay, P. Kauppinen, Comparison of several polymeric sorbents for selective boron removal from reverse osmosis permeate, React. Funct. Polym. 67 (2007) 1622–1627.

[52] O. Recepoglu, U. Beker, A preliminary study of boron removal from Kizildere Turkey geothermal wastewater, Geothermics 20 (1991) 83–89.

[53] Y.K. Recepoğlu, N. Kabay, I. Yılmaz-Ipek, M. Arda, M. Yüksel, K. Yoshizuka, S. Nishihama, Packed bed column dynamic study for boron removal from geothermal brine by a chelating fiber and breakthrough curve analysis by using mathematical models, Desalination 437 (2018) 1–6.

[54] S. Samatya, E. Orhan, N. Kabay, A. Tuncel, Comparative boron removal performance of monodisperse-porous particles with molecular brushes via "click chemistry" and direct coupling, Colloids Surf. A Physicochem. Eng. Asp. 372 (2010) 102–106.

[55] S. Samatya, N. Kabay, A. Tuncel, A hydrophilic matrix for boron isolation: monodisperse porous poly(glycidyl methacrylate-co-ethylene dimethacrylate) particles carrying diol functionality, React. Funct. Polym. 70 (2010) 555–562.

[56] S. Samatya, N. Kabay, A. Tuncel, Monodisperse porous N-methyl-D-glucamine functionalized poly(vinylbenzyl chloride-co-divinylbenzene) beads as boron selective sorbent, J. Appl. Polym. Sci. 126 (2012) 1475–1483.

[57] S. Samatya, A. Tuncel, N. Kabay, Boron removal from geothermal water by a novel monodisperse porous poly(GMA-co-EDM) resin containing N-methyl-D-glucamine functional group, Solvent Extraction Ion Exch. 30 (2012) 341–349.

[58] S. Samatya, A. Tuncel, N. Kabay, Boron removal from RO permeate of geothermal water by monodisperse poly(vinylbenzyl chloride-co-divinylbenzene) beads containing N-methyl-D-glucamine, Desalination 364 (2015) 75–81.

[59] S. Samatya, P. Koseoğlu, N. Kabay, A. Tuncel, M. Yuksel, Utilization of geothermal water as irrigation water after boron removal by monodisperse nanoporous polymers containing NMDG in sorption-ultrafiltration hybrid process, Desalination 364 (2015) 62–67.

[60] P. Santander, B.L. Rivas, B.F. Urbano, I. Yılmaz Ipek, G. Özkula, M. Arda, M. Yuksel, M. Bryjak, T. Kozlecki, N. Kabay, Removal of boron from geothermal water by a novel boron selective resin, Desalination 310 (2013) 102–108.

[61] M.O. Simonnot, C. Castel, M. Nikolai, C. Rosin, M. Sardin, H. Jaufferet, Boron removal from drinking water with a boron selective resin: is the treatment really selective? Water Res. 34 (2000) 109–116.

[62] I. Yilmaz, N. Kabay, M. Bryjak, M. Yuksel, J. Wolska, A. Koltuniewicz, A submerged ion exchange hybrid process for boron removal, Desalination 198 (2006) 310–315.

[63] I. Yilmaz-Ipek, N. Kabay, M. Yuksel, R. Holdich, M. Bryjak, Effect of ionic strength of solution on boron mass transfer by ion exchange separation, Sep. Sci. Technol. 42 (5) (2007) 1013–1029.

[64] I. Yilmaz-Ipek, R. Holdich, N. Kabay, M. Bryjak, M. Yuksel, Kinetic behavior of boron selective resins for boron removal using seeded microfiltration system, React. Funct. Polym. 67 (2007) 1628–1634.

[65] I. Yilmaz-Ipek, N. Kabay, M. Yuksel, Ö. Kirmizisakal, M. Bryjak, Removal of boron from Balçova-Izmir geothermal water by ion exchange process: batch and column studies, Chem. Eng. Commun. 196 (1) (2009) 277–289.

[66] I. Yilmaz-Ipek, P. Koseoglu, U. Yüksel, N. Yasar, G. Yolseven, M. Yuksel, N. Kabay, Separation of boron from geothermal water using a boron selective macroporous weak base anion exchange resin, Sep. Sci. Technol. 45 (2010) 809–813.

[67] I. Yilmaz-Ipek, N. Kabay, A.R. Ozdural, Non-equilibrium sorption modeling for boron removal from geothermal water using sorption-microfiltration hybrid method, Chem. Eng. Process. Process Intensif. 50 (2011) 599–607.

[68] I. Yilmaz-Ipek, N. Kabay, M. Yuksel, Modeling of fixed bed column studies for removal of boron from geothermal water by selective ion exchange resins, Desalination 310 (2013) 151–157.

[69] Bryjak, M., Kabay, N. Boron removal from water by sorption-membrane filtration hybrid process. In: Kabay, N., Bryjak, M.&Hilal, N. (eds.) Boron Separation Processes. Elsevier, Amsterdam. (2015) pp. 237–248.

[70] N. Kabay, I. Yilmaz-Ipek, I. Soroko, M. Makowski, O. Kirmizisakal, S. Yag, M. Bryjak, M. Yuksel, Removal of boron from Balcova geothermal water by ion exchange microfiltration hybrid process, Desalination 241 (2009) 167–173.

[71] N. Kabay, P. Köseoğlu, E. Yavuz, U. Yüksel, M. Yüksel, An innovative integrated system for boron removal from geothermal water using RO process and ion exchange-ultrafiltration hybrid method, Desalination 316 (2013) 1–7.

[72] N. Kabay, P. Köseoğlu, D. Yapıcı, U. Yüksel, M. Yüksel, Coupling ion exchange with ultrafiltration for boron removal from geothermal water-investigation of process parameters and recycle tests, Desalination 316 (2013) 17–22.

[73] E. Çermikli, F. Şen, E. Altıok, J. Wolska, P. Cyganowski, N. Kabay, M. Bryjak, M. Arda, M. Yüksel, Performances of novel chelating ion exchange resins for boron and arsenic removal from saline geothermal water using adsorption-membrane filtration hybrid process, Desalination 491 (2020), 114504.

[74] Şen, F., Altıok, E., Cyganowski, P., Wolska, J., Bryjak, M., Kabay, N., Arda, M., Yüksel, M., Reclamation of RO Permeate and Concentrate of Geothermal Water by New Chelating Resins Having N-methyl-D-glucamine Ligands, Separation and Purification Technology 254 (2021) 117558.

[75] Ş.G. Öner, N. Kabay, E. Güler, M. Kitiş, M. Yüksel, A comparative study for the removal of boron and silica from geothermal water by cross-flow flat sheet reverse osmosis method, Desalination 283 (2011) 10–15.

[76] E. Yavuz, E. Güler, G. Sert, Ö. Arar, M. Yüksel, Ü. Yüksel, M. Kitiş, N. Kabay, Removal of boron from geothermal water by RO system-I—effect of membrane configuration and applied pressure, Desalination 310 (2013) 130–134.

[77] E. Guler, D. Ozakdağ, M. Arda, M. Yuksel, N. Kabay, Effect of temperature on seawater desalination-water quality analysis for desalinated seawater for its use as drinking water and irrigation water, environ, Geochem. Health 32 (2010) 335–339.

[78] E. Yavuz, Ö. Arar, M. Yüksel, Ü. Yüksel, N. Kabay, Removal of boron from geothermal water by RO system-II-effect of pH, Desalination 310 (2013) 135–139.

[79] W. Górecki, A. Sowiżdżał, M. Hajto, A. Wachowicz-Pyzied, Atlases of geothermal waters and energy resources in Poland, Environ. Earth Sci. 74 (2015) 7487–7495.

[80] B. Tomaszewska, New approach to the utilisation of concentrates obtained during geothermal water desalination, Desalin. Water Treat. 128 (2018) 407–413.

[81] W. Bujakowski, B. Tomaszewska, M. Miecznik, The Podhale geothermal reservoir simulation for long-term sustainable production, Renew. Energy 99 (2016) 420–430.

[82] V.G. Gude, Geothermal source potential for water desalination-current status and future perspective, Renew. Sust. Energ. Rev. 57 (2016) 1038–1065.

[83] Bourouni K., Chaibi, M.T., Application of Geothermal Energy for Brackish Water Desalination in the South of Tunisia, Proceedings World Geothermal Congress 2005 Antalya, Turkey, 24–29 April 2005.

[84] B. Kárason, Utilization of Offshore Geothermal Resources for Power Production (Thesis) Master of Science in Sustainable Energy Engineering, School of Science and Engineering, Reykjavík University, 2013.

[85] F. Manenti, M. Masi, G. Santucci, G. Manenti, Parametric simulation and economic assessment of a heat integrated geothermal desalination plant, Desalination 317 (2013) 193–205.

[86] M.C. Suárez-Arriaga, J. Bundschuh, F. Samaniego, Assessment of submarine geothermal resources and development of tools to quantify their energy potentials for environmentally sustainable development, J. Clean. Prod. 83 (2014) 21–32.

[87] S.A.L. Bouguecha, M. Dhahbi, Fluidised bed crystalliser and air gap membrane distillation as a solution to geothermal water desalination, Desalination 152 (1–3) (2002) 237–244.

[88] 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, Desalination 356 (2015) 94–114.

[89] A. Hepbasli, Z. Alsuhaibani, A key review on present status and future directions of solar energy studies and applications in Saudi Arabia, Renew. Sust. Energ. Rev. 15 (2011) 5021–5050.

[90] C. Karystsas, Mediterranean Conference on Renewable Energy Sources for Water Production, European Commission, CRES Santorini, Greece, 1996, pp. 128–131.

[91] Sephton Water Technology, VTE Geothermal Desalination Pilot/demonstration Project, 2010.

[92] Sephton Water Technology, VTE geothermal desalination pilot/demonstration project, (2012).

[93] Rodriguez, G., Rodriguez, M., Perez, J., Veza, J., A systematic approach to desalination powered by solar, wind and geothermal energy sources, Proc Mediterranean Conference on Renewable Energy Sources for Water Production, European Commission, EURORED Network, CRES, EDS, 10–12 June 1996, Santorini, (1996), 20–25.

[94] M. Kaczmarczyk, B. Tomaszewska, L. Pająk, Geological and thermodynamic analysis of low enthalpy geothermal resources to electricity generation using ORC and Kalina Cycle Technology, Energies 13 (6) (2020), 1335, https://doi.org/10.3390/en13061335.

[95] M. Kaczmarczyk, B. Tomaszewska, A. Operacz, Sustainable utilization of low enthalpy geothermal resources to electricity generation through a Cascade System, Energies 13 (10) (2020), 2495, https://doi.org/10.3390/en13102495.

[96] H. Gutiérrez, S. Espíndola, Using low enthalpy geothermal resources to desalinate seawater and electricity production on desert areas in Mexico, GHC Bull. 19-24 (2010).

[97] C. Karystsas, D. Mendrinos, G. Radoglou, The current geothermal exploration and development of the geothermal field of Milos Island in Greece, GHC Bull. (2004) 17–21.

[98] C.J. Koroneos, A.L. Polyzakis, D.C. Rovas, Combine desalination-cooling plant in Nisyros Island utilizing geothermal energy, in: Proc 3rd IASME/WSEAS Int Conf, Agios Nikolaos, Greece, 2007.

[99] A. Herndon, Energy Makes Up Half of Desalination Plant Costs: Study. Bloomberg. http://www.bloomberg.com/news/2013-05-01/energy-makes-up-half-of-desalination-plant-costs-study.html, 2013.

[100] M.A.M. Khan, S. Rehman, F.A. Al-Sulaiman, A hybrid renewable energy system as a potential energy source for water desalination using reverse osmosis: A review, renew, Sust. Energ. Rev. 97 (2018) 456–477.

[101] Ghermandi, A., Messalem, R., Solar-driven desalination with reverse osmosis: the state of the art, Desalination Water Treat. 7 (1–3) (2009) 285–296.

[102] M. Alhaj, S.G. Al-Ghamdi, Why is powering thermal desalination with concentrated solar power expensive? Assessing economic feasibility and market commercialization barriers, Sol. Energy 189 (2019) 480–490.

[103] J. Rheinländer, D. Geyer, Photovoltaic Reverse Osmosis and Electrodialysis, Application of Solar Photovoltaic Energy Production to RO and ED Desalination Processes, Seawater Desalination: Conventional and Renewable Energy Processes, Springer, Berlin Heidelberg, Berlin, Heidelberg, 2009, pp. 189–211.

[104] L. Anne, V. Michel, Solar Photovoltaic Energy, Institution of Engineering & Technology, Stevenage, United Kingdom, 2010.

[105] S.M. Wazed, B.R. Hughes, D. O'Connor, J.K. Calautit, Solar driven irrigation systems for remote rural farms, Energy Procedia 142 (2017) 184–191.

[106] A. Ruiz-García, I. Nuez, Long-term intermittent operation of a full-scale BWRO desalination plant, Desalination 489 (2020), 114526.

[107] M.H. El-Awady, H.H. El-Ghetany, M. Abdel Latif, Experimental investigation of an integrated solar green house for water desalination, plantation and wastewater treatment in remote arid Egyptian communities, Energy Procedia 50 (2014) 520–527.

[108] X. Tong, S. Liu, Y. Chen, J. Crittenden, Thermodynamic analysis of a solar thermal facilitated membrane seawater desalination process, J. Clean. Prod. 256 (2020), 120398.

[109] A.B. Pouyfaucon, L. García-Rodríguez, Solar thermal-powered desalination: a viable solution for a potential market, Desalination 435 (2018) 60–69.

[110] Delgado-Torres, A.M., García-Rodríguez, L., Peñate, B., A. de la Fuente, J., Melián, G., Current trends and future developments on (bio-) membranes, chapter 3 - water desalination by solar-powered RO systems, Renew. Energy, (2019), 45–84.

[111] E.L. Peterson, S.R. Gray, Effectiveness of desalination powered by a tracking solar array to treat saline bore water, Desalination 293 (2012) 94–103.

[112] G. Filippini, M.A. Al-Obaidi, F. Manenti, I.M. Mujtaba, Design and economic evaluation of solar-powered hybrid multi effect and reverse osmosis system for seawater desalination, Desalination 465 (2019) 114–125.

[113] F. Calise, F.L. Cappiello, R. Vanoli, M. Vicidomini, Economic assessment of renewable energy systems integrating photovoltaic panels, seawater desalination and water storage, Appl. Energy 253 (2019), 113575.

[114] M.A. Abdelkareem, M. El Haj Assad, E.T. Sayed, B. Soudan, Recent progress in the use of renewable energy sources to power water desalination plants, Desalination 435 (2018) 97–113.

[115] S. Loutatidou, N. Liosis, R. Pohl, T.B. Ouarda, H.A. Arafat, Wind-powered desalination for strategic water storage: techno-economic assessment of concept, Desalination 408 (2017) 36–51.

[116] M. Gökçek, Ö.B. Gökçek, Technical and economic evaluation of freshwater production from a wind-powered small-scale seawater reverse osmosis system (WP-SWRO), Desalination 381 (2016) 47–57.

[117] M.S. Miranda, D. Infield, A wind-powered seawater reverse-osmosis system without batteries, Desalination 153 (1) (2003) 9–16.

[118] A. Dehmas, N. Kherba, F.B. Hacene, N.K. Merzouk, M. Merzouk, H. Mahmoudi, M. F. Goosen, On the use of wind energy to power reverse osmosis desalinationplant: a case study from Ténès (Algeria), Renew. Sust. Energ. Rev. 15 (2) (2011) 956–963.

[119] S. Aminfard, F.T. Davidson, M.E. Webber, Multi-layered spatial methodology for assessing the technical and economic viability of using renewable energy to power brackish groundwater desalination, Desalination 450 (2019) 12–20.

[120] I. Padrón, D. Avila, G.N. Marichal, J.A. Rodríguez, Assessment of hybrid renewable energy systems to supplied energy to autonomous desalination systems in two islands of the canary archipelago, Renew. Sust. Energ. Rev. 101 (2019) 221–230.

[121] A. Maleki, F. Pourfayaz, M.H. Ahmadi, Design of a cost-effective wind/photovoltaic/hydrogen energy system for supplying a desalination unit by a heuristic approach, Sol. Energy 139 (2016) 666–675.

[122] R. Fornarelli, F. Shahnia, M. Anda, P.A. Bahri, G. Ho, Selecting an economically suitable and sustainable solution for a renewable energy-powered water desalination system: a rural Australian case study, Desalination 435 (2018) 128–139.

[123] M.T. Mito, X. Ma, H. Albuflasa, P.A. Davies, Reverse osmosis (RO) membrane desalination driven by wind and solar photovoltaic (PV) energy: state of the art and challenges for large-scale implementation, Renew. Sust. Energ. Rev. 112 (2019) 669–685.

[124] A. Mollahosseini, A. Abdelrasoul, S. Sheibany, M. Amini, S.K. Salestan, Renewable energy-driven desalination opportunities-A case study, J. Environ. Manag. 239 (2019) 187–197.

[125] T.N. Bitaw, K. Park, D.R. Yang, Optimization on a new hybrid forward osmosis-electrodialysis-rverse osmosis seawater desalination process, Desalination 398 (2016) 265–281.

[126] M.O. Atallah, M.A. Farahat, M.E. Lotfy, T. Senjyu, Operation of conventional and unconventional energy sources to drive a reverse osmosis desalination plant in Sinai Peninsula, Egypt, Renew. Energy 145 (2020) 141–152.

[127] M.S. Azhar, G. Rizvi, I. Dincer, Integration of renewable energy based multigeneration system with desalination, Desalination 404 (2017) 72–78.

[128] V. Okati, A. Ebrahimi-Moghadam, A. Behzadmehr, M. Farzaneh-Gord, Proposal and assessment of a novel hybrid system for water desalination using solar and geothermal energy sources, Desalination 467 (2019) 229–244.

[129] A. Colmenar-Santos, E. Palomo-Torrejon, F. Mur-Perez, E. Rosales-Asensio, Thermal desalination potential with parabolic trough collectors and geothermal energy in the Spanish southeast, Appl. Energy 262 (2020), 114433.

[130] P.M. Biesheuvel, J.E. Dykstra, Physics of Electrochemical Processes, in: http://www.physicsofelectrochemicalprocesses.com, 2020.

[131] P.M. Biesheuvel, A. Van der Wal, Membrane capacitive deionization, J. Membr. Sci. 346 (2010) 256–262.

[132] D. Brogioli, Extracting renewable energy from a salinity difference using a capacitor, Phys. Rev. Lett. 103 (2009), 058501.

[133] D. Brogioli, R. Ziano, R.A. Rica, D. Salerno, F. Mantegazza, Capacitive mixing for the extraction of energy from salinity differences: survey of experimental results and electrochemical models, J. Colloid Interface Sci. 407 (2013) 457–466.

[134] R.A. Rica, R. Ziano, D. Salerno, F. Mantegazza, R. Van Roij, D. Brogioli, Capacitive mixing for harvesting the free energy of solutions at different concentrations, Entropy 15 (2013) 1388–1407.

[135] N.Y. Yip, D. Brogioli, H.V.M. Hamelers, K. Nijmeijer, Salinity gradients for sustainable energy: primer, progress, and prospects, Environ. Sci. Technol. 50 (2016) 12072–12094.

[136] A. Siekierka, K. Smolinska-Kempisty, M. Bryjak, Charge-doped electrodes for power production using the salinity gradient in CapMix, Desalination 495 (2020), 114670.

[137] G.R. Iglesias, S. Ahualli, M.M. Fernandez, M.L. Jimenez, A.V. Delgado, Stacking of capacitive cells for electrical energy production by salinity exchange, J. Power Sources 318 (2016) 283–290.

[138] X. Kong, A. Gallegos, D. Lu, Z. Liu, J. Wu, A molecular theory for optimal blue energy extraction by electrical double layer expansion, Phys. Chem. Chem. Phys. 17 (2015) 23970–23976.

[139] S.A. Hawks, A. Ramachandran, S. Porada, P.G. Camphell, M.E. Suss, P. M. Biesheuvel, J.G. Santiago, A. Stadermann, Performance metrics for the objective assessment of capacitive deionization systems, Water Res. 152 (2019) 126–137.

[140] A. Omosebi, Z. Li, N. Holubowitch, X. Gao, J. Landon, A. Cramer, K. Liu, Energy recovery in capacitive deionization systems with inverted operation characteristics, Environ. Sci. 6 (2020) 321–330.

[141] D.J. Oyarzun, S.A. Hawks, P.G. Campbell, A. Hemmarifar, A. Krishna, J. S. Santiago, M. Stadermann, Energy transfer for storage or recovery in capacitive deionization using a DC-DC converter, J. Power Sources 448 (2020), 227409.

[142] J. Ma, P. Liang, X. Sun, H. Zhang, Y. Bian, F. Yang, J. Bai, Q. Gong, X. Huang, Energy recovery from the flow-electrode capacitive deionization, J. Power Sources 421 (2019) 50–55.

[143] H. Lim, Y. Ha, H.B. Jung, P.S. Jo, H. Yoon, D. Quyen, N. Cho, C.Y. Yoo, Y. Cho, Energy storage and generation through desalination using flow-electrodes capacitive deionization, J. Ind. Eng. Chem. 81 (2020) 317–322.

[144] M. Qin, A. Deshmukh, R. Epszein, S.K. Patel, O.M. Owoseni, W.S. Walker, M. Elimelech, Comparison of energy consumption in desalination by capacitive deionization and reverse osmois, Desalination 455 (2019) 100–114.

[145] S. Porada, L. Zhang, J.E. Dykstra, Energy consumption in membrane capacitive deionization and comparison with reverse osmosis, Desalination 488 (2020), 114383.

[146] J. Kang, T. Kim, H. Shin, J. Lee, J.I. Ha, J. Yoon, Direct energy recovery system for membrane capacitive deionization, Desalination 398 (2016) 144–150.

[147] Z. Jalili, K.W. Krakhella, K.E. Einarsrud, O.S. Burhaim, Energy generation and storage by salinity gradient power: a model-based assessment, J. Energy Storage 24 (2019), 100755.

[148] B. Tomaszewska, L. Pająk, M. Bodzek, Application of a hybrid UF-RO process to geothermal water desalination. Concentrate disposal and costs analysis, Archiv. Environ. Prot. 40 (3) (2014) 137–151.