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Recent progress in the use of renewable energy sources to power water desalination plants

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ABSTRACT

Rapid population growth and industrial development have propelled water resources to the forefront of challenges facing modern societies. While water covers about two thirds of the surface of earth, < 1% is suitable for domestic and industrial use. Conventional fossil-fuel powered desalination techniques consume extensive amounts of energy and have highly damaging impact on the environment. Abundant cheap and clean renewable energy sources are a promising alternative for powering modern desalination processes. In this work we review latest developments in the renewable energy systems to power desalination plants. The review focuses on desalination processes powered by solar, geothermal, wind, and ocean energy. Towards the end, the work also outlines existing challenges and makes recommendations about future directions.

1. Introduction

Although water covers two thirds the surface of earth, only a small portion of this water is suitable for human consumption and use [1]. Currently, one fifth of the world's population is facing scarcity in water resources. Another one quarter do have access to water, however they lack proper treatment methods to make it potable [2]. By 2030, this water shortage is expected to affect up to 40% of world inhabitants [3]. Therefore, finding sufficient fresh water resources has become a top priority in the strategic plans of most governments as it affects the potential for economic growth and social well-being of billions of people [4].

Saline water represents 97% of the total available water resources on Earth [5]– [6]. Naturally, sustainable water desalination becomes a principle means for many societies to secure fresh water [7]– [8]. This is reflected in the almost exponential increase in global desalination plant capacity as shown in Fig. 1. During the period of 2000 to 2015, desalination plant capacity has increased by around 60 million cubic meters per day [9].

In its basic form, water desalination is the process of removing salt from saline water. Water desalinating has many advantages such as utilizing readily available water resources (seawater and brackish water), the ability to secure water in arid and coastal areas, and techniques that cover a wide range of operating conditions. Desalination processes are categorized into two main types: thermal processes and membrane processes. Membrane desalination processes use membranes that possess unique properties, such as ion selectivity in electro-dialysis (ED), electro-dialysis reversal (EDR), capacitive deionization (CDI), semi-permeability in reverse osmosis (RO), and membrane distillation (MD). Thermal desalination processes, on the other hand, are based on phase change processes, such as multi-stage flash distillation (MSF), multi-effect distillation (MED), humidification dehumidification (HDH), and vapor compression distillation (VCD). Among the different desalination techniques, MSF, MED and RO are widely used for the production of fresh water in large scale [9]– [10]. As shown in Fig.1, RO accounts for 65% of production capacity, MSF accounts for 21%, MED accounts for 7%, ED accounts for 3%, and the remaining 4% are obtained through the other desalination technologies. The main drawbacks of the different desalination technologies can be enumerated as: high energy consumption, discharge of contaminated brine with its negative effect on aquatic life, environmental pollution when fossil fuels are used, and the high upfront capital cost.

In particular, high energy consumption is a critical factor that affects the economics of desalination. Table 1 shows a comparison of energy consumptions for the commonly used water desalination techniques. In general, thermal-based desalination techniques consume significantly more energy as compared to membrane-based techniques [11–13]. For instance, total specific energy requirements for MSF and

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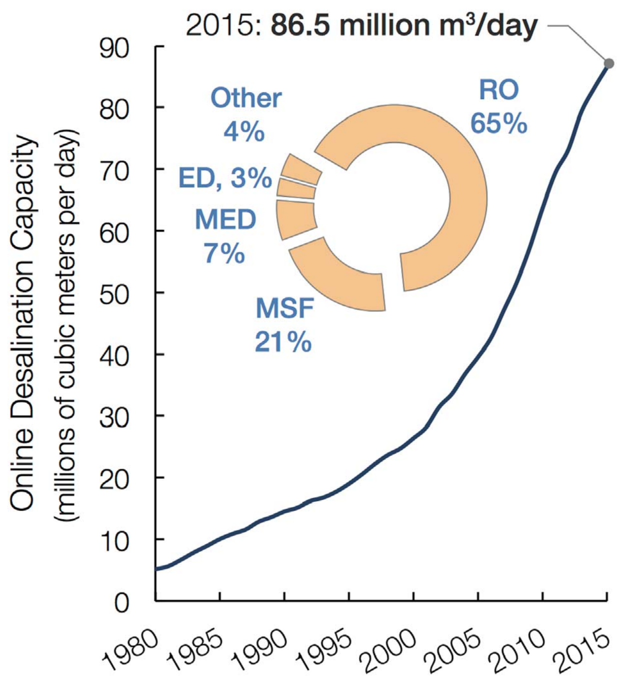

Fig. 1. Worldwide collective desalination unit capacity for the period 1980–2015 [9].

MED are 20–27 kWh m^{-3} and 14–21 kWh m^{-3} respectively, compared to 4–6 kWh m^{-3} for seawater RO(SWRO), and 1.5–2.5 kWh m^{-3} for brackish water RO (BWRO). Conventionally, fossil fuels are used to provide the energy required to operate the different desalination techniques. In addition to the high associated expense, burning fossil fuels produces significant amounts of gasses that have severe environmental impact. It is expected that by 2050 the worldwide emissions from fossil fuel driven desalination units will reach an annual rate of 400 million tons of carbon equivalents [14]– [15]. Therefore, it becomes imperative to find alternative clean sources of energy for desalination.

It is possible to generate clean energy from renewable sources such as sunlight, geothermal heat, hydroelectric energy, wind, among others using various energy conversion devices and systems [16]– [17]. Renewable energy is relatively inexpensive, ubiquitous, and presents no negative environmental impact compared to traditional fossil fuels [18]. The use of renewable energy for desalination has increased from 2% in 1998 to 23% in 2016 [19]– [20].

While the use of renewable energy to power desalination plants preserves environmental integrity and increases sustainability, it also has the potential to lower the eventual cost to the end-user – which is crucial for inhabitants of underprivileged societies [21]. Table 2 shows the current status of renewable energy use in different desalination technologies and the required energy levels for each technology.

At present, only 131 desalination plants worldwide (representing about 1% of current global water desalination capacity) are powered using energy from renewable sources [15], [22]. About 43% of these plants are powered using solar photovoltaic (PV), 27% are powered using solar thermal, and 20% are powered using wind energy; while the remaining 10% are based on hybrid renewable energy sources [22,23]. The chart in Fig. 2 presents a classification of the presently operating renewable energy powered desalination techniques [15].

Countries across the world are investing heavily into desalination plants driven by renewable energy sources. For example, the Kingdom of Saudi Arabia (KSA), a leading country in the use of renewable energy to power desalination units, is currently installing a PV-RO plant in Al-Khafji with capacity of 60,000 m^3 d^{-1} [15]. Australia, on the other hand, has a wind-RO plant utilizing 48 wind turbines with maximum output power of 80 MW to drive a 26 MW RO plant [24].

This topic has also garnered interest from leading researchers in the field of desalination and water resources. Sharon et al. summarized the progress in the application of solar energy to drive new water desalination technologies such as forward osmosis (FO), natural vacuum desalination, and freezing and adsorption desalination [25]. Shahzad et al. reported the connection between energy and water, as well as how water desalination affects the environment [15]. The application of solar energy in different water desalination techniques has been reported in [22], [26]. Ghaffour et al. reported the potential for using available renewable energy sources such as solar, wind and geothermal energies in the different conventional and novel water desalination technologies [12], [27].

The importance of this topic and its effect on billions of people around the world has motivated us to undertake this review of the different options for using renewable energy in the water desalination process. In this paper, we present an extensive review of the published literature on various desalination technologies using solar energy, geothermal energy, wind energy, and ocean energy (wave and ocean thermal, tidal and salinity gradient). The paper also discusses the use of new technologies for desalination such as nanofluids, plasmonic nanoparticles and plasmonic membranes. In addition, the paper also discusses the application of salinity gradient energy (SGE) in water desalination plants for simultaneous energy production and brine reclaim.

2. Water desalination units powered by renewable energy

The high cost of conventional desalination plants coupled with greenhouse gasses emitted by the associated power generation process have necessitated identifying alternative cheap and environmentally friendly sources of energy. However, it is difficult to determine the most efficient form of renewable energy that can maximize the output permeate while consuming the minimum amount of energy. This is mainly due to the hugely varied desalination techniques and renewable energy sources. Many parameters affect the choice of renewable energy source, such as desalination plant size, location, feed pressure, characteristics of feed water, and expected water product cost. Fig. 3 shows the possible matching between available renewable energy sources and water desalination techniques based on the type of energy required. Low intensity and intermittence of several renewable energy sources

Table 1
Energy consumption in the common water desalination techniques [11].

Properties	MSF	MED	MVC	TVC	SWRO	BWRO	ED
Typical unit size (m^3/day)	50,000–70,000	5000–15,000	100–3000	10,000–30,000	Up to 128,000	Up to 98,000	2–145,000
Electrical energy consumption (kW h/m^3)	2.5–5	2–2.5	7–12	1.8–1.6	4–6 with energy recovery	1.5–2.5	2.64–5.5
Thermal energy consumption (MJ/m^3)	190–282	145–230	None	227	None	None	None
Equivalent electrical to thermal energy (kW h/m^3)	15.83–23.5	12.2–19.1	None	14.5	None	None	None
Total electricity consumption (kW h/m^3)	19.58–27.25	14.45–21.35	7–12	16.26	4–6	1.5–2.5	2.64–5.5, 0.7–2.5 at low TDS
Product water quality (ppm)	≈ 10	≈ 10	≈ 10	≈ 10	400–500	200–500	150–500