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State-of-the-art of renewable energy sources used in water desalination: Present and future prospects

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HIGHLIGHTS

- Installations powered by ocean thermal energy still need to be optimised.
- Biomass energy is not used separately to power desalination systems.
- Low-enthalpy geothermal sources can be wildly used as a direct heat for several thermal-based desalination.
- Salinity gradient energy can be considered as an interesting and valuable technique for RE production and storage.

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ABSTRACT

The last decade has seen a worldwide increase in the use of alternative energy sources, especially renewable energy (RE), including its application in desalination. In the past many experimental and pilot investigations were presented which allowed the costs and effectiveness of such integrated solutions to be estimated. The present review describes experience related to the use of solar thermal technologies (solar collector and concentrated solar power technologies), solar electricity (photovoltaic and concentrator photovoltaics), wind, hydroelectric (hydropower, tidal, wave and ocean thermal energy), biomass and geothermal energy (power and thermal) as well as hybrid systems. The costs relating to energy and desalinated water production are investigated in the case of various technological processes used in desalination. The main directions for development of the RE systems investigated are discussed and their advantages and disadvantages are assessed. Such a comprehensive review showed that the expansion of the effective use of RE sources is still hampered by several techno-economic aspects. The paper focuses on the main concerns of the need to optimise energy processes, especially by creating more energy-efficient and economically effective solutions, energy storage, energy recovery and the expansion of off-grid systems. As a result of the analysis it was concluded that, despite some disadvantages, the combining of RE with desalination processes requires further intensive research and demonstration units for longer term performance. Regulations to develop less energy-intensive desalination technologies are also still needed.

1. Introduction

As a result of the excessive use of freshwater resources compared to their renewability, the constant deterioration of groundwater and surface water quality and the climate change observed in recent years, access to drinking water quality is becoming limited, including in new areas where water supply was not a critical problem [1]. One solution to this problem is water treatment or desalination, which can provide suitable water quality for crop irrigation and industry as well as household purposes. Today, several countries, mainly in the Middle East and North Africa, are experiencing structural and periodic water shortages [2]. Freshwater shortage is also felt in Central and Western

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European countries as well as in Latin America (Fig. 1), and this is additionally exacerbated by the local occurrence of toxic pollutants of geogenic and anthropogenic origin, such as arsenic, boron, fluoride, chromium, uranium etc. in shallow-circulating waters [3–6]. This, combined with a significant increase in population numbers, has caused the amount of water per capita to fall well below 1500 m^3/year, i.e. the level determined by the United Nations as the minimum of existence. Currently, water desalination and treatment processes cover a significant part of demand for high-quality water, providing a solution that is in a sense economically viable as well as technologically feasible [7–11]. Nowadays, an estimated number of 15,906 desalination plants are currently operational, located in 177 countries with a total desalination capacity of about 95.35 million m^3/day (34.81 billion m^3/year) [12], and this figure is going to increase very fast due to the installation of mega plants around the world [13]. What is more, the capacity of the desalination plants which were contracted worldwide in the first of 2019 was about 4 million m^3/d [14]. According to data presented by Jones et al. [12], large numbers of desalination facilities are located in the Middle East and North Africa (4826 plants, 47.5% of global desalination capacity), East Asia and Pacific (3505 plants, 18.4% global capacity), North America (2341 plants, 11.9% global capacity), Western Europe (2337 plants, 9.2% global capacity), Latin America and the Caribbean (1373 plants, 5.7% global capacity), Southern Asia (655 plants, 3.1% global capacity), Eastern Europe and Central Asia (566 plants, 2.4% global capacity) and Sub-Saharan Africa (303 plants, 1.9% global capacity). Moreover, it can be pointed out that countries such as Israel, United Arab Emirates, Kingdom of Saudi Arabia cover more that 50% of their demand with desalinated water, which is used both for industrial and household purposes, but also for power, irrigation, military and other uses.

Seawater provides an unlimited source of water for desalination processes. The second potential source is brackish water, which is sourced mainly from underground sources in many regions. The average salt content of seawater is 35,000 mg/L (range: 24,000 to 42,000 mg/L depending on the location). Brackish waters are less salty (ranging: 2000 to 10,000 mg/L) [12,16]. However, there are some areas, reservoirs such as geothermal, where salt content is higher than seawater [16]. The salinity of geothermal waters varies in a broader range: from 500 to even 120,000 mg/L [16]. World Health Organization [17] drinking water recommendation call for salinity below 600 mg/L due to palatability, however no health-based guideline value for TDS has been proposed.

In desalination processes, membrane technologies play a dominant role nowadays – 69–73% of all installed systems globally [12,18], while thermal techniques account for ca. 27% [18]. Among membrane techniques, reverse osmosis (RO) dominates the global market. RO is currently the most economical process for a wide range of salinity (seawater and brackish water). For low salinity feeds, mature processes such as electrodialysis (ED) and electrodialysis reversal desalination (EDR) are considered. Other emerging processes, such as forward osmosis (FO), adsorption desalination (AD), and membrane distillation (MD) are under development and may have a great potential in the future [19]. An interesting process is also Capacitive Deionization (CDI), which can be considered as desalination technology for brackish water. This technology uses the transport of ions from saline water to electrodes with high ion retention capacity, however the electrodes which are the main factor determines its applicability and lifetime. According to Voutchkov [20], the studies conducted so far indicate the possibility of using this method with the use of brackish waters. When using carbon aerogel electrodes, the efficiency in recovering fresh water is estimated at over 80%, with the (theoretical) physical size of the installation and reducing its capital costs by over 30%. It may be added, that advantages of electrochemical processes using membranes, such as ED, EDR, CDI, electrodeionization (EDI) or Electrodialysis with bipolar membrane (EDBM) are high efficiency of separation of substances and possibility to optimisation desalination systems by creating hybrid solutions e.g. with RO (like RO-CDI for ultrapure water production or maximizing water recovery).

Hybrid systems, which combine different desalination techniques and energy sources, appear to offer the most promising solutions [21]. In regions with emerging water scarcity and high solar radiation, novel hybrid solar (or wind) energy driven systems coupled with highly efficient desalination processes show promise. In addition, research is being conducted worldwide to improve the efficiency of already commonly used desalination processes (e.g. RO) and to find new solutions: metal-air desalination batteries [22], desalination via gas hydrate [23], and also new materials: 3D printing for membrane separation [24], carbon nanotubes [25], Janus composite hollow fibre membrane-based direct contact distillation [26], single-layer graphene membranes [276] and nanofibrous membranes [28]. As concerns the outlook for the future, it appears that the development directions observed over the last three years will be continued. A comprehensive action is needed to ensure the sustainable operation of renewable energy sources and water resources, mostly in regions with high water scarcity [29].

Despite the progress in desalination technologies which has been observed over the last decades, they are still widely regarded as energy-intensive, and as a result solutions are required to reduce unit cost and thus improve the economic viability of such projects. One direction is the use of renewable energy sources (RESs) [9,14,30–31], which, given important trends in the fight against climate change, play a particularly important role [32–40]. However, there is still a need to identify

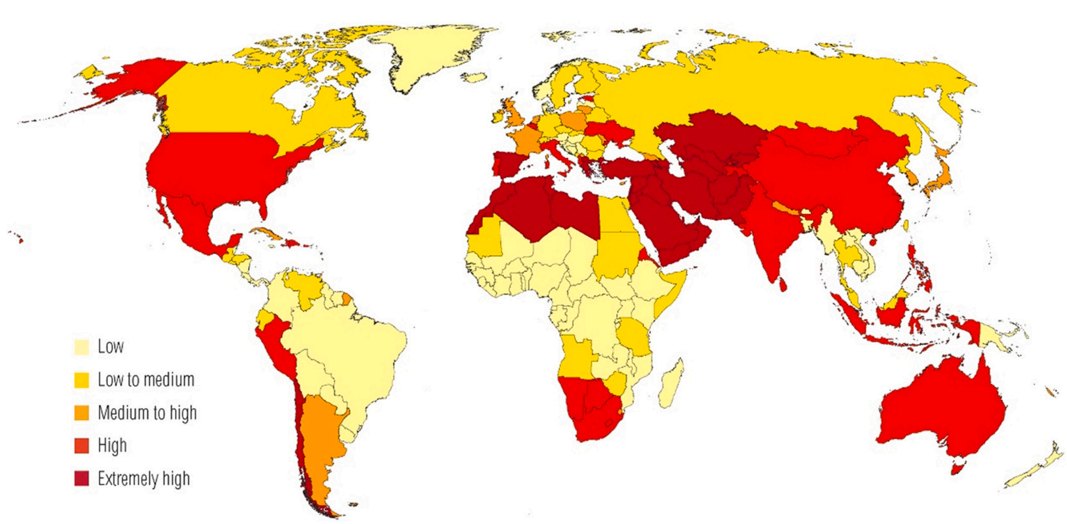

Fig. 1. Predicted water stress in the world by 2040 (based on [15]).

efficient and economical RES-based solutions that can support desalination processes [40] for long term operation.

This review paper addresses every mature renewable energy sources (RES) currently in use and feasible in the future, taking into account their advantages, disadvantages, investment and operating costs, and environmental impact. The review refers to the latest scientific publications on the use of renewable energy in desalination processes, at the same time pointing to the need to develop such systems in the direction of integration both between individual RES technologies, for off-grid remote locations and with energy storage systems. The paper focuses on limitations and challenges by highlighting the failures of most of the demonstration plants run for long term.

2. Combination of renewable energy and desalination processes

Renewable energy and desalination are two different technologies that can be combined in various fashions. Successful integrated designs rely on joining efforts of experts of the two different fields – renewable energy and desalination sectors. The desalination process can be assisted by energy generated on site from locally available renewable energy sources. This energy may be generated in various forms: as heat, electricity or mechanical energy. Theoretically, any RES technology can work with a water desalination plant, especially in the context of those desalination methods that use electricity. Even taking into account the fact that electricity generation is not stable or continuous during a given day or season, e.g. in the case of solar or wind power systems, the energy used for desalination is offset by connecting these installations to the power grid. Thus, there is a balance between the energy consumed and the energy produced (compensation concept). Moreover, a lot of work is currently devoted to desalination plants powered by solar or wind energy, in off-grid systems, in many cases equipped with batteries for energy storage, to reduce the technical complexity of desalination system [41–43]. Additionally there are desalination technologies that require considerable amounts of heat, namely multi-stage flash (MSF), multiple effect distillation (MED), and membrane distillation (MD), so improved energy storage technologies are highly desirable in those cases. On the other hand, there are RES technologies, e.g. based on geothermal energy, which allow stable heat and electricity generation regardless of the time of day or changing weather conditions.

In order to achieve the optimal economic effect, the selection of the appropriate RES technology for desalination processes will depend on a number of factors, including geographical location, the characteristics/source of raw water for the desalination plant, water demand and desalination plant size, the available power grid infrastructure, the distance from customers (market), the potential and possibility of using a specific type of RES (geological, topographical and weather conditions) as well as predicted investment outlays and operating costs [9,14,44]. Fig. 2 shows, in a schematic form, the potential for using individual RES technologies in connection with desalination methods.

In general, desalination systems using RESs can be divided into two categories: thermal and electromechanical processes. Depending on the energy source, RES-driven desalination plants form non-consolidated systems in places where electricity from the grid is not available. Non-consolidated systems are often hybrid integrated systems that combine more than one RES (e.g. wind and solar, solar and geothermal or solar and biomass, possibly with the inclusion of a diesel generator). To ensure their continuous or semi-continuous operation, non-consolidated systems usually include energy storage devices [45].

Global experience shows that there are no significant technical obstacles to combining RES technologies with desalination. However, it

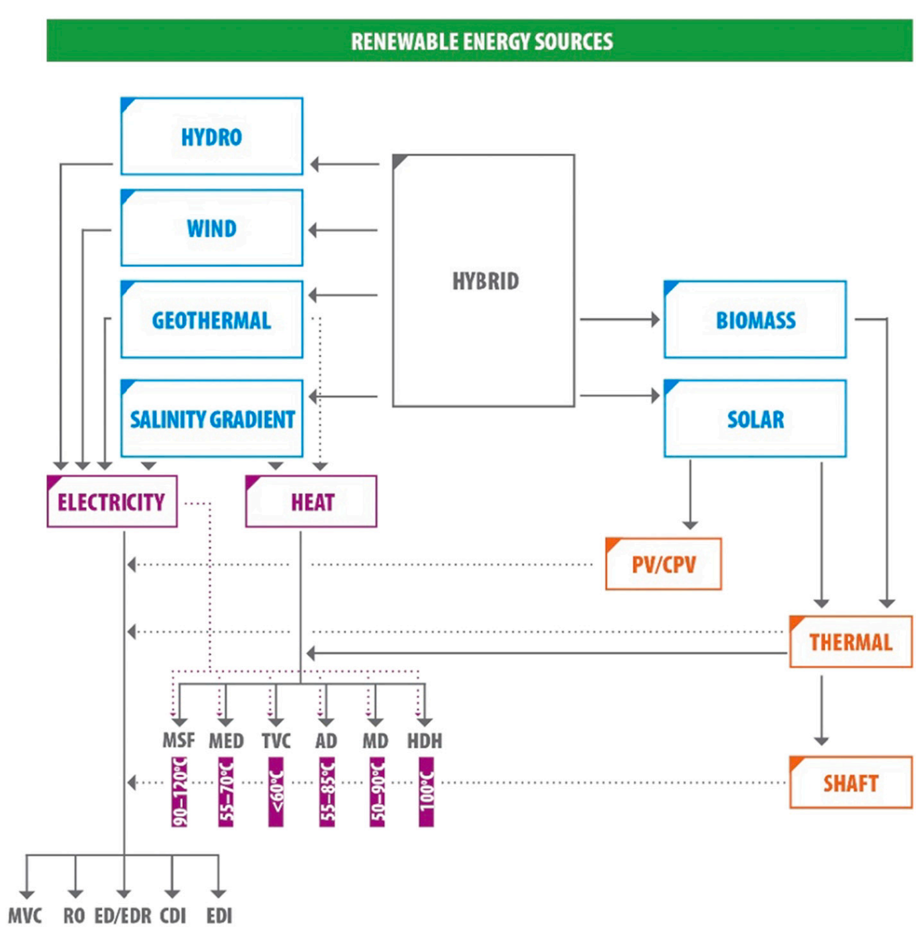

Fig. 2. Possible renewable energy sources (RES) combined with conventional and innovative desalination processes (based on [9,18] updated). Abbreviations: PV/CPV – photovoltaic/concentrator photovoltaics, MSF – multi-stage flash, MED – multiple effect distillation, TVC – thermal vapour compression, AD – adsorption desalination, MD – membrane distillation, HDH – humidification–dehumidification, MVC – mechanical vapour compression, RO – reverse osmosis, ED/EDR – electrodialysis/electrodialysis reversal; CDI - Capacitive Deionization, EDI - Electrodeionization.

can be claimed that the world's dominant RES technology which supports desalination processes is solar power [18,43,46–52]. The most commonly used combinations are photovoltaic installations coupled with the RO technology (PV-RO). The combination of MD and AD which are considered to be low energy intensity technologies, with RESs also shows promising results [53]. Several pilot MD installations powered by solar and geothermal energy have been implemented, and model and pre-implementation work related to their possible broader application is in progress [6,38,54–58]. In their review of progress in the use of renewable energy sources to power water desalination processes, Ali et al. [38] noted that the most commonly used technologies are solar and wind power. However, they pointed out that in the future, geothermal energy should be used to a larger extent to drive desalination processes because of the predictability and sustainability of energy generation using this method regardless of the time of day or year. At the same time, the authors pointed out that in the future, desalination processes will be accompanied by the production of raw materials, what is a challenge nowadays for performance enhancement by the combination of conventional with novel materials technologies. In addition, the integration of processes such as MD with pressure retarded osmosis (PRO) or reverse electrodialysis (RED) will improve desalination efficiency and ensure the sustainability of processes that are currently energy-intensive [59,60]. Mentioned PRO, RED, Capacitive Reversed Electrodialysis (CRED) and also Capacitive Mixing (CapMix) are considered as more and more attractive methods of energy generation from salinity gradient. Officially called as Salinity Gradient Energy (SGE), Salinity Gradient Power (SGP), Salinity Difference Energy (SGE) or Blue energy is a method of harvesting energy by mixture two salt solutions with different, high and low concentration [61–64]. Such energy harvesting was analysed by Brogioli et al. [65], Jia et al. [66], Bryjak et al. [67], Jang et al. [68] and others. Jia et al. [66] pointed out, that salinity energy, stored as the salinity difference between saline and freshwater is a renewable resource and can be converted to electricity. As was pointed by Tuffa et al. [69] RED in connection with membrane based seawater desalination technologies such as RO, MD, ED/EDR or CDI can be considered for the simultaneous generation of renewable energy and drinking water (Fig. 3). For controlled mixing of high saline water with low mineralized water not only seawater may be considered as an attractive feed source. Fig. 4 presents different options with theoretically calculated available energy extraction. One should be noted that nowadays PRO and RED systems are well-recognized, in contrast to CapMix which is relatively new. However, as it was presented by Tufa et al. [69] the major limitation for the wide RED application are 1) still lack of low resistance ion-conductive membrane materials at a low cost

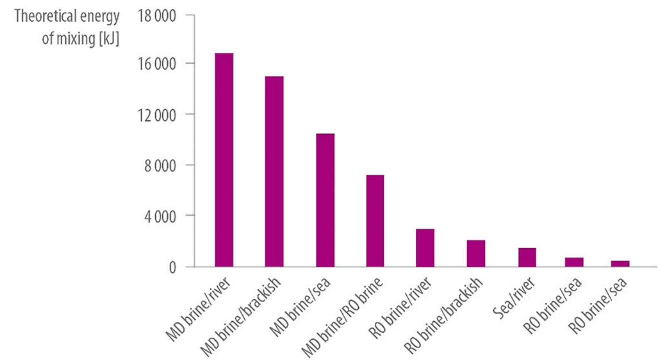

Fig. 4. Theoretical amount of energy (kJ) obtained from different solutions, by mixing 1 m^3 of high saline solution and 1 m^3 of low mineralized solution (based on [69]).

(<4.8 USD/m2) and with high permselectivity (>95%) and 2) membrane scaling and fouling as a results of the presence of organic compounds and divalent ions in natural feed water. The review of various membrane modules used in PRO process, technical challenges, feasibility and future perspectives can also be found in work presented by Gonzales et al. [62].

In recent years, water treatment, including seawater desalination, wastewater and geothermal water treatment, has been the subject of research all over the world. Despite the development of desalination technology, commonly used techniques are still considered as energy-intensive, which requires looking for solutions to increase the efficiency of the desalination process or develop novel technologies. Water desalination/treatment technologies have been investigated all over the world in terms of increasing process efficiency [70,71], using new materials [24–28,72–73], combining different technologies [74–80], designing new techniques [23,81–83] and reducing energy demand [18,84–85] or procuring new energy sources [14,22,86–88].

3. Renewable energy sources compatible with desalination processes

3.1. Solar

Solar energy is radiation from the sun that can be harnessed using several technologies, such as: 1) solar thermal technologies which extract thermal energy from the sun's radiation using solar collector or

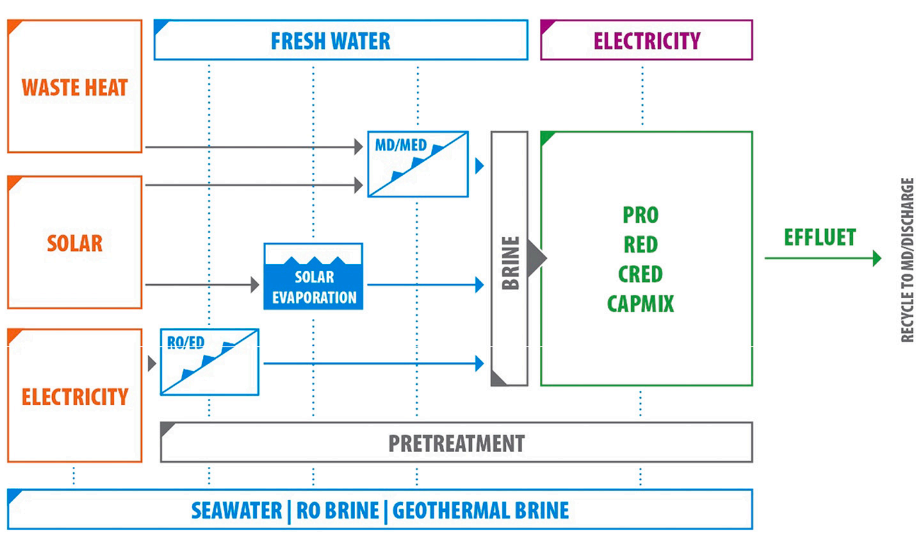

Fig. 3. Concept of simultaneous generation of renewable energy and drinking water production (based on [69] updated).

concentrated solar power technologies (CSP); 2) solar electricity – photovoltaic (PV)/concentrator photovoltaics (CPV) – solar modules which are used to harness the solar energy carried by photons as electricity.

3.1.1. Solar thermal – solar collector and CSP

Thermal desalination is one of the most popular, most common and oldest RES applications globally. Technologies that use the heat generated by solar radiation include MSF, MED and vapour compression distillation (VCD). These are energy-intensive processes, especially in areas with higher water salinity, such as Middle East countries (can reach 45 g/L) [89]. On the other hand, however, these regions exhibit favourable conditions in terms of solar irradiation, which ranges from 2200 to 2400 kWh/m^2 per year [90]. These factors, i.e. the scarcity of water and the availability of high-level solar radiation, make solar energy the most suitable RES solution for water production in desalination systems [18,57]. Fang et al. [91] proposed a new desalination method consisting in obtaining freshwater from brackish water in Southern

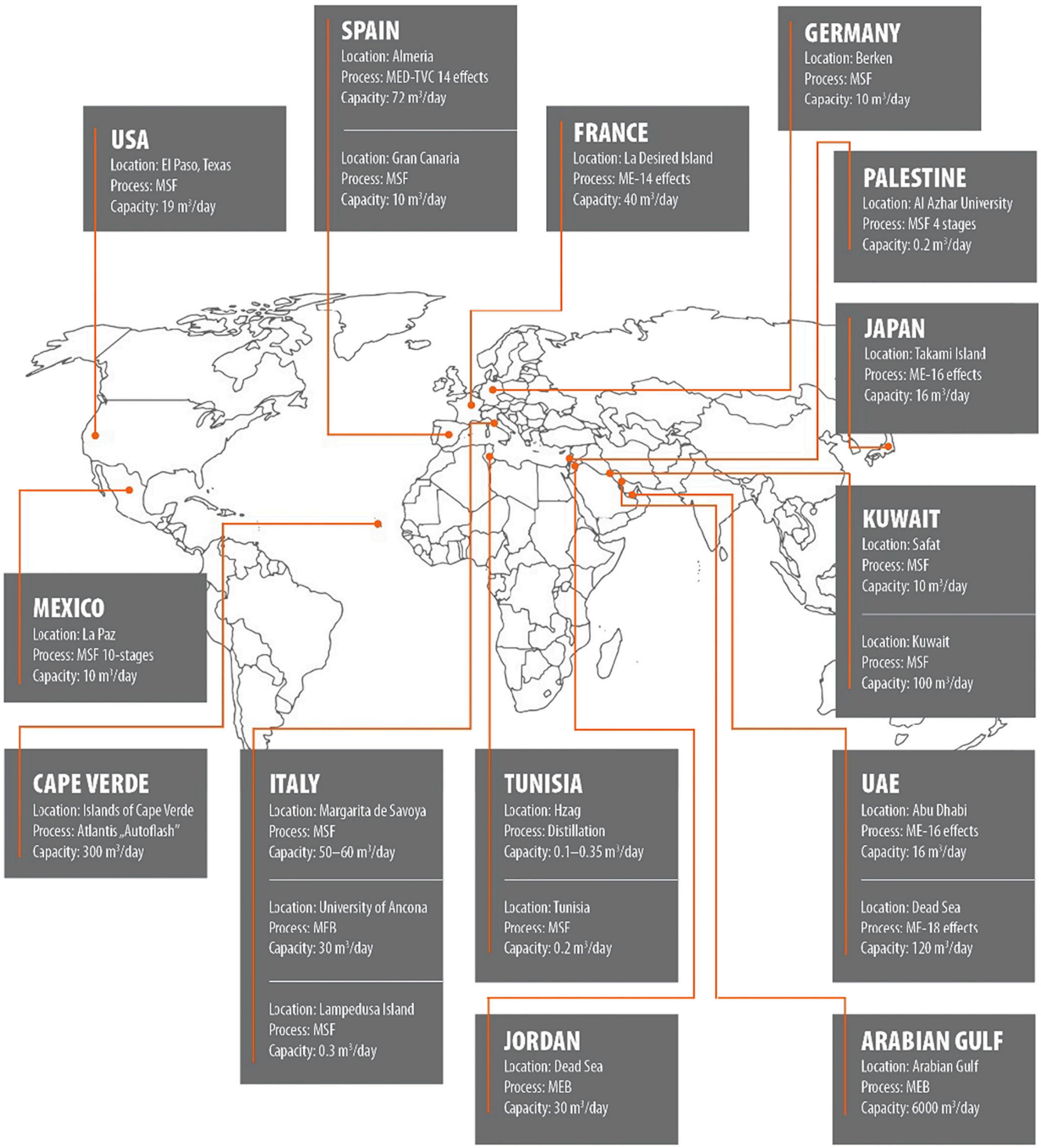

Fig. 5. Selected solar thermal desalination installations worldwide (based on [9,95–108]).

Xinjiang (China) by the solar photothermal method (using a combination of membrane processing equipment and an evaporator). On the other hand, the study carried out at the University of Almería (Spain) was focused on the use of solar energy together with a desalination process based on the vacuum multi-effect membrane distillation technology [92].

Chen et al. [93] investigated the potential and possibility of coupling desalination technologies with solar power to overcome future problems with the scarcity of freshwater in China. Huang et al. [94] proposed a novel solar-driven desalination distiller system with improved water yield, which consists of a thermal concentration design combined with a multistage latent heat recovery structure. The system has a great potential for application in small- and industrial-scale desalination. Ahmed et al. [18] analysed solar-powered desalination plants with focus on the technologies used and energy consumption. They concluded that solar energy is an attractive source of energy for powering desalination plants, especially since emerging problems with freshwater scarcity and high solar irradiation coincide in many regions. The most important desalination installations using solar power in the world are presented on Fig. 5.

Solar thermal desalination installations in the world are located in Spain (2 installations), France (1), Germany (1), Italy (3), USA (1), Mexico (1), Cape Verde (1), Tunisia (2), Palestine (1), Jordan (1), Kuwait (2), UAE (2), Arabian Gulf (1) and in Japan (1). This gives a total of 20 installations. Dominant technology of desalination processes is MSF, which occurs in 10 locations. Next, there are ME technologies (4 installations), MEB (4), Autoflash (1) and Distillation (1). The highest capacity was achieved in the Arabian Gulf with the use of MEB technology and amounts to 6000 m^3/day. Installations with a capacity of more than 100 m^3/day are located in Islands of Cape Verde – 300 m^3/day (Autoflash), Dead Sea – 120 m^3/day (ME) and Kuwait – 100 m^3/day (MSF). For 4 locations (Al Azhar University in Palestine, Hzag, Tunisia and Lampedusa Island in Italy) the capacity does not exceed 0.35 m^3/day, leading to the conclusion that these are experimental units.

Classic thermal desalination with the use of solar energy requires a very large land surface area, and thus a large surface area of devices that concentrate solar radiation. This has a negative economic impact compared to the use of conventional fuels. A technological and economic model aimed at the optimisation of RO thermal water desalination processes using solar energy has been developed by, among others, Zheng and Hatzell [51]. Based on theoretical data, they analysed the conditions prevailing in seven U.S. coastal cities and concluded that the optimal location is Miami (Florida). The results obtained in their technological and economic model indicated that the discounted cost of freshwater production at the rate of 1000 m^3/day given a solar collector unit price of USD 100/m^2 and collectors operating at 40% efficiency would be USD 0.97 per m^3 [51], which is indeed an impressive achievement in comparison with the observed global trends in unit cost of obtaining water fit for human consumption both in systems with and without desalination techniques.

CSP is a power generation technology based on the use of solar energy concentrated in a small area, using mirrors to better focus sunlight and convert it into heat. Four CSP technologies are known – parabolic trough collector systems, linear Fresnel reflectors, solar/power towers and parabolic dish collectors. However, two of them are most commonly used: power towers and parabolic trough collectors [18]. A design based on an absorber tube makes it possible to obtain very high temperatures of 350–400 °C [109]. The vast majority of such installations are currently located in Spain (mainly in Andalusia) and in the U.S. High investment outlays are the disadvantage of using CSP systems in water desalination/treatment processes. In addition, the use of such systems is limited to areas with high insolation levels and they require a large land surface area. On the other hand, the clear advantage of installations of this type is undoubtedly their ability to store thermal energy, which allows for balancing the operation of the entire installation and economic optimisation, provided that the investment outlays incurred are offset by lower operating costs [110]. For instance, the first (2011) large-scale commercial project which successfully uses energy storage in molten salt tanks while being able to generate electricity around the clock is the 19.9 MW_e Gemasolar CSP-tower plant located in Spain [111–112]. The plant is still working, producing about 80 GWh/year and reduces more than 28,000 tons of CO_2 emission per year [113].

According to Ahmed et al. [18], solar collectors currently have a thermal efficiency between 60% and 75%, and the cost of generating energy using these systems ranges from 0.05 to 0.09 USD per kWh_{th}. Thermal solar installations are also considered in the context of power generation: to drive turbines in binary, ORC or similar systems, which is a promising solution for 200–2000 kW_e commercial plants [114–115]. The heat obtained from the sun can be stored in a thermal energy storage (TES) system [18]. A comparison of available CSP technologies is shown in Table 1.

Among real-world CSP technologies, plants based on the parabolic trough collector system are considered to be the solution which is the most established on the market and the cheapest one from the large scale technology – 0.012–0.020 USD/kWh (Table 1) [116–117]. However, this technology requires by far the largest area of land compared to other solutions, which may be an obstacle in the investment process. In addition, it should be noted that CSP technologies require significant amounts of water for the condensation and cooling process. For example, in the case of the PTC system and LFR technologies, this amounts to 3000 L/MWh [117–118], 2000–3000 L/MWh in case of SPT and 50–100 L/MWh in case of PDC. This water demand may pose a significant problem in the implementation of these technologies in water scarcity areas. The exception, however, are locations close to the coast where seawater can easily be used for cooling. Mohammadi et al. [119] claim in their comprehensive review that this technology is optimal for desalination processes because it makes it possible to generate both electricity and heat. Hetal et al. [120] claim that MED and MSF are the

Table 1
Comparison of available CSP technologies (based on [116,117]).

Kay aspects	Parabolic trough collector (PTC)	Linear Fresnel reflector (LFR)	Solar power tower (SPT)	Parabolic dish collectors (PDC)
Land occupancy	Large	Medium	Small	Small
Relative cost	Low	Very low	High	Very high
Thermo-dynamic efficiency	Low	Low	High	High
Operating temperature range [°C]	20 – 400	50 – 390	3250 – 565	120 – 1500
Solar concentration ratio	15 – 80	10 – 100	150 – 1500	100 – 3000
Installed capacity (MWe)	1.1 (City of Medicine Hat ISCC Project (pilot project), Canada) – 280 (Solana Generating Station and Mojave Solar Project, US)	–	1 (Dahan Power Plant, China) - 392 (Ivanpah Solar Electric Generating System, US)	1.5 (Tooele Army Depot, US[a])
Under development (Max capacity (MWe)	600 (DEWA CSP Trough Project, UAE)	–	450 (Tamarugal Solar Energy Project, Chile)	–
Operational & maintenance cost [USD/kWh]	0.012 – 0.02	–	0.034	0.21

[a] Non-operational.

most suitable technologies for thermal desalination of water using solar energy. In the case of PV installations and CSP systems, RO and ED are indicated as the optimal solutions. Already a decade ago, Ghermandi and Messalem [121] recognized that CSP and RO are the most promising combination of RESs and large-scale desalination technologies. The authors even ventured a claim that such installations may soon provide a viable economic alternative to plants based on the use of conventional energy sources. As it was mentioned by Kettani and Bandelier [122] for Middle East and North Africa region, a potential 146 billion m^3/year by 2050 can be expected and also about 400 million m^3/year only for Morocco. The authors evaluated, using mathematical models, that the use CSP with storage and the grid (based on CSP Noor I experiences with molten salt storage) for the large scale RO desalination plan (275,000 L/d) the average cost of electricity reaches 0,13 USD/kWh with compare to 0,094 USD/kWh in case of PV and grid power supply and 0,135 USD/kWh in case of PV with storage and grid power supply.

3.1.2. Solar electricity – PV and CPV

The undoubted advantage of PV installations is their universal nature and ease of installation in almost any location provided that the values of the local solar radiation are high enough. Additionally, it should be noted that most areas with a freshwater shortage are characterized by relatively high values of solar irradiation, which makes it possible to generate the amount of energy required for desalination processes.

The studies carried out so far indicate primarily the possibility of using PV technology for water treatment in RO processes (PV-RO). Historically, work in this direction was carried out, inter alia, in Jordan [123,124], Egypt [125], Australia [126], Italy (Agrigento and Ginostra in Sicily) [127–128] as well as in Spain on Gran Canaria [129–130].

The first works related to the evaluation of desalination systems using RO and PV were conducted by Tzen et al. [131], Kalogirou [132] and Bouguech et al. [133], and cost analyses were carried out by Al Suleimani and Nair [134] who described the operating experience related to the Heelat ar Rakah plant (Oman), as well as by Hasnain and Alajlan [135] who performed a cost analysis of the installation in Riyadh (Saudi Arabia). The authors of the last of the works cited [135] estimated the cost of desalinating 1 m^3 of water at 0.5 USD. The installed capacity of the entire installation is at the level of 5.8 m^3/day.

Interesting research results were published in a paper by Calise et al. [136] referring to the use of a combined cooling, heat and power process based on PV and the installation of solar collectors for seawater desalination. A number of studies on the application of PVs in the RO process for the desalination of seawater without the use of a battery system were presented in Thomson et al. [137,138]. The possibility of using a DC micro-grid including hybrid short-term energy storage was analysed by Karavas et al. [139]. Interesting proposals for small-scale ($\leq$500 Wp) installations located in rural areas were put forward by Joyce et al. [140] and by Khaydarov and Khaydarov [141]. Similar conclusions were drawn by Li et al. [142] who stated that low-power PV installations can be a particularly interesting solution in places situated far away from the power grid.

PV installations can be integrated with the RO technology, but it can also be claimed that a more attractive direction is using PV to power desalination processes based on ED [9]. The evidence for this is provided by the pilot installations operating worldwide and by the conclusions related to their operation presented, among others, by Kvajic [143] and Al Madani [144]. Research was also conducted for installations located in Japan [145–146] and India [147–148]. The evaluation of operating parameters of such installations was presented by Al Madani [144] as well as by Ortiz et al. [149] who put forward a mathematical model making it possible to predict the operation of an ED system powered by a PV installation. However, nowadays PV technology can be expected as competitive with conventional resources as a result of its increasing popularity and, consequently, the gradually decreasing investment outlays and operating costs. Moreover, the lifetime of PV panels as well as their efficiency are still increasing. For this to happen, it is necessary to solve certain problems, both of an energy nature and those resulting from climatic conditions. It should be noted that there may still be an increase in the efficiency of PV installations, resulting on the one hand from the development of this technology, but on the other hand from such prosaic reasons as fouling of PV panels, lowering their efficiency and limiting the power with which they can work. Additionally, it should be noted that PV installations are often used in areas where there are high values of solar radiation. It causes directly into energy yields, but it can also be a problem from the point of view of their cooling. What is more, depends on the monthly and daily differences in weather conditions, wind speed, direction and humidity, especially in hot regions, soiling and dust can be a major problem which may influence on energy losses. That is why, the PV panels cleaning need to be considered. Based on the experimental studies, Chiteka et al. [150] have developed an empirical soiling loss model, which showed, in case of Muzarabani in Zimbabwe, that it is necessary to clean once in 15 days in order to minimise electricity production losses. It has to be mentioned that in locations where it is possible, PV should charge into the normal grid cause in that kind of installation the desalination plant can use power as needed (e.g. in Australia).

Researchers from Spain presented the preliminary results of operating an innovative hybrid solar (PV)-powered seawater RO desalination system [151]. As concerns future outlook, although coupling solar systems to desalination systems can be favourable, the sustainability, economic, and environmental issues related to such systems still need to be evaluated. Also, these systems must be optimised for different plant scales and locations [43,52; 79]. An interesting direction for the development of desalination processes was proposed by Xu et al. [49], who demonstrated interfacial desalination using a printed paper-based solar absorber which controls the salt concentration gradient. On the other hand, in his article reviewing the use of nanoparticles in desalination processes powered by PV installations, Bait [152] indicated this development direction (nanotechnology) as a promising one from the point of view of reducing the costs associated with the removal of e.g. bacteria in the water treatment process. Evolution of PV technology for performance enhancement is also analysed. Suman et al. [153] pointed, that to increase clean and green technology in solar cell, nanotechnology: 1) nanomaterials (silicon, indium gallium phosphide, gallium arsenide, indium gallium arsenide, quantum dots) as a third generation and 2) nanostructures (metallic nanoparticles, metal oxides, carbon nanotubes, graphene, gallium arsenide) as a fourth generation will being use for fabrication and production PV panels on a large scale. It is highly likely that the carbon nanoparticles and also its allotrope forms such as graphene, carbon nanotubes and fullerenes will be use as higher performance compared to silicon based cells.

CPV systems are also considered an interesting alternative. Their operating principle is analogous to that of traditional PV installations, but they use additional mirrors which focus solar radiation on PV cells, significantly reducing the number of cells required. These solutions usually require a solar tracking system so that they can automatically follow the sun all day long. Owing to their greater efficiency and thus higher energy yields per megawatt of installed capacity, CPV systems can provide an alternative to conventional PV installations [154], especially in the Middle East, North Africa, South USA, South China, Southern Africa and Australia [155]. However, the studies did not discuss the consequences of the desalination performance in case of unstable energy supply when batteries are not used. What is more, as was analysed by Maka and O'Donovan [155] high optical concentration increases the energy yield however, at the same time increases the operating temperature. That is why heat dissipations by the process such as passive or active heat dissipation are required to save the cells from or thermal damage. MD water desalination concept, integrated with cooled CPV (CPVC) as a cogeneration system has been presented by Elminshawy et al. [156]. Electricity is produced with the simultaneous release of excess heat generated during the cooling process to the desalination of water. In case of climatic conditions of Port Said in Egypt, the authors concluded that up to about 83% of solar irradiance can improve CPVC module generated power up to about 25% in comparison to conventional CPV system. A list of PV power stations used in desalination processes is presented in Table 2 and on Fig. 6.

Out of the selected 23 PV desalination installations presented in the Fig. 4, the vast majority use brackish water (BW) – this is 17 installations. For the remaining 6, sea water is used. Due to the wide variety of data on PV plant capacity and permeate quantity, it is difficult to directly compare these plants. This is due to, among other things, the various conditions of insolation, which translates into the amount of electricity generated with the use of PV technology. In fact, for data to be comparable, it is necessary to refer to the amount of energy, not to power. Selected installations can be found in Spain (1 installations), Greece (2), Uzbekistan (1), Jordan (2), KSA (2), UAE (3), India (5), Malaysia (1), Australia (5) and Brazil (1). The values of the specific energy consumption (SEC) coefficient for these installations range from 1.1 to 26, with the dominant values not exceeding 5. The installation with the coefficient of 26 located in Jordan is an exception to the analysed cases.

During the preparation of this article, an attempt was made to verify the current condition of the discussed installations. Unfortunately, access to information is very limited when it comes to, for example, the websites of the operators of these installations, and the information relates to the design state or to the date when the installation started to work. However, in the case of one installation, located in Spain (Gran Canaria), it was possible to establish that it is fully operational [180].

3.2. Wind energy

Apart from solar energy, wind energy is the most popular renewable energy source used and analysed in the context of being coupled with water desalination installations. In this context, the RES is used to produce electricity to run an independent desalination unit [181]. The latest reviews of wind power use have been compiled by e.g. Ma and Lu [182], Abdelkareem et al. [157], Vargas et al. [183], Baxter et al. [184] and by Díaz and Soares [185] in accordance to offshore wind farms. This aspect of the use of wind energy is particularly interesting for seawater desalination. In recent years the offshore wind energy has been noting an important increase in energy sector. As was pointed by Díaz and Soares [185] 112 offshore wind farms are currently operated and 712 projects are developed. However, the vast majority of studies and publications do not concern desalination installations powered solely by wind energy, but rather wind energy used in combination with other RESs, mainly solar power, as analysed in the chapter on hybrid installations (presented in prat 4) more data about costs of water desalination using wind energy and/or hybrid RES technology is presented in Section 6. Wind energy installations supplying power for RO processes worldwide are shown in Table 3 and on Fig. 7.

Nevertheless, in recent years there have been several studies concerning exclusively using wind power in desalination processes. In chronological order: Dehmas et al. [190] presented a model allowing for an economic viability analysis of using wind energy in desalination processes based on SWRO in Ténès in Algeria, taking into account the reduction in carbon dioxide emissions. A small 2.2 kW wind energy installation combined with an RO desalination unit was analysed by Miranda and Infield [191], focusing on the impact of wind speed changes on optimising the freshwater production rate. Gökçek and Gökçek [192] also analysed small wind energy plants (with a capacity of 6–30 kW). They performed a technical and economic evaluation for the Gokseada Island installation in Turkey, analysing a system designed to produce 1 m^3/h of freshwater. The results presented by the authors showed that the cost of water desalination using a RO process varies from 2.962 to 6.457 USD/m^3. At the same time, it was demonstrated that at a capacity of 30 kW, the reduction in carbon dioxide emissions would be 80,000 kg/year. The potential for the industrial use of wind turbines operating at low wind speeds has been analysed by Loutatidou et al. [193] in the United Arab Emirates. Using the RO process, the authors calculated the levelised cost of water (LCOW) depending on the freshwater production rate, obtaining results of 1.57–1.63 USD/m^3 for 7000 m^3/day, 1.83–1.96 USD/m^3 for 10,500 m^3/day and 2.09–2.11 USD/m^3 for 14,000 m^3/day.

The use of wind energy in desalination processes is dominated by

Table 2
Overview of selected photovoltaic installations used in desalination processes.

Country	Year	Feed	PV power [kW]	Permeate production [m^3/d]	SEC [kWh/m^3]	Hybrid	Energy recovery	References
Australia	2007	BW	0.3	0.25 (–)	1.2	Battery	No	[158]
India	2007	SW	10.4	0.50 (10 h)	–	Biodiesel	No	[159]
Greece	2008	SW	0.85	0.083 (–)	3.8	–	Clark pump	[160]
Greece	2008	SW	1.6	0.35 (4 h)	4.6	–	Clark pump	[161]
UAE	2008	SW	11.25	20 (24 h)	7.73	Diesel	Yes[a]	[162]
UAE	2008	SW	22.49	20 (10.92 h)	7.33	–	Yes[a]	[162]
Australia	2008	BW	–	1.106 (12 h)	2.3	–	No	[163]
Brazil	2009	BW	0.165	0.26 (8.24 h)	1.57	–	No	[164]
Australia	2009	BW	0.38	2.76 (10 h)	2.2	–	No	[164]
Australia	2009	BW	0.12	0.4 (–)		–	Yes[a]	[165]
KSA	2009	SW	44.83	100 (14 h)	6.3	Battery	No	[166]
KSA	2009	SW	40	100 (14 h)	5.7	Battery	Yes[a]	[166]
Spain	2010	BW	0.36	0.2 (12 h)	1.3	Battery	No	[167]
Uzbekistan	2010	BW	0.03	0.075 (9.5)	–	Battery	No	[168]
Tunisia	2011	BW	30.8	57–1151(–)	–	Wind	No	[169]
Australia	2011	BW	–	4.8 (12 h)	1.9	–	No	[170]
Egypt	2012	BW	5	5 (24 h)	9	Wind-Battery	No	[171]
Jordan	2012	BW	0.432	5.7 (24 h)	26	Battery	No	[172]
Jordan	2012	BW	0.432	5.7 (24 h)	19.4	Battery	Yes[a]	[172]
UAE	2015	SW	720	200 (3.57 h)	6.99	Grid	No	[173]
India	2015	BW	0.075–3	1.04 (4 h)	–	Battery	No	[174]
India	2015	BW	0.075–3	1.068 (4 h)	–	Battery	Yes[a]	[174]
India	2015	BW	0.075–3	1.68 (4 h)	–	Battery	Yes[a]	[174]
India	2015	SW	0.667	0.64 (5 h)	–	Storage of permeate	–	[175]
Qatar	2015	BW	–	100	–	–	–	[176]
Malaysia	2016	BW	2	5.1 (10 h)	1.1	Battery	–	[177]
Jordan	2016	BW	15–111	13–63 (–)	6.9–10.5	–	Yes[a]	[178]
Turkey	2017	SW	20	24 (24 h)	4.38	Wind-Diesel-Battery	No	[179]

BW – 2-10 g/L; SW – 24-42 g/L.
[a] Lack of detailed data.

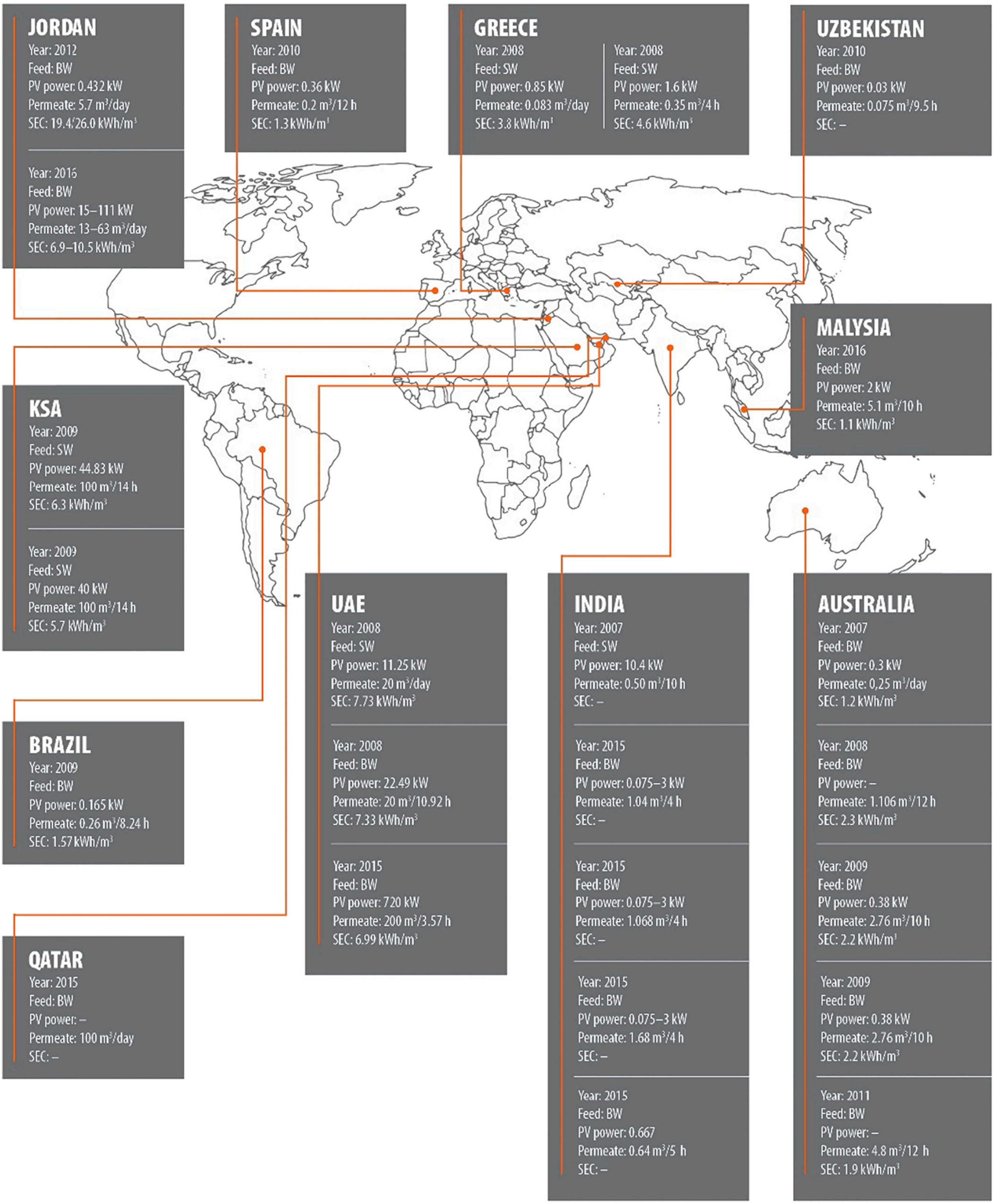

Fig. 6. Selected PV desalination installations worldwide (based on [157]).

Table 3
List of wind energy installations supplying power for desalination processes (RO) (based on [157,182,186–189]).

Country	Location	Year	Feed	Capacity [L/h]	SEC [kWh/m3]
France	Ile de Planier	1983	SW/BW	500	4
Australia	Debenham	1991	BW	5,400	30
Australia	Perth (Kwinana)	2006	SW	143,700[b]	80
Australia	Sydney	2010	SW	250,000[b]	140
Spain	Fuerteventura	1995	SW	2333	225
Greece	Thersasia Island	1997	SW	200	15
Greece	Syros Island	1998	SW	2,500 - 37,500	–
Greece	Keratea	2001/2002	SW	130	–
Greece	Milos Island	2007/2008	SW	6 × 600,000	–
Greece	Heraklia Island	2007	SW	3,300	30
Spain	Gran Canaria-Pozo Izquierdo	1995	SW	8 × 1000	2 × 230
Spain	Gran Canaria-Pozo Izquierdo	2003/2004	SW	800	15
UK	Loughborough University	2001/2002	SW	500	2.5
Germany	Enercon	2006	SW	7300–58,000	200
Germany	Enercon	2006	BW	14,600–104,000	200
Germany	Island of Suderoog	1983	BW	250 - 370	6
Germany	Island of Heligoland[a]	1988	BW	40,000	1.2
The Netherlands	Delf University	2007/2008	BW	200 - 400	–

BW – 2-10 g/L; SW – 24-42 g/L.
[a] Plus diesel.
[b] m^3/d.

European countries (7 installations), and the exception in this group is the installation located in Debenham, Australia. Of the installations shown in Fig. 5, five of them use sea water, two use brackish water, and one (Ile de Planier in France) uses both sea water and brackish water. The amount of permeate varies greatly, ranging from 200 to 104,000 L/h, with SEC rates of 2.5 to 225 kWh/m^3. The installation in Loughborough (Great Britain) with the SEC of 2.5 kWh/m^3 and the permeate amount of 500 L/h is characterized by the lowest power expenditure in relation to desalinated water unit [157].

Verification of the current operational state of the installation, similarly to PV installations, allowed verbally that the unit located in Spain (Gran Canaria) is fully operational, and the current power of wind turbines is 460 kW (2 × 230 kW) [180].

What is more, the large- and medium-scale desalination plants that have been implemented to date, such as Perth and Sidney (Table 3) have commonly opted for the installation of wind farms and the connection of both subsystems to conventional power distribution grids [194]. Such projects basically use two strategies for wind and conventional energy management when it comes to powering the desalination plants [194–195]: 1) wind farms feeds all the energy that it generates into the conventional grid and the desalination plant is treated like another load in the system - the income generated through the sale of wind energy is used to reduce the energy bill of the desalination plant; 2) the electrical energy generated by the wind energy is used primarily to cover the instantaneous energy needs of the desalination plant. In this case, the mismatches in instantaneous energy between the electrical energy generation of the wind and the consumption of the desalination plant are corrected by taking from the conventional grid the amount of energy that is required and by feeding into that grid any surplus wind energy production. With both presented strategies, SWRO modules currently tend to be operated in continuous mode and under constant pressure and flow conditions [181]. However, these strategies, can also generate problems of instability in the power system. In consequence, the integration of wind energy powered desalinations into the conventional grid may be limited even in the case of high wind energy potential [196].

The wind energy powered desalination systems developed to date that are not connected to a conventional grid are in effect stand-alone microgrids. Such microgrids have been configured to handle above all small-scale desalination, with comparatively few implemented for medium-scale desalination projects [194,197]. Most of these microgrids have required the incorporation of energy storage systems, mainly batteries [194]. It should be noted, however, that this is an expensive solution, therefore it should be more desirable to search for the possibility of using stable sources, such as geothermal energy.

3.3. Hydroelectric energy

For the time being, however, it should be noted that the use of solutions based on hydroelectric energy directly in water desalination is at the conceptual, or at best experimental, stage. One of them is pumped storage hydropower (PSH) concept based on closed-loop PSH planned in three location: 1) the Eagle Mountain Project in California, 2) the Gordon Butte Project in Montana, and 3) the Swan Lake North Project in Oregon which can increase combined generating and storage capacity from 101 GW to near 150 GW by 2050 in the U.S. [198]. In case of the Eagle Mountain PSH installation it will be connected with RO water treatment system, to protect groundwater quality near iron ore mine reservoirs. To mitigation of environmental impact, this project initial capital cost is estimated on 45,400,000 USD (2018) and calculated annual O&M cost is 715,000 USD [199].

In the future, the use of hydroelectric energy in desalination processes may offer an interesting alternative to the RES which are currently used. This is mainly due to the fact that the desalination of seawater requires the supply of electricity in coastal areas. Tidal, wave or ocean thermal energy appears to be a natural solution. Among these methods, those that convert tidal and wave energy to electricity have been by far the most popular [200]. As Lehmann et al. [201] noted, the advantage of this type of RES in comparison with unstable generation using wind or solar power is its predictability and continuous availability.

First attempts at using sea wave energy to power the RO process were made by Hicks et al. [202] who designed a system consisting of a buoy, a pump and an anchor fixing the installation to the ocean floor. The study indicated that 6 m^3/day of freshwater could be produced in this manner. Studies on the use of wave energy were also conducted by Sharmila et al. [203], who, however, analysed a more advanced system consisting of a turbine, an alternator, an inverter and a battery, which was also used for powering the RES process. Recent studies by Ylänen and Lampinen [204], Corsini et al. [205], Song et al. [206] as well as Zhou et al. [207] point to technical possibilities of integrating systems that use wave energy with desalination processes. The results presented by Song et al. [206] and Zhou et al. [207], which indicate that it is possible to produce freshwater in the SWRO process at a rate above 30 m^3/h, give particular grounds for optimism. In turn, the possibility of using tidal energy in the RO process was analysed by Ling et al. [208] who indicated savings at a level of 31–41.7% compared to conventionally powering processes of

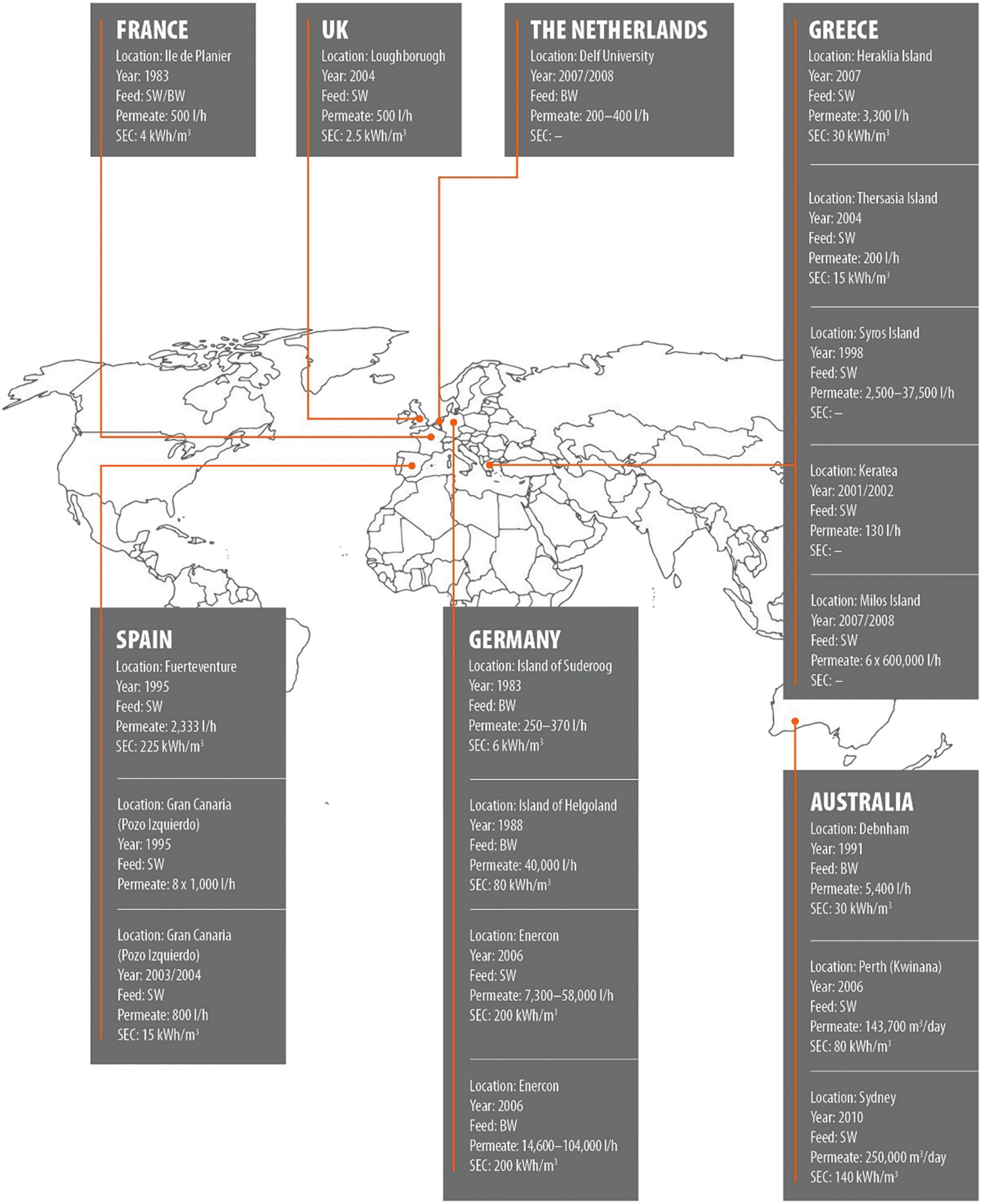

Fig. 7. Selected wind energy desalination installations worldwide (based on [157,182,186–189]).

this type, and not just in terms of economic savings, but also in terms of water recovery (40%).

In the near future, some potential can certainly be demonstrated by installations using ocean thermal energy resulting from the temperature difference between shallower and deeper water layers, using the Organic Rankine Cycle (ORC) or the Kalina Cycle. One of the first studies on the feasibility of combining this technology with desalination processes was conducted by Kim et al. [53]. The authors analysed a number of parameters (primarily water flow rate and temperature) in order to determine the predictability of system performance. Similarly, as with the use of the ORC or the Kalina Cycle to generate electricity from geothermal energy or waste heat, the temperature of the condensation medium was demonstrated to be of crucial importance. That Is why, the lower the temperature of the cooling medium, the better in terms of optimising the operation of geothermal installations, hence the optimal use of e.g. water from streams with a temperature of several Celsius degrees. Additionally, the authors pointed out the impact of the amount of cold water sourced on pumping costs and the production rate. Additionally, Kumar et al. [209] found that increasing temperature at the evaporator and lowering the pressure increases freshwater production efficiency.

In turn, Prieto et al. [210] considered the possibility of using sea wave energy in desalination processes, but their research focused mainly on the electricity generation potential. Analysing the northern part of the island of Gran Canaria and the Arucas-Moya and Arucas-Moya 1 installations, the authors concluded that the amount of energy produced by sea waves would be sufficient to power these installations.

3.4. Biomass energy

Biomass energy is the only energy source which has not been used in water desalination processes so far. However, in recent years, results of several studies were published which analysed the possibilities of using biomass energy in hybrid systems in combination with other renewable and non-renewable energy sources.

Sahoo et al. [211] considered a hybrid system combining solar energy and biomass, and analysed the possibility of using such a system for both energy generation and cooling. The installation is designed in such a manner that a PTC (parabolic trough collector) system provides an energy source which pre-heats the working medium before it is directed to the biomass system exchanger and evaporated. The temperature of steam directed to the turbine is 500 °C at 60 bar and at a mass flow rate of 5 kg/s. Thermodynamic analysis has demonstrated that this combination of different renewable energy sources allows energy efficiency of 49.35% to be achieved.

Behzadi et al. [212] focused on the use of biomass for gasification and thus, adding a gas turbine to their system, powered a water desalination plant based on RO. The authors additionally conducted comparative studies for variable parameters of system operation to determine its economic and environmental effects. The results showed that exergy efficiency was 27.07% at an energy generation cost of 66.46 USD/GJ, and emission reduction amounted to 0.2837 t/MWh in the optimal variant.

3.5. Geothermal energy

In the case of geothermal energy, both electricity and heat production are considered in the context of water desalination, however high enthalpy geothermal resources are very limited but low enthalpy resources are much more available [59].

The feasibility of electricity generation from geothermal waters is strictly dependent on the local hydrogeological conditions and rock mass temperature prevailing in the area in question. The geothermal energy sector is a well-developed one and could be adapted for water desalination purposes. Depending on the type of energy carrier and its temperature, there are several basic ways of converting the thermal energy accumulated in geothermal steam and water as well as in hot dry rocks into electricity. These are: a system with the direct use of saturated dry steam (180–300 °C), a system utilising single-stage, two-stage or three-stage wet steam expansion (150–320 °C), or the ORC and Kalina Cycle (90–150 °C) [213]. Most geothermal power plants in the world use the energy accumulated in wet or, less frequently, dry geothermal steam [214].

The least technologically complex system is the one used in the case of saturated dry steam, which consists of directing the dry geothermal steam brought to the surface, via particle and moisture filters, to a turbine connected with a generator. However, the use of this solution is currently limited to two places in the world, namely the Larderello geothermal fields in Italy (where the first geothermal power plant in the world was constructed) and the Geysers geothermal field in California (U.S.). The vast majority of high-temperature geothermal reservoirs in the world contain a mixture of geothermal steam and water (wet steam). It is therefore necessary to separate these types of steam by including a separator and an additional check valve in the thermodynamic system in order to prevent geothermal water from entering the turbine. The basic methods of producing electricity using low-enthalpy geothermal energy are the ORC and the Kalina Cycle; these technologies provide an opportunity for the development of the geothermal sector in locations where electricity is necessary for the desalination processes but at the same time cannot be produced in a conventional manner [215–216]. What is more, this concept will replace all colocation plants using fossil fuel. An innovative method of integrating the MED technology with the ORC was proposed by Aguilar-Jiménez et al. [217]. The use of the ORC was suggested, since it allows the integrated generation of electricity and desalination using low-temperature resources in the first stage of MED operation. In their calculations, the authors demonstrated that compared to a conventional MED system, the system integrated with the ORC is 22% more efficient in water desalination, requiring a heat exchange rate higher by just 6.9% [217]. As it has been mentioned above, geothermal power generation technologies are already mature and their integration into desalination processes would be desirable.

Owing to the stability of thermal energy generation from geothermal resources, they provide a very attractive energy source. There are several low-cost geothermal resources [59]:

- low-temperature, shallow geothermal aquifers;
- geothermal springs;
- hot water separated from hydrocarbon fields;
- water discharged from underground mines;
- rest heat from different processes, also from geothermal power plants.

The supply of heat to desalination/treatment plants using geothermal resources can generally be considered more economically viable than in the case of solar energy [9]. Therefore, this solution can be very advantageous in areas where adequate geothermal resources are available, provided that this is confirmed by the economic analysis conducted for each individual case [59].

Geothermal energy (in form of heat) can be used in such desalination processes as MSF and MED as well as in combination with the emerging MD and AD methods. Both in the case of MD (50–90 °C) and AD (55–85 °C), the required geothermal water temperature is relatively low [6,9,218–220]. It should be noted that not just geothermal heat can be used in desalination processes; geothermal water itself can be treated provided that it has an acceptable chemical composition [221–226]. Detailed research on the use of geothermal waters for human consumption purposes was conducted by Tomaszewska and Bodzek [227,228], Tomaszewska and Dendys [229], Tomaszewska et al. [230,231] and Tomaszewska [232]. Çermikli et al. [233] demonstrated that treated geothermal waters can be used e.g. for irrigating crops. Geothermal waters are also considered in the context of their extraction. Currently, a number of desalination/treatment plants based on geothermal heat operate worldwide (Table 4, Fig. 8), however these are usually small installations [233–236].

Technical possibilities of desalinating geothermal waters with a temperature of 80 °C using the MED and MSF technologies were presented by Rodriguez et al. [236] and Gutiérrez and Espíndola [237]. In the first of the aforementioned articles, the authors indicate that 14 m^3 of geothermal water are required to desalinate 1 m^3 of sea water (Mexico). In the second case, the authors designed and tested a prototype unit in their laboratory, obtaining 20 m^3/day of desalinated water with a geothermal water consumption of 118 m^3. Another example of a pilot installation is the plant using MED on the island of Kimolos (Greece). It uses geothermal waters with a temperature of 60–61 °C extracted from a depth of 188 m below ground level (b.g.l.) The installation enables the desalination of 80 m^3 of water per day with a geothermal water demand of 1440 m^3/day [9,238]. Other studies from Greece, which did not, however, translate into pilot installations were also conducted on the islands of Milos and Nisyros. In the first case, the study indicated water desalination potential at a level of 75–80 m^3/day using geothermal water extracted from a depth of 85–184 m b.g.l. with a flow rate of 12,840 m^3/day [238]. For the island of Nisyros, the freshwater production potential was estimated at 225 m^3/day [239]. It is not possible to arbitrary present how much geothermal water is required to desalinate 1 m^3 of salt water. It is always dependent of energy needed, geothermal water resources and its temperature, desalination process used and others. That is why it needs a detailed feasibility study in each case.

The list of geothermal installations used in the desalination of water is presented in Table 4 and on Fig. 8. One should be noted, that generally there is no scale limitation of the desalination plant when using geothermal energy, in particular low-temperature heat, if the well has a good capacity, which is a considered as strength.

A thorough review of the directions and possibilities of using geothermal energy in water treatment processes was conducted by Gude [30]. He presented the potential for future implementations of geothermal sources to electricity and/or heat production, and examples of specific solutions operated in Australia, the Caribbean Islands, Central America (Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama), India, Israel, the Kingdom of Saudi Arabia, UAE, USA and Sub-Saharan Africa.

The use of geothermal energy in desalination processes is undoubtedly a very promising direction of development, mainly due to the possibility of generating both electricity and heat. Of the installations shown in Fig. 8, two are located in the USA (Salton Sea), one in Mexico (Baja, California), one in Greece (Kimolos), and two in Tunisia (Tunisia). All except installation in Greece use seawater. The dominant desalination technology is MED, but MSF and HDH are also used. Considering these installations in terms of daily production, the highest values are achieved in Tunisia – 1382 m^3/day, and the lowest in Mexico – 1 m^3/day [157].

The locally occurring worldwide high salinity of geothermal waters also allowed to undertake research work aimed at generating energy from the salinity gradient, what is more and more interesting nowadays (see Section 2). Nowadays, energy extraction from high mineralized geothermal water can be possible using PRO, RED or CAPMIX processes [65]. It can be also innovative technological processes.

Table 4
Overview of geothermal installations used in the desalination of water (adapted from [157]).

Country	Location	Desalination technique	Water source	Production capacity [m^3/d]	References
Mexico	Baja, California	MED, MSF	SW	1	[66]
Greece	Kimolos	MED	BW	80	[240]
Tunisia	Tunisia	HDH	SW	–	[241]
Tunisia	Tunisia	MD, MED	SW	1382	[242]
USA	Salton sea	MED/VTE(2)	SW	18.9	[243]
USA	Salton sea	MED/VTE (15)	SW	79.5	[244]

BW – 2-10 g/L; SW – 24-42 g/L.

4. Hybrid and integrated systems of RES technology

Of course, apart from the possibility of using individual RES technologies, these can be combined in hybrid systems. Studies towards the construction of hybrid or integrated systems have been carried out by many researchers. Missimer et al. [245] used a hybrid combination of solar and geothermal energy to balance the operation of the installation and minimise the risk of geothermal reservoir depletion. Similar studies to identify the potential present in south-eastern Spain were carried out by Colmenar-Santos et al. [246]. They studied a theoretical desalination plant with a capacity of 9000 m^3/d in a specific area of Almería (Spain) through the hybridisation of solar energy and geothermal energy. They considered the possibility of using a hybrid solar-geothermal system, and theoretical results of their research indicated that the combination of the two aforementioned sources would be possible for 76% of the year. However, it should be noted that this result was, among other things, the effect of geothermal water temperature of 41.8 °C achieved for a well depth of 490 m. In order for this figure to reach 100%, the working temperature of the desalination system would have to be 70 °C, and therefore it would be necessary to drill a well at least 790 m deep (this follows from the thermal gradient in the area analysed, which is 8.87 °C/100 m). The authors also estimated that the depreciation period would be 6 years, and the installation would make it possible to reduce CO_2 emissions to the atmosphere by 510 387,920 kg per year.

A novel hybrid system for water desalination using solar and geothermal energy was proposed by researchers from Iran [68]. The authors underlined that the proposed geothermal-solar energy driven plant could produce freshwater even during night-time (when there is no solar radiation) in regions with humid climate.

Rosales-Asensio et al. [130] analysed the hybrid use of solar and wind energy, which takes into account the energy used to power water desalination installations and the surplus energy generated which is supplied to the power grid. The case study was carried out for the island of Gran Canaria with an assumed water production level of 5600 m^3 per day. Assuming that a RO process with a demand of 3 kWh/m^3 would be used for this purpose, the authors have calculated the annual electricity demand at 5.88 GWh/year. Results of the simulation conducted showed that the output of the PV installation should be 866 kW and the output of the wind power plant should be 4100 kW. The construction cost of the desalination plant was estimated at about 1,178,000 USD (EUR 981,600), that of the PV plant at about 1,100,000 USD (EUR 909,300) and of the wind farm at about 5000,000 USD (EUR 4,099,337). Additionally, the cost of an energy storage installation (at 1050. USD/EUR 871.70 per kWh) was factored in, which gives a total cost of 7,200,000 USD (EUR 5,991,109). A technical and economic model based on the combination of solar (PV) and wind energy in the RO process, however with an installation in Iran as a case study, was also developed by Maleki and Pourfayza [247], and by Aminfard et al. [248]. In connection with the economic assessment (determination of life cycle costs) conducted and the probability of interruptions in electricity production, which they estimated at 0–10%, the authors additionally considered the possibility of using hydrogen tanks [247]. Aminfard et al. [248] provided a detailed technical and economic assessment of the feasibility of using RES in desalination processes in Texas. Their analysis was based on a multi-layered spatial model taking into account such aspects as the availability of water resources, the depth at which they are present and their salinity level, the potential of local RES as well as the price of water in the area in question. The authors analysed 1445 locations, 193 of which were considered promising. The results demonstrated that in 145 locations, geothermal energy was an appropriate source, while in 28

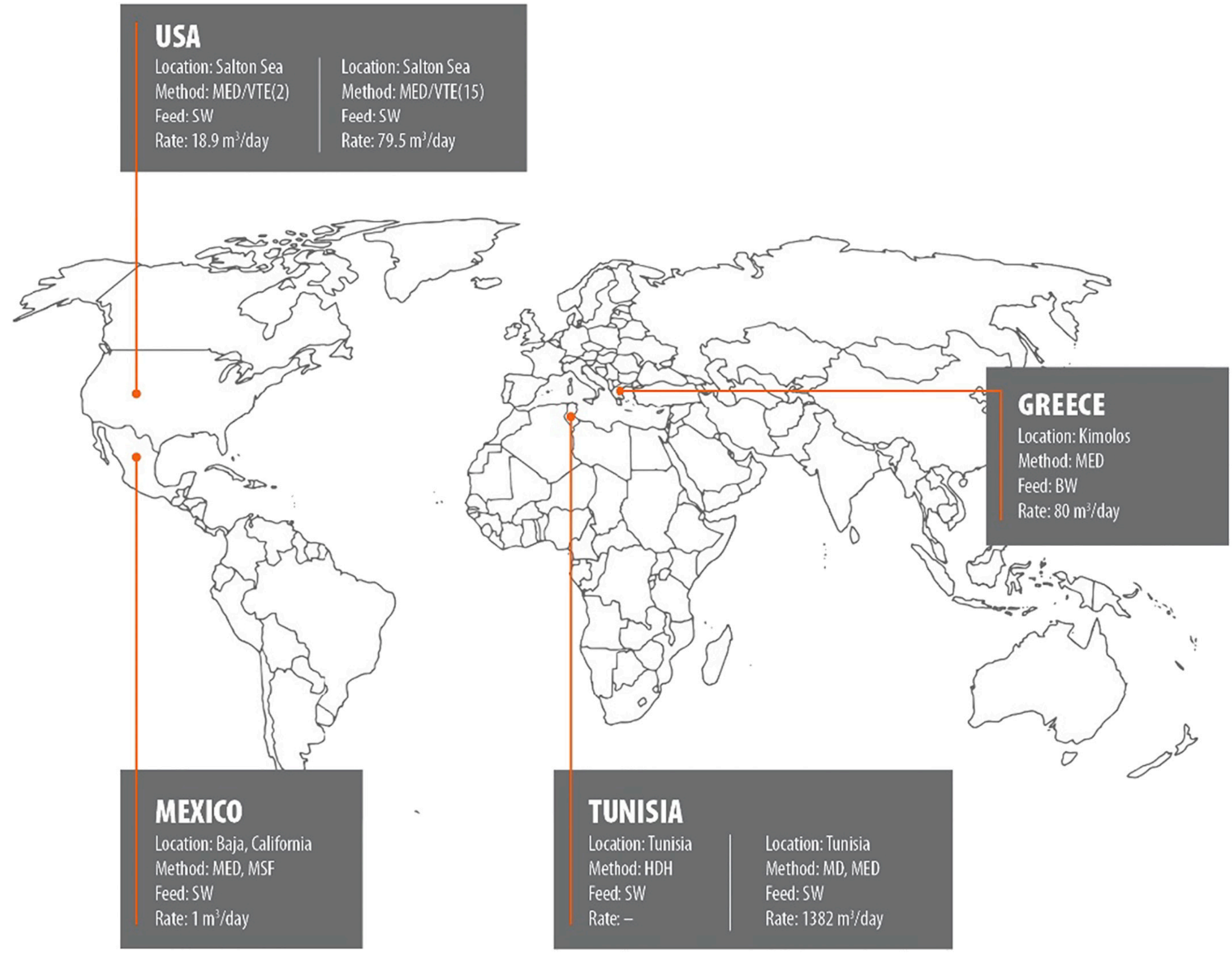

Fig. 8. Selected geothermal energy desalination installations worldwide (based on [157]).

locations, the use of solar energy was indicated as more cost-effective. At the same time, it was found that decreasing prices (in terms of renewable energy investment outlays) and their impact on lowering the cost of energy production would cause the number of promising locations to increase in the future.

Mollahosseini et al. [249] presented a review of renewable energy-driven desalination opportunities in Iran, which is a country suffering from severe droughts. They indicated that the most promising solution for Iran would be wind- and solar-assisted energy generation for powering the desalination plant. The total capacity potential of the three RES (wind, solar and geothermal) was estimated at 140,200 MWe. According to the authors, the use of this amount of power for energy generation would make it possible to desalinate about 28 billion m^3/d. The required investment outlays were estimated at about USD 260 billion. Interesting results of model studies were presented by Padrón et al. [250] who analysed the technical and economic feasibility of using RES to power RO desalination plants with a water production capacity of up to 50 m^3/day. The research was conducted for two islands (Lanzarote and Fuerteventura) using the HOMER software. This is another analysis of the potential for using wind and solar energy, taking into account the electricity demand of the desalination plant and the relatively high local potential of these renewable energy sources. The research was aimed at developing an autonomous desalination system. The best results were obtained for the installation located on the island of Lanzarote where the energy cost amounted to 0.404 USD/kWh. The proposed system consists of a 30 kW wind turbine, a 5 kW photovoltaic system and a 10 kW conventional generator. Additionally, the system included 160 batteries with a capacity of 360 Ah. According to the authors, this optimised system would make it possible to cover 96% of electricity demand. In the case of the island of Fuerteventura, the system was designed very similarly, but using a conventional generator with a capacity of 15 kW and 200 batteries, which translated into 92% of energy demand covered at a unit cost of 0.478 USD/kWh. Additionally, the economic aspects of integrating the two discussed technologies were analysed, e.g. by Ismail et al. [251], and the possibilities of using such a solution on a commercial scale in the RO process were studied [79]. The state of the art and challenges for the large-scale implementation of a hybrid wind-solar (PV) energy driven RO membrane desalination installation were investigated by Mito et al. [79]. In their work, the authors focused on optimising the management of energy generation processes based on wind and solar (PV) energy by identifying technical challenges and potential solutions in order to implement this type of installation on a commercial scale. The authors pointed out, among other things, that one technical challenge is to avoid the shortening of life of RO membranes, and as a solution they proposed modulating the operation of the installation depending on the availability of renewable energy from commercial plants at any given time. However, in order for this solution to be effective, it cannot be a random process, but rather a precisely managed one, which requires further research. Additionally, the authors pointed out that the research conducted so far on membrane performance has been limited to short periods in relation to membrane lifetime, and that additional studies are required in this connection.

Hybrid use of RESs was also proposed by Azhar et al. [252] who analysed the possibility of integrating the use of solar, geothermal and ocean thermal energy. The total output is estimated at about 55 MW, with OTEC (ocean thermal energy conversion) only accounting for 30.49 kW. The energy and exergy efficiency of the system has been estimated as well. The former amounted to 13.94% and the latter to 17.97%. The system proposed by the authors is capable of producing 18.54 kg of fresh water per second. An analysis of technical capabilities of a hybrid system using solar (PV) energy and wind energy in rural areas of Australia was presented by Fornarelli et al. [253]. The proposed solution consists of a 2.4 MW wind power plant and a 2.8 MW on-grid solar power plant. In their research, the authors considered not only the possibility of powering the desalination plant (1.2 GWh of electricity) but also of supplying the local community (14 GWh). The system designed in this manner reduces the cost compared to current energy prices from 0.146 USD/kWh to 0.077 USD/kWh, i.e. by 47%. At the same time, this translates into 37% less dependence on the power grid. As the authors point out, this approach makes it possible to present the process of water desalination using RESs to the local community as economically desirable. A more complex hybrid system was proposed by Atallah et al. [254]. They analysed the technical possibilities of powering the RO process using a hybrid RES system based on the use of wind turbines and PV panels in combination with a conventional diesel generator. The research was conducted using the HOMER software for the village of Nakhl in Egypt, with the assumption that freshwater production would amount to 100 m^3/day. Ultimately, the system included a 160 kW PV installation and a 50 kW diesel generator. The system was additionally supplemented by 39.3 kW converters and 190 lead-acid batteries (in 19 chains) with a capacity of 3.11 kWh. The energy generation cost estimated by the authors is 0.107 USD/kWh. The share of RESs in the energy generation process is 93.1%, which translates into a 94% reduction in CO_2 emissions. A system based on wind and hydro power was also presented by Tsai et al. [29] as a solution to the water scarcity problem in the city of Taichung in Taiwan. Among recent research, attention should be paid to Delgado-Torres et al. [43], in which paper the SWRO technology is analysed, with the installation powered by a hybrid system which uses PV and tidal energy. The authors demonstrated that the combination of these two technologies can extend the operating time of the desalination plant by a factor of 1.8–2.6. Selected desalination installations using hybrid RES in the world are presented on Fig. 9.

Among the hybrid installations shown in Fig. 7, it can be seen that the hybrid models primarily assume the cooperation of photovoltaic installations with wind farms. It may be supplemented by a conventional generator, as is the case with an installation located in Turkey, as well as an energy storage system. Considering these installations from the point of view of the power of photovoltaic panels as the most dynamically developing technology among RES, the largest is in Tunisia (30.8 kW), and the amount of permeate for it ranges from 57 to 1151 m^3/day. For installations in Turkey and Egypt, the values are 24 m^3/day and 5 m^3/

Fig. 9. Selected hybrid energy desalination installations worldwide (based on [171,179,255]).

day, respectively [79,254].

5. Energy storage

The storage of electricity and, even more, the thermal energy used to drive desalination processes is one of the key issues arising from the mismatch between energy supply and demand. As it has already been mentioned, in the case of the most commonly used desalination technology, i.e. solar energy, the problem is the strong dependence of energy generation on weather conditions. Whereas in the case of electricity, this problem can be solved by connecting the installation to the power grid (assuming that the requisite infrastructure exists) or by using the well-known battery technology, more complex solutions must be sought where thermal energy is required. To this end, e.g. process oils or molten salt can be used. Especially the latter solution is interesting because of the parameters that characterise molten salt, especially its high density [256].

Energy storage is becoming a requirement for the uninterrupted and reliable operation of desalination plants, and therefore, the following section presents the available thermal energy storage technologies. Fig. 10 shows the possibilities of storing electricity and thermal energy depending on the technology. Gude [257], in a critical review of the energy storage options available for diverse RE powered desalination processes, focused on thermal and battery energy storage systems.

The first possibility of storing thermal energy is to use the specific heat of substances by increasing the temperature of the storage medium. Energy may be accumulated both in solids (e.g. granite, sandstone) and in liquids (e.g. water, process oils, refrigerants). It is a well-known and simple method. Other methods involve the use of phase change materials (PCMs) and chemical change materials (CCMs). In the first case, phase-shifting substances are used to absorb, accumulate and subsequently release energy in their phase transition temperature range. The materials most commonly used in this storage method include paraffins, fatty acids, ionic liquids and molten salts. As concerns the use of chemical change materials, research is currently underway in the field of energy storage using this method and the materials which could potentially be used, but the high cost and complexity of the process (the use of *exo*- and endothermal reactions) constitute an obstacle to its broader adoption. Detailed review of existing CSP installations with TES systems in the world and those in the construction has been presented by Achkari and Fadar [117]. They concluded that 45.5% of the operational CSP plants worldwide are connected with TES, however 95.6% of them use liquid sensible heat storage (SHS) materials due to their reliability, low cost and easy operation. Solid SHS systems are implemented in demonstration projects [117]. What is why, that CSP with TES connected to desalination plant is still an interesting option if no grid power is available. As was pointed also by Tehrani et al. [112] based on theoretical analysis of the performance of various TES alternatives integrated with mentioned in Section 3.1.1, Gemasolar installation a shell-and-tube heat exchanger which include a sensible or phase change material (PCM) as the storage can be considered as a future alternative to the two-tank molten salt system. It can reduce the amount of storage material used and ensure optimal storage utilization. However, such designs need to be further evaluated [112].

The methods commonly used and feasible in the case of desalination include mentioned previously TES. It is an optimal solution, especially from the point of view of being combined with solar energy. The energy can be stored in ground or water (UTES – Underground Thermal Energy Storage) or in surface reservoirs (TTES – Tank Thermal Energy Storage). The most popular technologies involve energy accumulation in the ground (BTS) and in aquifers (ATES). In the first case, these are usually vertical heat exchangers with a depth of up to 200 m b.g.l. whose heat capacity can be estimated at around 15–30 kWh/m^3. However, the exact value depends on local geological and hydrogeological conditions. However, a clear disadvantage of such solutions is the high costs related to the necessity of drilling a significant number of wells. In the case of ATES systems, thermal capacity is estimated at around 30–40 kWh/m^3, which is due to the water present in the layers which provide heat storage. However, the highest thermal capacities of around 60–80 kWh/m^3 can be achieved for PTES and TTES systems where the accumulation

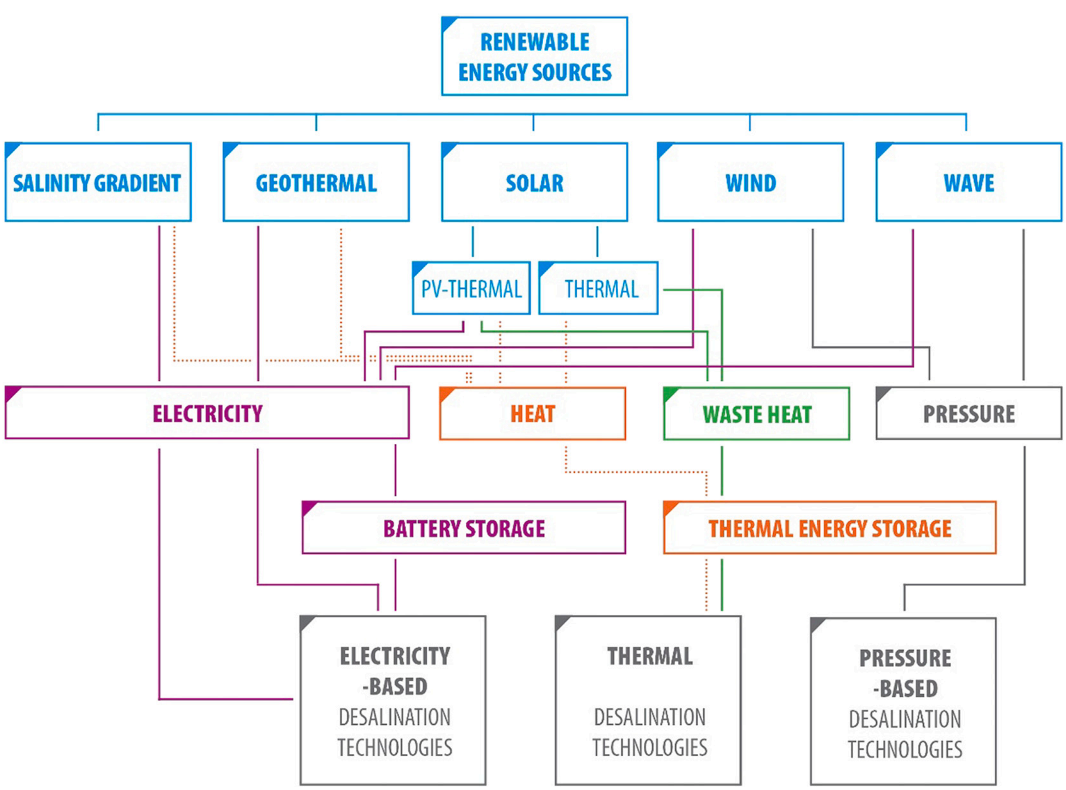

Fig. 10. Storage of electricity and thermal energy in connection with water desalination technologies (based on [257], updated).

medium is water placed in a reservoir below ground surface [258]. TES reservoirs are schematically shown in Fig. 11.

A comprehensive study on the feasibility of using individual energy storage technologies depending on the type of renewable energy source as well as on the desalination process selected was presented in Gude [257]. Koohi-Fayegh and Rosen [45] also reviewed storage technologies in general, indicating the direction in which the sector is developing. They concluded that the use of batteries for storing electricity probably remains the cheapest form of energy storage. However, it is worth noting that work on improving this technology is ongoing and is currently focused on introducing new energy storage materials. This concerns both small- and large-scale storage. In addition, the authors pointed out that the pumped hydro energy storage (PHES) and compressed air energy storage (CAES) technologies are mature and cost-effective, but more research is needed to improve their efficiency further. A detailed review of recent research into MESSs (mechanical energy storage systems) was carried out by Mahmoud et al. [259], who, in addition to the already mentioned PHES and CAES systems, also analysed FESSs (flywheel energy storage systems) in the context of their possible combination with wind and solar energy generation.

On the other hand, a new direction for energy storage was proposed by Karavas et al. [139]. Analysing the possibilities for seawater desalination in the RO process, the authors proposed to use the concept of a direct current (DC) microgrid with short-term electric and hydraulic energy storage. In the case of electricity, hybrid capacitors were considered, while in the case of hydraulic energy, pressure vessels could be used. This concept was proposed in order to replace conventional electricity storage devices, i.e. batteries. The results obtained by Karavas et al. [139] indicate that in the case of electricity storage, the energy demand of desalination would be covered for 10 min, and in the case of pressure vessels for 20 min, which indicates that it is possible to ensure the smooth operation of the desalination installation combined with the photovoltaic installation throughout the day.

The design of a RED or CapMIX unit can work as a concentration gradient flow battery [61,69]. As it was presented in Section 2, the RED mode is one of the solution to obtain renewable energy. Such system, during regeneration of the chemical potential at the ED mode (charging) (Fig. 12), may play a storage device. The energy efficiency obtained was about 62–77% with an average power density of 0.07–0.44 W/m^2. Further studies in this field are needed to obtain better results to implement it.

The need for further research was also indicated in the case of thermal energy storage with the use of adsorption processes, which the authors considered to be currently not economically viable (among others, the need to conduct studies on materials to avoid adsorbent instability and to optimise temperatures during the charging and discharging processes was indicated).

The possibilities of using self-charging fuel cells in cooperation with a photovoltaic installation in the RO process were analysed by Rezk et al. [260]. The authors analysed a 150 m^3/d system to irrigate remote areas using the HOMER software. The obtained results indicate that it is a competitive solution in relation to the expansion of the grid, as well as the construction of a conventional diesel-fueled installation. These results allow fuel cells to be an effective solution to the problems related to the instability of energy generation from renewable energy sources and energy storage systems.

In addition, the costs of energy storage systems must be taken into account. Carnegie et al. [261] and Koohi-Fayegh and Rosen [45] claim that such costs depend on the manner of their use. In addition, the costs of energy storage systems are influenced by e.g. system location and size as well as the costs of conventional energy sources used as an alternative to storing the energy generated from renewable sources. The fact that local conditions have an impact on the cost of storage systems is confirmed by the conclusions formulated by Zakeri and Syri [262] who claim that costs for CAES solutions range from 1 USD/kWh to 30 USD/kWh depending on the geological structure.

Despite the development of the use of renewable energy technologies on an increasing scale in desalination processes, their percentage share in relation to conventional technologies is only 1% [263]. In many cases, it is related to the necessity of using expensive solutions for storage systems, which poses challenges for locations where there is no technical possibility of connecting to the power grid [194–195].

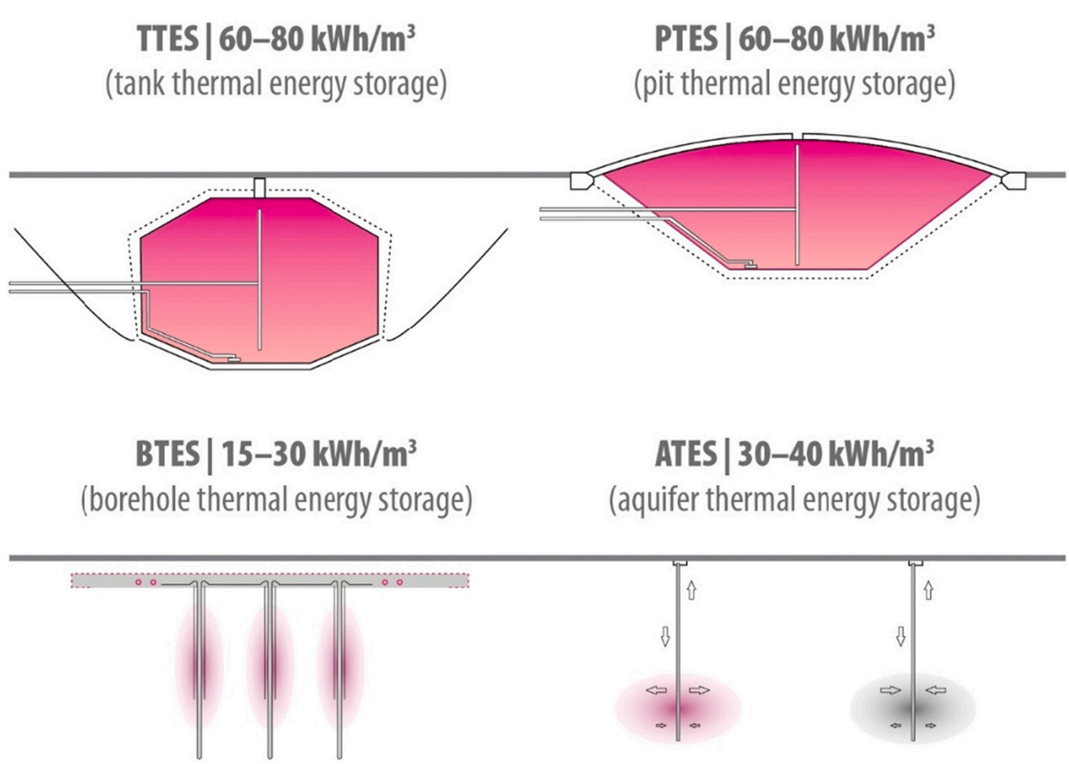

Fig. 11. TES methods (based on [258]).

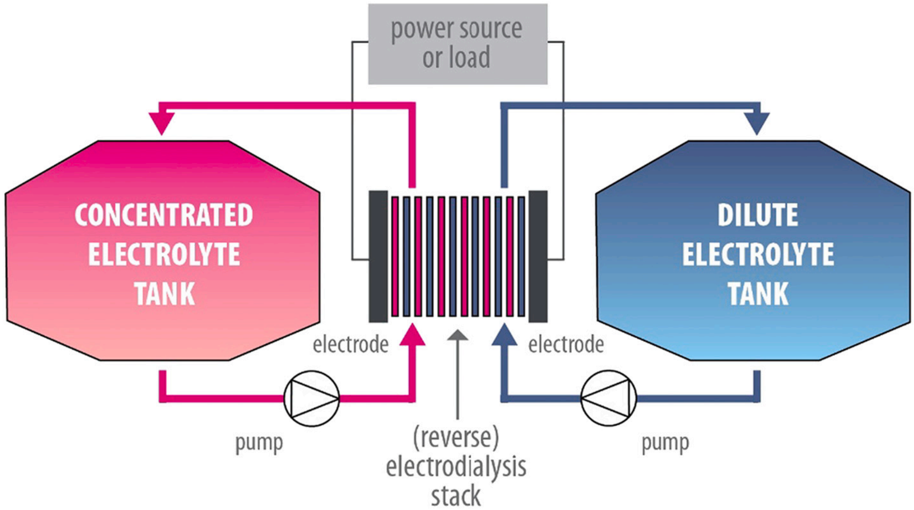

Fig. 12. Concept for concentration gradient flow battery in RED system (based on [69]).

6. Energy demand and desalination costs

The review presented indicates that process efficiency, improvements in energy recovery systems and mostly the search for novel renewable-energy driven desalination systems have been the directions pursued in recent years.

An important parameter in the selection of the RES technology for the desalination process is the consumption of electricity or heat per unit of desalinated water expressed in cubic metres. This parameter varies depending on the desalination technology used. According to Ghaffour et al. [2], in the case of electricity for the SWRO technology, it is 3–4 kWh/m^3 for very large capacity (such as several hundred m^3/h) desalination plants and this cost goes very high at lower capacities (1–5 m^3/h). Interesting information in the context of energy consumption using SWRO technology is provided by Voutchkov [20], distinguishing individual component processes. Referring to these data, it can be concluded that SWRO is responsible for the consumption of 2.54 kWh/m^3, which is 71% of the total energy consumption. The second of the most energy-consuming processes is pretreatment with a 10.8% share (0.39 kWh/m^3). In the following places are intake – 5.3% (0.19 kWh/m^3) and product water delivery – 5.0% (0.18 kWh/m^3). Complementing to mentioned above are other accompanying processes, which constitute 7.6% (0.27 kWh/m^3).

For the MSF technology, it is about 2.5–4 kWh/m^3 of electricity and about 7.5–12 kWh/m^3 of thermal energy, giving a total of about 10–16 kWh/m^3, yet this is for large scale capacity with a cogeneration system combining the desalination unit with a power plant from which low pressure steam is used as waste thermal heat for desalination. For the MED technology, it is about 1.2–2 kWh/m^3 of electricity and 4–7 kWh/m^3 of thermal energy, giving a total of about 7.5–12 kWh/m^3, in a cogeneration large scale system. Continuous progress in water treatment processes has resulted in the development of technologies which can be considered low-energy intensive. These are AD and MD, for which total energy consumption is estimated at around 2 kWh/m^3, but these reports estimate thermal energy as non-payable considering the required low operation temperatures (up to 60–70 °C) could be harvested from low-grade waste heat, which is not a fair comparison [9]. Lee et al. have shown that the energy required for MD is much higher than in conventional processes [264]. One should notice that about 61% of desalination installation is fed with seawater and about 21% from brackish and the latter is more economically since its salinity is lower and require less energy [9,265].

As regards to the economics of desalination plants using RES, the costs are high, which is mainly due to the high energy intensity of desalination processes. However, in order to meet the global demand for drinking water and water used for agricultural purposes, desalination processes are becoming a necessity. A comparison of the costs of desalinating water using solar energy is presented on Fig. 13. It can be seen that costs and energy consumption per cubic metre vary broadly. For example, in the case of RO process in combination with PV installations, energy consumption ranges from 5 to 19 kWh and the desalination price is 15.6–27 USD/m^3 [38,266]. However, as observed in recent years rapid technological advances in PV (mentioned in part) may result in PV costs decreasing down to about 0.05–0.06 USD/kWh [14] what will definitely affect the desalination price. In addition, when the energy recovery system is included with RO process, using e.g. Pelton-wheel turbines, Francis turbines or turbocharger energy from rejected brine can enable up to 90% energy recovery [14,43]. Similar differences can be observed in the case of MD. The amount of energy required for water desalination ranges from 100 to 2200 kWh/m^3 and the price from 10.4 to 19.5 USD/m^3 [14,38; 56,267]. However, typical capacity of solar MD is 0.15–10 m^3/d [14,268].

Taking into account the size of the installation due to the amount of desalinated water during the day, it should be noted that in the case of using solar energy, dominate capacities not exceeding 100 m^3/day. The exception is the use of CSP systems, for which the capacity is estimated at over 5000 m^3/day. Additionally, these technologies are mostly applicable (solar still, PV SWRO, solar multi-effect humidification) or in the phase of advanced R&D (solar MD and PV EDR). Only solar SWRO is classified in the phase of basic research, hence the capacity of over 0.1 m^3/day is very general information. Among the technologies that can be commonly used, RO elevators with capacities of 50–2000 m^3/day and geothermal MED with capacities of 50–1000 m^3/day should be mentioned [269]. Among wind energy technologies, wind MVC are also in the advanced research phase, and wind ED are in the preliminary research phase. The use of wave energy (wave RO) with the value of 1000–3000 m^3/day stands out for a high potential. It is also a technology for which unit costs are the lowest among the analysed ones, ranging from 0.7 to 1.2 USD [14,269].

The second largest costs are for solar still ranging from 1.4 to 6.5 USD/m^3, and solar/CSP MED where it is 2 to 2.5 USD/m^3. In the last case, the upper limit of the production costs of 1 m^3 of desalinated water is particularly important. The highest costs were determined for the MD solar technology (10.4–19.5 USD/m^3) and for PV SWRO (11.7–15.6 USD/m^3). This is one of the reasons why hybrid RES systems are becoming more and more popular, as it is about optimising the costs incurred per unit of desalinated water, which is possible with the integration of various RES technologies.

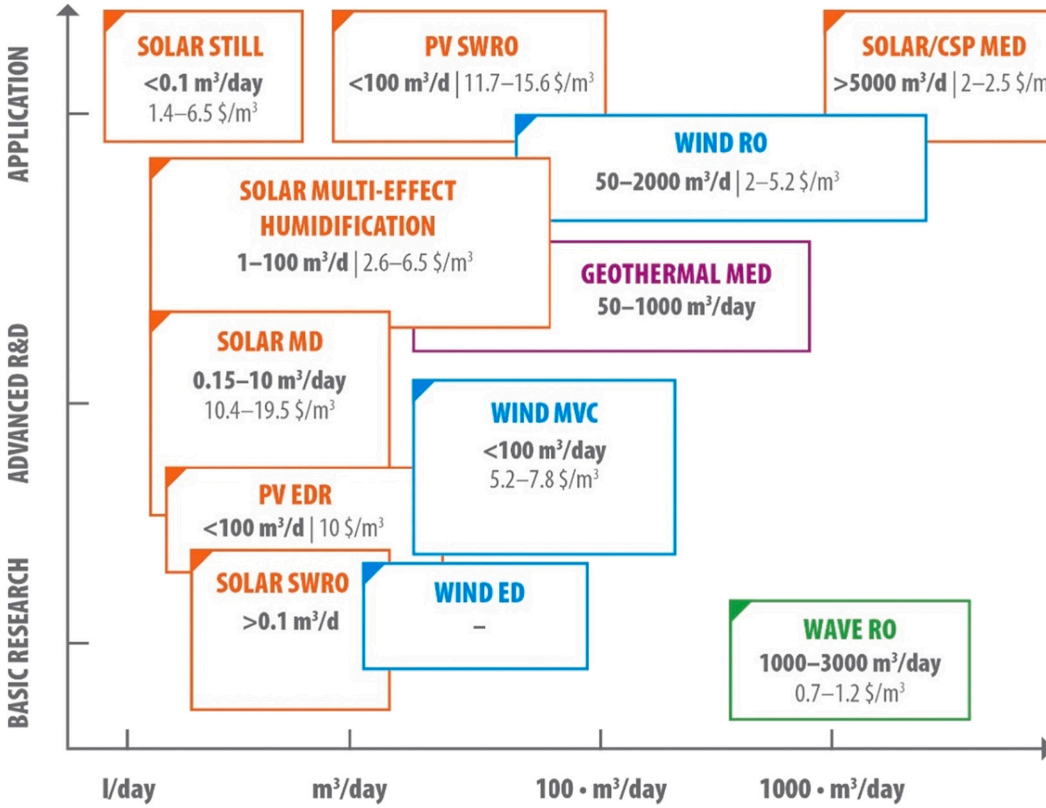

Fig. 13. Commercialisation status of various desalination technologies (based on [269]).

Table 5
Global comparison of investment outlays connected with selected RES technologies in 2015 and 2018 [273–274].

Region	Solar PV			Solar CSP			Geothermal		
	2015 [USD/kW]	2018 [USD/kW]	Change [%]	2015 [USD/kW]	2018 [USD/kW]	Change [%]	2015 [USD/kW]	2018 [USD/kW]	Change [%]
Africa	2649	1621	38.81	14,153	6181	56.33	3818	4612	−20.80
Asia	1624	1921	−18.29	4423	4285	3.12	3148	3612	−-14.74
Central America and the Caribbean	2076	1402	32.47	–	–	–	3413	3688	−8.06
Eurasia	2775	1287	53.62	–	–	–	3113	4793	−53.97
Europe	1408	1098	22.02	8839	7718	12.68	5209	7192	−38.07
Middle East	2553	1342	47.43	3705	6645	−79.35	–	–	–
North America	2365	1557	34.16	6794	7301	−7.46	5017	3833	23.60
Oceania	2857	1554	45.61	9829	6958	29.21	3796	3794	0.05
South America	2249	1542	31.44	–	–	–	3587	3140	12.46
China	1439	879	38.92	3680	4228	−14.89	1943	–	–
India	1403	793	43.48	4328	4408	−1.85	2169	–	–
USA	2336	1549	33.69	6794	7301	−7.46	5961	5555	6.81

Region	Biomass			Wind on-shore			Wind off-shore		
	2015 [USD/kW]	2018 [USD/kW]	Change [%]	2015 [USD/kW]	2018 [USD/kW]	Change [%]	2015 [USD/kW]	2018 [USD/kW]	Change [%]
Africa	1654	1220	26.24	2080	1451	30.24	2155	–	–
Asia	1486	2408	−62.05	1280	2237	−74.77	–	4843	–
Central America and the Caribbean	1021	1768	−73.16	2268	2277	–	–		–
Eurasia	1756	1401	20.22	1751	1998	–	–	–	–
Europe	3249	2917	10.22	1917	1950	−1.72	2053	4992	−143.16
Middle East	2895	4022	−38.93	2497	2313	7.37	–	–	–
North America	3584	3877	−8.18	1874	1546	17.50	2251	10,080	−347.80
Oceania	3851	2450	36.38	2533	1638	35.33	–	–	–
South America	1662	1081	34.96	1871	1763	–	–	–	–
China	1576	1383	12.25	1251	1173	6.24	2115	2747	−29.88
India	1112	1350	−21.40	1228	1201	2.20	–	–	–
USA	4076	2370	41.85	1770	1659	6.27	2250	10,080	−348.00

Criticisms concerning the use of RESs in desalination processes were presented by Lawal and Qasem [270] and by Kasaeian et al. [47]. However, the authors ultimately pointed out that RESs may be the right choice in places where there is no power grid. In some cases, the use of RESs can be considered a necessity, mainly on islands and remote rural areas where there is no transmission grid infrastructure and there is a natural problem with access to fresh water [270]. Such statement has been the conclusion of past studies, but it is feasible for very small capacities. This is confirmed by research carried out by Wang et al. [271] who studied this possibility not just in order to desalinate water, but also to meet electricity needs using exclusively RESs. The research results presented by Mentis et al. [272], who analysed the possibility of using RESs on three Greek islands (Patmos, Lipsoi and Thirasia), are also in line with this trend. The authors demonstrated that, depending on the size of the island, the cost of desalination varies between 1.45 and 2.6 EUR/m^3 (1.74–3.12 USD/m^3) – the larger the island, the lower the cost, i.e. it is far less than the current price of supplying water to the islands, which ranges from 7 to 9 EUR/m^3 (8.4–10.8 USD/m^3).

When indicating the investment outlays connected with the RES analysed in this article, it is necessary to take into account changes in the situation in the global markets in recent years. Differences in installation costs per kilowatt of solar capacity (PV and CSP) as well as of geothermal capacity are shown in Table 5. The comparative analysis conducted for 2015 and 2019 shows that for PVs, there was a significant reduction in investment outlays, which decreased from 22.02 to 53.62% depending on the region. The exception is Asia with an 18.29% increase in price per kilowatt of installed capacity. For CSP installations, it can be considered that outside the Middle East, the situation is stable in terms of investment outlays, and for Africa, Oceania and even Europe it is favourable. Unfavourable price changes can unfortunately be observed in the case of geothermal installations what can be as a result of sharing harder-to-reach high-temperature deposits. However, it should be noted that for this energy sector, hasty conclusions should not be drawn from the analysis presented, since the issue of constructing geothermal installations is very complex and requires more in-depth studies. There are several low cost geothermal options as it was outlined by Bundschuh et al. [59] from low enthalpy geothermal sources (see Section 3.5).

In the case of biomass installation costs, it is difficult to draw clear conclusions, as these vary greatly and percentage changes have ranged from −73.16% to 41.82%. More clear-cut results emerge in the case of the wind power industry, where there is a clear downward trend in price per kilowatt of installed capacity for onshore power generation and significant cost increases, even of 348%, can be observed for offshore installations. Hydropower is not included in the list due to the fact that the averaged data mainly refer to conventional flow-through and pumped-storage hydro plants, whereas in the case of desalination processes tidal, wave and ocean thermal energy are of rather greater importance.

Water desalination/treatment can be considered an environmentally friendly and desirable technology, e.g. in view of the reduction in the use of conventional fuels for this purpose [275]. This issue becomes particularly important when the data published by the Food and Agriculture Organization of the United Nations (FAO) are analysed, which indicate that due to global population growth, food production will increase by 70% by 2050 [276]. This problem was also noticed by Manju and Sagar [277] who discussed the problem of water scarcity in India. They pointed out that the rate of population growth in India results in more freshwater being required to meet basic needs, and this in turn can cause water shortages. India's total population is expected to reach 1.60 billion by 2050, and by 2040 the country will be ranked 40th globally in terms of water scarcity [277]. Similar problems can be expected in many parts of the world where a shortage of drinking water is already felt today.

Research conducted worldwide in recent years demonstrates that apart from the very essence of integrating RESs into water desalination/treatment processes, sustainability and environmental aspects of these desalination processes [32] as well as economic, environmental and social issues [278] are discussed. These issues go hand in hand with the aim of optimising these processes and thus improving their efficiency and reducing energy consumption.

Analysing the research on life cycle assessment (LCA) in the field of desalination, Aziz and Hanafiah [279] showed that 62 studies were carried out over the years 2004–2019 in the field. However, taking into account individual desalination technologies, most studies concerned the membrane processes, and more precisely RO (55). The second most frequently analysed method was MSF (12) and MED (8), while the remaining technologies were analysed in single studies. It should be noticed, that the LCA is a method very sensitive to variables such as the impact on the ecosystem, local environmental and social conditions, comparing the results with each other is difficult to be considered reliable. This does not mean, however, that conclusions should not be drawn from the studies conducted so far. However, these indicate that the main cause of the negative impact of desalination processes on the environment is the use of conventional fuels to generate electricity or heat that is necessary for desalination. This is confirmed, among others studies, by Alhaj et al. [280] and Goga et al. [281]. In these situations it is obvious that RES are desirable to cooperate with desalination processes. Following this line of reasoning and looking for a desalination technology that will have the lowest environmental impact, first of all, attention should be paid to the energy consumption of individual technologies. On the other hand, when discussing the LCA topic, it has to be remembered that the study should also take into account the impact of RES installations in terms of its entire life cycle.

Appropriate algorithms for simulating hybrid desalination systems in the context of their optimisation in order to obtain best results are provided by Bitaw et al. [71]. The authors pointed out that the highest carbon dioxide emission reduction rate (63%) was achieved with ED-RO. On the other hand, an environmental life-cycle assessment was conducted by Cherif et al. [282] who analysed a hybrid wind-solar power system. A comparison of pollutant emissions from conventional (coal-fired) and geothermal power plants was presented by Lund [283] and Fridleifsson et al. [284]. The average sulphur dioxide and carbon dioxide emissions from coal-fired power plants are 25 times higher than in the case of geothermal plants.

7. Conclusion and future roadmap

This review article has presented global experience of the use of RES in different configurations to run water desalination systems based on different feed water sources: sea, brackish or geothermal water. Considerable experience gained through experiments and analyses, as well as deployment in practice, has demonstrated that renewable and alternative technologies can successfully be combined with many desalination methods. However, there is still a need to optimise some techno-economic aspects in order to produce systems that are effective in the long-term. Here is a summary of potential links between RES and desalination:

- solar thermal: it is necessary to improve application in small- and industrial-scale desalination, optimising the surface area of devices that concentrate solar radiation by using new technologies, improving materials for solar energy collectors and increasing heat energy storage, e.g. by connection of CSP solutions with TES. In such areas there is a need for optimisation of fluid solutions and materials for energy storage;
- solar electricity: a positive aspect is that nowadays PV technology can be expected to be competitive with conventional resources as a consequence of gradually decreasing investment outlays and operating costs and still increasing lifetime. That is why this sector of RES has shown increasing popularity. However, it is necessary to solve certain problems, both of an energy nature and those resulting from climatic conditions, like the fouling of PV panels, soiling, dust and

cleaning needs, and cooling problems in regions where there are high values of solar radiation. There are also some technological challenges like increasing the use of clean and green technology in solar cells, nanotechnology, nanomaterials such as silicon, indium gallium phosphide, gallium arsenide, indium gallium arsenide, quantum dots as a third generation and nanostructures (metallic nanoparticles, metal oxides, carbon nanotubes, graphene, gallium arsenide) as a fourth generation for the fabrication and production of PV panels on a large scale. CPV systems can also be analysed as an alternative to conventional PV installations, however this solution also needs an effective cooling system;
- wind: wind energy powered desalination systems which are not connected to a conventional grid are in effect stand-alone micro-grids and generally have been configured to handle small-scale desalination projects. The challenges for the effective use of wind energy also include the incorporation of energy storage systems;
- hydroelectricity: this is mainly considered due to the fact that the desalination of seawater requires the supply of electricity in coastal areas where using tidal, wave or ocean thermal energy appears to be a natural solution. Some positive potential can certainly be shown in the near future by installations powered by ocean thermal energy. These use the Organic Rankine Cycle (ORC) or the Kalina Cycle to exploit the temperature difference between shallower and deeper layers of water. Such systems still need to be optimised;
- biomass: nowadays biomass energy is not used separately to power desalination systems. Generally this works in combination with other renewable and non-renewable energy sources in hybrid systems;
- geothermal energy (power and thermal): power solution can be very advantageous for desalination in areas where adequate geothermal resources are available provided that this is confirmed by the economic analysis conducted for each individual case. Furthermore, there is generally no limitation to the scale of the desalination plant when using geothermal energy if the well has a good capacity, which is considered as a strength. It also should be highlight that low-cost, low enthalpy geothermal heat sources can be wildly use as a direct heat applications for several conventional thermal-based water desalination technologies;
- salinity gradient energy: can be considered as an very interesting and valuable technique for renewable energy production and storage. However further research is needed to effectively implemented it in industrial scale as a source of energy to desalination.

Especially in case of solar and wind energy, it is noted that the key issue to be addressed is still the lack of stability of energy production which drives a search for energy storage solutions and the expansion of off-grid systems. However, despite some disadvantages, it can be concluded that the use of RESs is a reasonable and desirable choice. At the same time, it should be noted that combining renewable energy with desalination processes requires further intensive research and demonstration units for longer term performance. The need to develop less energy-intensive desalination technologies should be supported by regulations.

CRediT authorship contribution statement

Conceptualization: J. Bundschuh, N. Ghaffour, B. Tomaszewska, M. Kaczmarczyk; **Writing-original draft preparation:** B. Tomaszewska, M. Kaczmarczyk, J. Bundschuh, N. Ghaffour; **Writing-review and editing:** J. Bundschuh, B. Tomaszewska, N. Ghaffour, M. Kaczmarczyk; **Supervision:** J. Bundschuh, N. Ghaffour, B. Tomaszewska; **Project administration:** B. Tomaszewska.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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