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A review of the water desalination systems integrated with renewable energy

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Abstract

Water and energy are indispensable entities for any flourishing life and civilization. The water and energy scarcities have emerged due to the dramatic growth in the population, standards of living, and the rapid development of the agricultural and industrial sectors. Desalination seems to be one of the most promising solutions to the water problem; however, it is an intensive energy process. The integration of the renewable energy into water desalination systems has become increasingly attractive due to the growing demand for the water and energy, and the reduction of the contributions to the carbon footprint. The intensive investigations on the conventional desalination systems, especially in the oil-rich countries have somewhat overshadowed the progress and implementation of the renewable energy desalination (RED) systems. The economic performance evaluation of the RED systems and its comparison with conventional systems is not conclusive due to many varying factors related to the level of technology, the source of energy availability, and the government subsidy. The small RED plants have a high capital cost, low efficiency and productivity which make RED systems uncompetitive with the conventional ones. However, the selection of the small RED plants for the remote arid areas with small water demands is viable due to the elimination of the high cost of the water transportation, and the connection to the electricity grid. The purpose of this paper is to review the technology, energy, and cost of the recent available desalination systems and their potential to be integrated with the renewable energy resources. This review suggests that the solar still distillation (SD) system, which is simply a natural evaporation-condensation process, is the most practical renewable desalination technique to be used in the remote arid areas; however, a further research is required to enhance their performance and to increase the productivities of these systems.

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1. Introduction

In spite of the fact that water covers about 71 percent of the Earth's surface area, however, it is a challenge to meet all humans, animals and plants demand to freshwater. Freshwater is about 2.5% of total water quantity, most of it is as glaciers, ice caps, and groundwater, only 0.008% represents the accessible surface freshwater [1]. Population growth and industrialization have worsened the problem of water shortage. One-third of the world residents currently undergo severe water stress and the percentage is expected to increase [2]. Water scarcity occurs when water supply falls below 1000 cubic meters per person per year [3]. One of the most promising solution to overcome the water shortcoming is desalination. Desalination is defined as, the process of removing dissolved salts and minerals from saline water to produce potable water. Saline water can be classified depending on the Total Dissolved Solids (TDS) for brackish water TDS is up to 10,000 ppm, and for seawater TDS is up to 45,000 ppm [4]. While the permissible limit of salinity in potable water is in the range of (500 to 1000 ppm) [5]. However, desalination is an extensive energy process in which to produce 1000 cubic meters of water per day it requires about 10000 tons of fossil fuel per year [6]. Replacing the depleted fossil fuel by renewable and sustainable energy resources becomes a crucial need to decrease the carbon footprint and greenhouse gases emission which they are the main reasons of global warming and climate change. The purpose of this paper is to review the technology, energy, and cost of the recent available desalination systems and their potential to be integrated with the renewable energy. This review hopes to help decision makers to compare the available options and researchers to select the appropriate desalination process for further investigations and developments.

2. Desalination systems

Desalination systems can be classified according to the energy source such as; thermal, mechanical, electrical and chemical energy sources. Another classification depends on the desalination process: evaporation-condensation, filtration, and crystallisation technique. Some of the desalination technologies are still under development such as; solar chimney, greenhouse, natural vacuum, adsorption desalination, membrane distillation (MD), membrane bio-reactor (MBR), forward osmosis (FO), and ion exchange resin (IXR). The reverse osmosis (RO) followed by multi-stage flashing (MSF) and multi-effects distillation (MED) systems are the most worldwide implemented desalination technologies. Figure 1(a) illustrates the main desalination techniques around the world. According to the International Desalination Association (IDA) 2015, more than 300 million persons depend on water produced by 18426 desalination plants in 150 countries, which are providing more than 86.8 million cubic meters per day [7]. The western and developed countries prefer RO systems due to its efficient power consumption, while the Middle East and Gulf countries prefer MSF and MED systems due to the abundant source of available oil. The largest desalination plant which started to operate at the end of 2014 is Ras Al-Khair in Saudi Arabia. This plant produces about 728,000 cubic meters of desalinated water per day by implementing both the MSF and RO technologies [8]. The second largest desalination plant is Carlsbad in California, USA which produces about 190,000 cubic meters of desalinated water per day by implementing RO technology, opened in December 2015 [9]. The simplest desalination technology is the solar still distillation (SD) system, which is suitable to the remote areas with a small water demand due to the low productivity of these systems. Figure 1(b) presents the recent global contribution of each desalination technology [10, 11]. Table 1 shows the advantages and disadvantages of some well-known commercial desalination technologies [12].

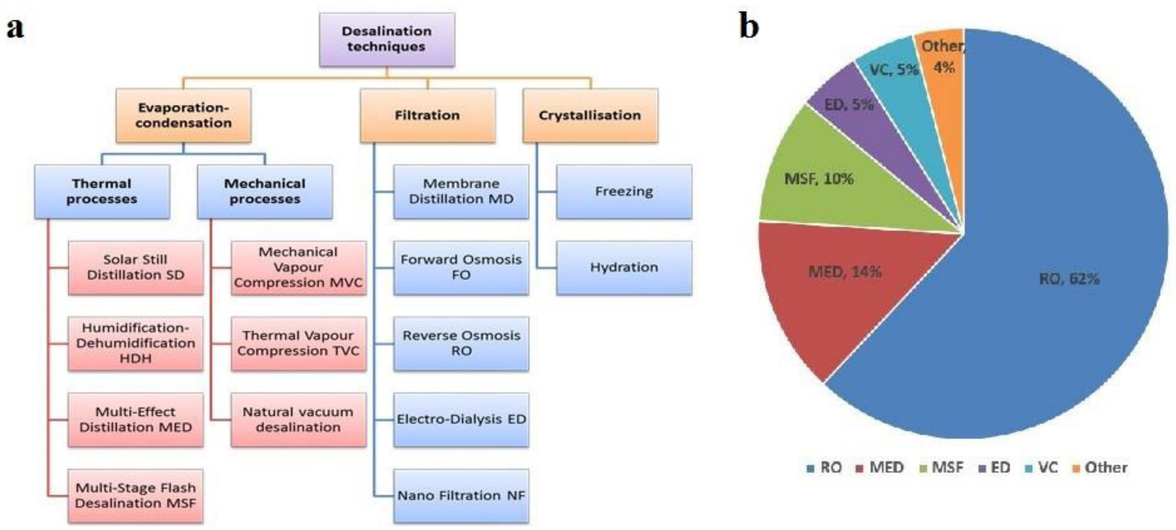

Fig. 1. (a) the main desalination processes; (b) the contribution of each desalination process to the world water production.

Table 1. Advantages and disadvantages of the main desalination processes.

	Advantages	Disadvantages
SD	Low investment cost.	Low productivity per unit area.
	Low maintenance.	
	Low energy requirement.	
	Environmentally friendly.	
MSF	Easy to manage and operate.	Cannot operate at below 60% capacity.
	Can treat very salty water up to 70,000 mg/l.	Not suitable to combine with renewable energies that have intermittent energy supplies.
		High energy use (3–5 kWh/m^3 electricity and 233 MJ/m^3–258 MJ/m^3 heat required).
MED	Can be operated between 0% and 100% capacity while MED unit is kept under vacuum and cold circulation.	Anti-scalents required to stop scale build-up on evaporating surfaces.
	Suitable to combine with RE sources that supply intermittent energy.	
	Suitable to link with RE.	
RO	Easily adapts to local conditions.	Requires comprehensive pre-treatments to be used for high saline water.
	Plant size can be adjusted to meet short-term increases in demand and expanded incrementally as needed.	Membrane fouling.
	Significant cost advantage in treating brackish groundwater.	Complex configuration.
	Can remove silica.	Requires skilled personnel for operation and maintenance.
	Capital cost approximately 25% less than thermal options.	
ED	High recovery rate of up to 94%.	Capital intensive and costly compared to RO.
	Longer-life membranes (up to 15 years when operated properly).	
	Can be combined with RO for higher water recovery of up to 98%.	

3. Energy requirements for the desalination process

It is important to know the amount of the conventional energy required by the desalination processes to understand why we need to move toward the renewable and sustainable energy resources. The contribution of the conventional desalination systems to the global warming phenomenon can be assessed by estimating the amount of the fossil fuel needed to be burned to produce a certain amount of fresh water. In the average, producing 1000 cubic meters of fresh water by desalination technology consumes about 5 tons of crude oil which produces about 10 tons of carbon dioxide or about 5000 cubic meters of greenhouse gases [13, 14]. The total global desalination capacity has witnessed a severe increase within the last few years, from 66.48 million cubic meters per day in 2011 to 86.6 million cubic meters per day in 2015 [7, 15]. Therefore, serious forward steps toward integrating the desalination systems with the renewable and sustainable energy technologies will be required to mitigate the negative effects of the desalination systems. Table 2 shows the energy requirement of the main desalination technologies [14, 16].

Table 2. Energy requirements of the main desalination techniques.

	MSF	MED-TVC	MED	MVC	RO	ED
Typical unit size (m^3 d^{-1})	50,000 - 70,000	10,000 - 35,000	5,000 - 15,000	100 - 2500	24,000	- 145,000
Electrical Energy Consumption (kWh m^{-3})	4 – 6	1.5 – 2.5	1.5 – 2.5	7 - 12	3 – 7	2.6 – 5.5
Thermal Energy Consumption (kJ kg^{-1})	190 – 390	145– 390	230– 390	None	None	None
Electrical Equivalent for Thermal Energy (kWh m^{-3})	9.5 – 19.5	9.5 – 25.5	5 – 8.5	None	None	None
Total Equivalent Energy Consumption (kWh m^{-3})	13.5 - 25.5	11 – 28	6.5 - 11	7 - 12	3 - 7	2.6 – 5.5

4. Renewable energy desalination

The renewable energy desalination (RED) systems are witnessing an increasing interest worldwide; more than 130 RED plants have opened within the last few years [17]. Table 3 shows selected RED plants in different countries [18]. Solar, wind, geothermal, wave and tidal energy are the main sources of renewable energy besides the hydropower and biomass energy. Hydropower and biomass energy are not suitable to couple with the desalination technology because they require water resources which may not be available in the water scarce countries. Solar energy is the most applicable source of renewable energy to be integrated with the desalination technology because it can produce the heat and electricity required by all desalination processes. Photovoltaic (PV), linear Fresnel, parabolic trough, and central receiver are the main solar harvesting technologies. Central receiver or concentrating solar power (CSP) is the most promising solar technology. CSP can produce high temperature about (500-1000 ºC) which is used to produce steam to run gas or steam turbine [19]. Currently, about 70% of renewable desalination plants run by solar energy [20]. However, collecting solar energy requires large land areas which may be used for other purposes .Wind energy is more suitable to the coastal areas where the wind and water are available. Wind energy is mostly combined with RO and ED desalination systems because they require electricity rather than heat [21]. Geothermal energy utilizes the high temperature of the earth's underground to produce steam or to store the heat energy. This source of energy requires underground drilling up to 5000 meters; however, the underground temperature should be greater than 180 ºC to be economical for the excavation works [22]. Wave and tidal energy are also suitable to the coastal areas. The world's first commercial-scale wave energy was lastly installed in Perth, Australia, connected to the electricity grid and used for desalination plant [23]. Figure 2(a) demonstrates the contribution of each renewable energy source to the desalination technology globally [20]. There are two configurations of coupling desalination plant with renewable energy either by direct connection or by adding the produced power to the electricity grid to overcome the intermittency of the renewable energy [24]. Figure 2(b) shows the main renewable energy resources and their potential coupling to the desalination plants. Table 4 shows the annual renewable energy potential for selected countries [19, 25].

Table 3. Selected RED plants.

Desalination plant name	Location	Desalination technology	Capacity (m^3/d)	Renewable energy source
Kimolos	Greece	MED	200	Geothermal
Keio University	Japan	MED	100	Solar collectors
PSA	Spain	MED	72	Concentrating solar power (CSP)
Ydriada	Greece	RO	80	Wind turbine
Morocco	Morocco	RO	12-24	Photovoltaics (PV)
Oyster	Scotland	RO	n.a.	Wave energy

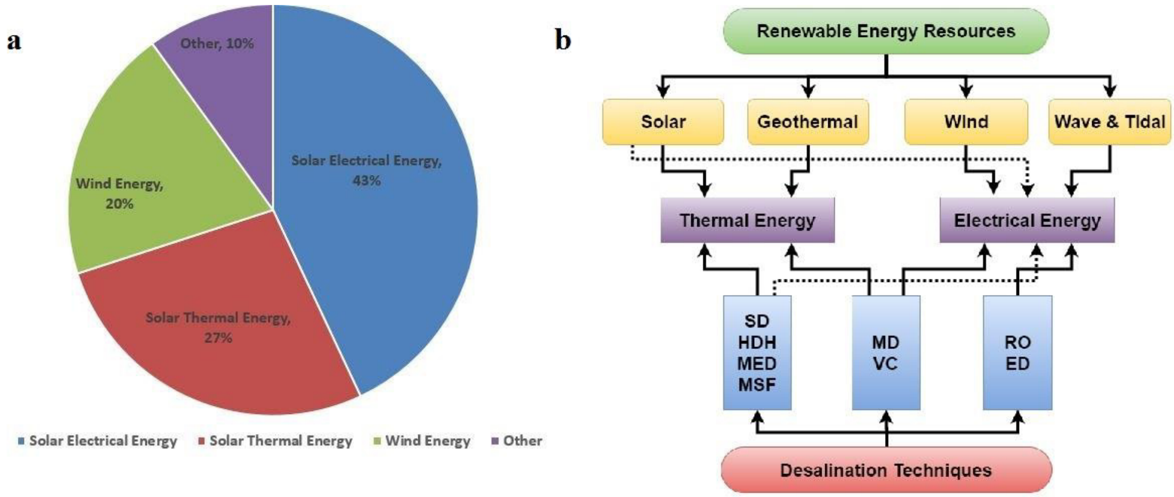

Fig. 2. (a) the percentage of the renewable energy source to the RED systems worldwide; (b) the integration of the desalination processes with the renewable energy sources.

Table 4. Potential renewable energy (TWh per year) of selected countries.

Country	CSP	PV	Wind	Geothermal
Egypt	57.14	54	125	25.7
Iran	32.13	54	120	11.3
Iraq	24.66	34.6	20	0

5. Desalination cost

Over the last thirty years, systematic research and development have reduced the cost of the desalination technology by lowering the energy consumption and enhancing the design. Table 5 shows the approximate cost of the main desalination technologies [26]. The capital investment and energy cost are the main two factors affecting the cost of the desalination technology, while other factors such as operation and maintenance cost are nearly at a fixed rate [27]. Water source salinity, energy source availability, the plant size, land cost, and the government subsidy are some other factors affecting desalination cost. Figure 3 shows the total annual cost percentage of each component to the main desalination techniques [25, 28]. Currently, the use of renewable energy sources in desalination systems are inefficient compared to the use of fossil fuel due to the high cost of harvesting these renewable resources and their requirements to a high level of technology and infrastructure. However, a further development and research may succeed in reducing the renewable energy cost in the near future. The approximate renewable energy cost is about (0.1-0.2 USD/kWh) but this price is expected to be about (0.05 USD/kWh) within the next 20 years which may be equivalent to the conventional energy cost [29, 30]. Table 6 shows the recent typical cost to the renewable energy desalination systems [31].

Table 5. Typical costs of the conventional seawater desalination (USD/m^3.day).

	MSF	MED	RO
Capital investment costs	1,700–2,900	1,700–2,700	1,300–2,500
Operational costs	0.65–1.25	0.67–0.96	0.58–0.88
Total annualized cost	0.84-1.6	1.21-1.59	1.06–1.36

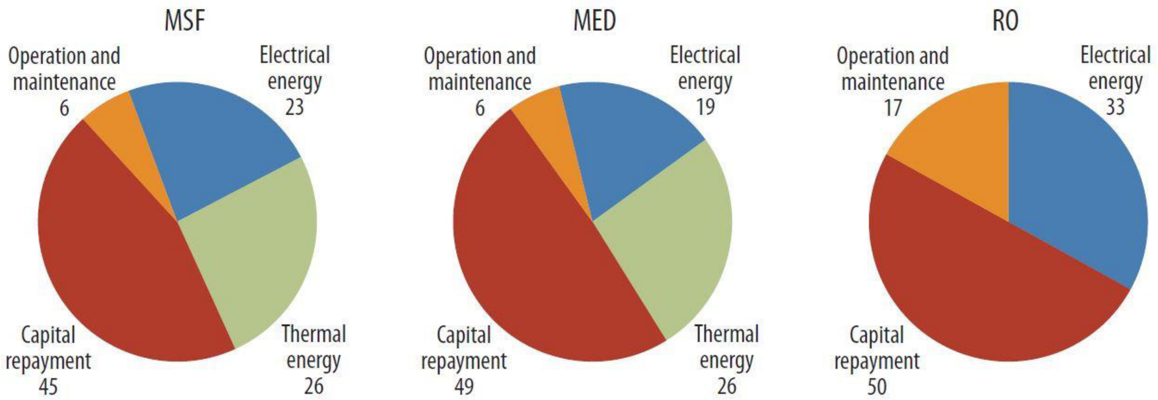

Fig. 3. total annual cost percentage to the main desalination technologies.

Table 6. Typical cost of the renewable energy desalination systems.

	Solar thermal energy			Solar electrical energy			Wind energy	
Desalination technique	MED	HDH	SD	ED	RO	MVC	RO	RO
Capacity (m^3/d)	>5000	>100	>1	>100	>100	>100	>50	>1000
Cost (USD/m^3)	2.5-3	2.8-7	1.4-12	11.2-12.6	12.5-16.8	5.6-8.4	7-9.8	2.1-5.6

6. Conclusion

Desalination integrated renewable energy systems offer a win-win solution to the energy and water problems. Renewable energy desalination (RED) technology provides sustainability and reduces the carbon footprint. Among different resources of renewable energy solar energy is the most promising alternative to the fossil fuel because it is more predictable and available than other resources. Currently, the cost of producing fresh water by RED systems is higher than that by the conventional desalination systems. However, increasing the efficiency and the water productivity of the RED systems requires further research and development to make them economically competitive with conventional desalination systems. Solar still distillation (SD) system is the most applicable technique to the remote and rural areas suffering from water and energy stresses. The only problem with the SD systems is the low productivity which makes it a costly choice. Therefore, a further research is required to enhance the performance and to increase the productivity of the SD systems. However, a small scale of water demands to a small Island, village or household level makes SD a viable option due to the high cost of the water transportation and connection to the electricity grids for the remote zones.

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