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Desalination technology; economy and simplicity

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Abstract

Water scarcity is a major problem, a seawater desalination process separates saline seawater into two streams: a fresh water stream containing a low concentration of dissolved salts and a concentrated brine stream Applied desalination technologies can be divided in to three groups, thermal desalination technologies, membrane based desalination technologies,and solar desalination technologies. Results show that solar energy coupled to desalination offers a promising prospect for covering the fundamental needs of power and water in remote regions such as grid-limited villages or isolated islands that have access to sea or brackish-water. Reverse osmosis (RO) and electrodialysis (ED) desalination units are the most favorable alternatives to be coupled with photovoltaic (PV) systems.

Keywords: Seawater desalination technologies; Multi-stage flash distillation desalination; Multiple-effect distillation desalination; Vapor compression distillation desalination; Reverse osmosis desalination; Solar evaporation desalination; electrodialysis

Introduction

Desalination technologies can be classified by their separation mechanism into thermal, membrane and solar based desalination. Thermal desalination separates salt from water by evaporation and condensation, whereas in membrane desalination water diffuses through a membrane, while salts are almost completely retained. Solar desalination can either be direct; use solar energy to produce distillate directly in the solar collector, or indirect; combining conventional desalination techniques, such as multistage flash desalination(MSF), vapor compression (VC), reverse osmosis (RO), membrane distillation (MD) and electrodialysis, with solar collectors for heat generation. Direct solar desalination compared with the indirect technologies requires large land areas and has a relatively low productivity. It is however competitive to the indirect desalination plants in small-scale production due to its relatively low cost and simplicity.

Applied desalination technologies can be divided in to three groups

1- Thermal desalination technologies

Multi-effect distillation (MED)
Multi-stage flash distillation (MSF)
Vapour compression distillation (VCD)

2- Membrane based desalination technologies

Reverse osmosis (RO)
Nanofiltration (NF)
Electrodialysis (ED)

3- Solar desalination technologies

Regenerative
Conventional
Double-glass-cover cooling

Thermal desalination technology was preferred in the Middle East, reverse osmosis and multi-stage flash are the techniques that are most widely used in commercials due to the amount and the cost of the product, Reverse osmosis (RO) is suitable for these applications but it requires a continuous supply of electrical or mechanical energy. Many developing countries which suffer from water scarcity also lack in resources which can generate these sources of energy (fossil fuels Energy consumption of reverse osmosis is the lowest among all options for seawater desalination, making it most cost efficient in regions with high energy cost [1]. Especially in brackish water desalination, reverse osmosis offers great advantages over thermal desalination technologies due to its much lower energy consumption at low salt concentration [2]. The variable cost of thermal desalination plants is almost independent of feed water salinity, while membrane process variable cost is nearly proportional to the feed water salinity and therefore lowers in brackish water than in seawater desalination, making reverse osmosis and electrodialysis the most economic processes [2]. However, some of these countries have an abundance of solar energy. Solar photovoltaics (PV) can be used to operate reverse osmosis units for small scale applications in these countries. But it may not be feasible due to the high cost of PV modules and maintenance of RO systems [3]. A much simpler option is to use the solar energy as a source of thermal energy. This requires us to develop desalination technologies which can use this energy in an efficient way.

	PV-RO system		RO-Solar Rankine system	
Energy system cost (€/m^3)	2.44	31%	8.29	66%
Desalination system cost (€/m^3)	5.32	69%	4.21	34%
Total (€/m^3)	7.77	100%	12.53	100%

Table 1 total and partial cost of the examined desalination systems(€/m^3)

Photovoltaic (PV) is a rapidly developing technology with declining costs table (1). And the study of coupling this technology with desalination methods has increased significantly in the last few decades. Moreover, the use of this technology is an excellent choice for providing desalinated water for small communities in remote arid areas and isolated islands that have access to sea or brackish-water. The reason includes the economic benefits and the solar system's modularity, low maintenance, low noise level, long life, and non-emission of greenhouse gases [4]. Typical desalination methods that require electricity and could be well-suited to this technology are reverse osmosis (RO) and electrodialysis(ED) figure (1). The coupling of these methods with solar PV systems holds great promise for increasing water supplies in water-scarce regions [5].

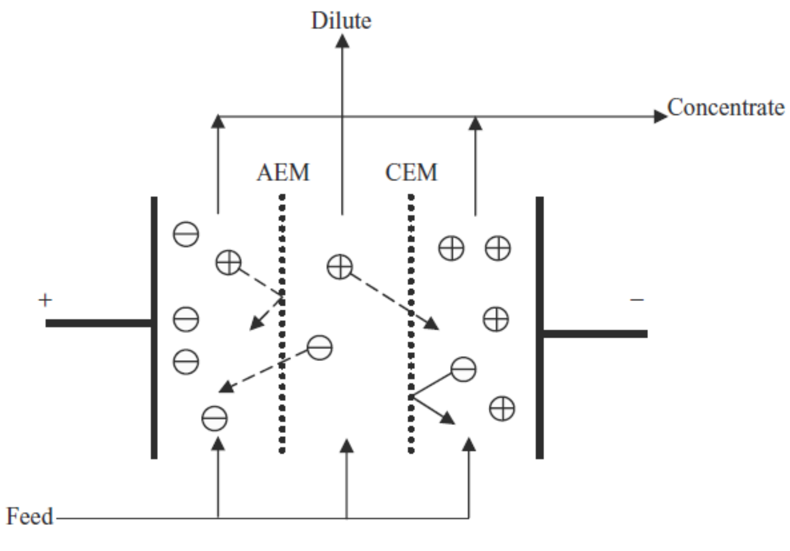

Fig. 1. Schematic view of an ED cell.

1.1. PV-RO system

RO technology description Reverse osmosis is a form of filtration in which the filter is a semi-permeable membrane that allows water, but not salt, to pass through. A typical RO system consists of four major subsystems pretreatment system, high-pressure pump, membrane module, and post-treatmentsystem [6]. Fig. (2) Is a schematic diagram of PV-RO system.

The RO membrane is semi-permeable, possessing a high degree of water permeability, but presents an impenetrable barrier to salts. It has a large surface area for maximum flow and is extremely thin so that it offers minimal resistance to water flow; but it is also sturdy enough to withstand the pressure of the feed stream [7] Polymers currently used for manufacturing RO membranes are based on either cellulose acetates (cellulose diacetate, cellulose triacetate, or combinations of the two) or polyamide polymers. Two types of RO membranes commonly used commercially are spiral wound (SW) membranes and hollow-fiber (HF) membranes. Other configurations, including tubular and plate-frame designs, are sometimes used in the food and dairy industries. SW membrane elements are most commonly manufactured from a cellulose osmotic pressure is applied on salt water (feed water) passing through the synthetic membrane pores separated from the salt. A concentrated salt solution is retained for disposal. The RO process is effective for removing total dissolved solid (TDS) concentrations of up to 50,000 parts per million (ppm), which can be applied for both brackish-water (1500–10,000 ppm) and seawater (33,000– 45,000 ppm). It is currently the most widely used process for seawater desalination. Feed water pretreatment is a critical factor in operating an RO system because membranes are sensitive to fouling. Pretreatment commonly includes sterilizing feed water, filtering, and adding chemicals to prevent scaling and bio-fouling. Using a high-pressure pump, the pretreated feed water is forced to flow across the membrane surface. RO operating pressure ranges from 17 to 27 bars for brackish-water and from 55 to 82 bars for seawater.

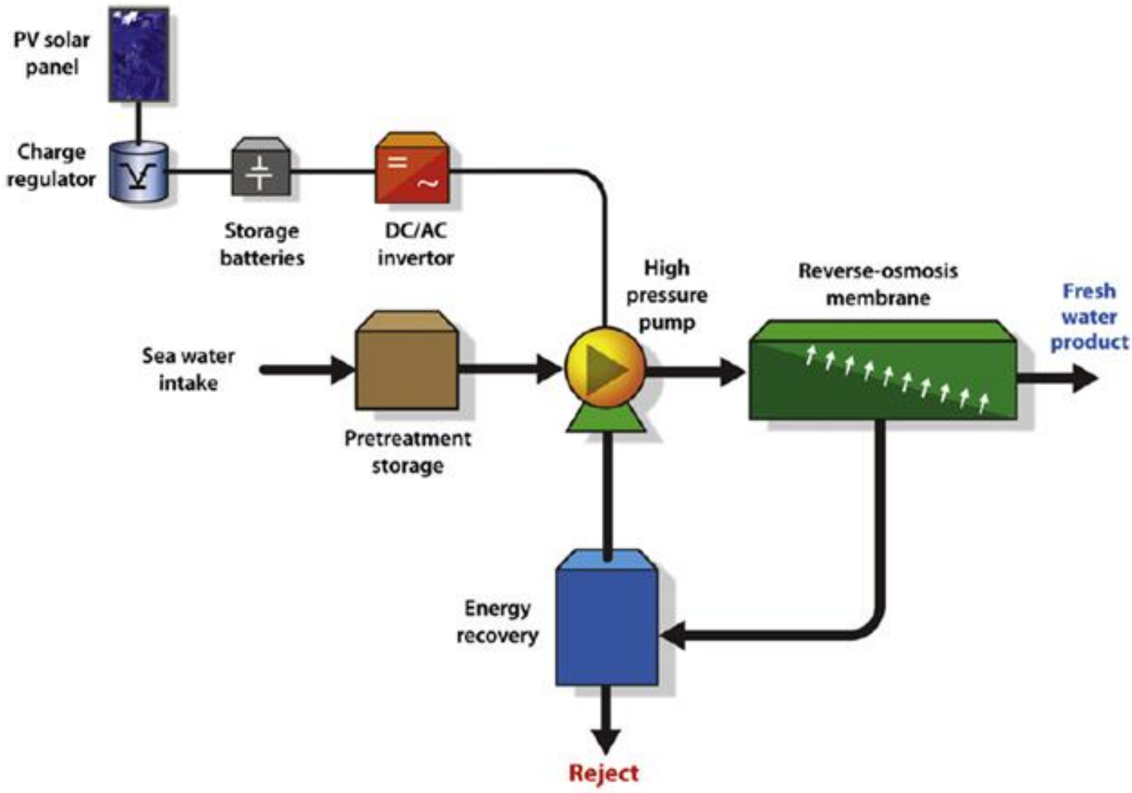

Fig. 2. A schematic diagram of a PV-RO system.

1.2. PV-RO systems applications

PV- reverse osmosis is considered one of the most promising forms of renewable-energy-powered desalination, especially when it is used in remote areas. Therefore, small scale RO has received much attention in recent years and numerous demonstration systems have been built. Two types of PV-RO systems are available in the market: brackish water reverse osmosis (BWRO) and seawater reverse osmosis (SWRO) PV-RO systems. Different membranes are used for brackish-water and much higher recovery ratios are possible, which makes energy recovery less critical [8].

1.3. PV-ED systems applications

In Japan, where PV technology is used to drive an ED plant fed with seawater, instead of the usual brackish-water of an ED system. The solar field consists of 390 PV panels with a peak power of 25 kWp, which can drive a 10 m³/d ED unit.

Run	Controllable factors			
	C (ppm)	*T* (°C)	*V* (V)	*F* (mL/s)
1	10,000	25	5	0.07
2	10,000	40	7	0.13
3	10,000	55	9	0.22
4	20,000	25	7	0.22
5	20,000	40	9	0.07
6	20,000	55	5	0.13
7	40,000	25	9	0.13
8	40,000	40	5	0.22
9	40,000	55	7	0.07

Table 2 controllable factors and their levels

The product-water quality is reported to be below 400 ppm TDS, and the ED stack is provided with 250 cell pairs. Figs. (3-5) show the effects of flow rate on separation percent at different voltages, temperatures and feed concentrations are illustrated.

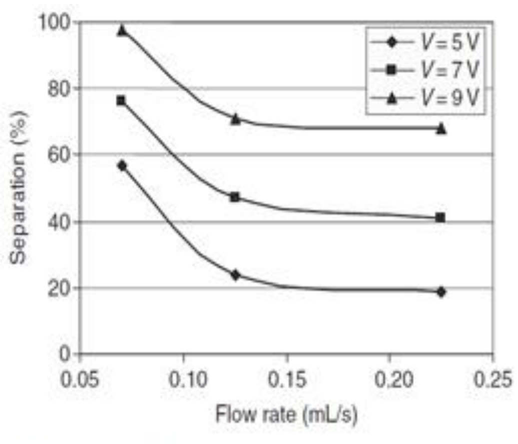

Fig.3 . Effect of flow rate on separation percent at different voltages.

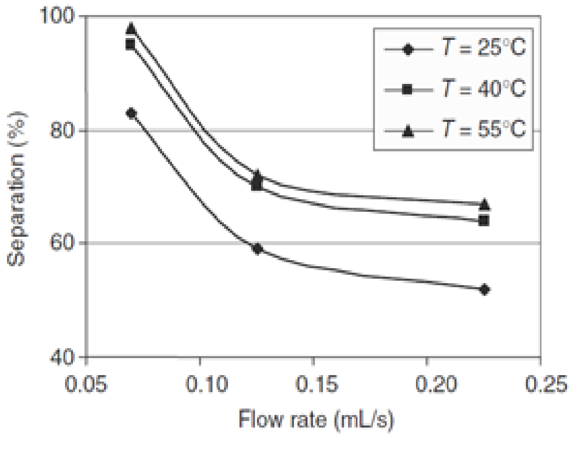

Fig. 4. Effect of flow rate on separation percent at different temperatures.

In the case of higher temperatures and voltages, electrical resistance of the feed solution decreases and subsequently ED separation performance increases. At higher feed concentrations, in spite of the fact that solution conductivity increases, separation percent decreases due to concentration polarization phenomenon at high concentrations and limited ion exchange capacity of the membranes.

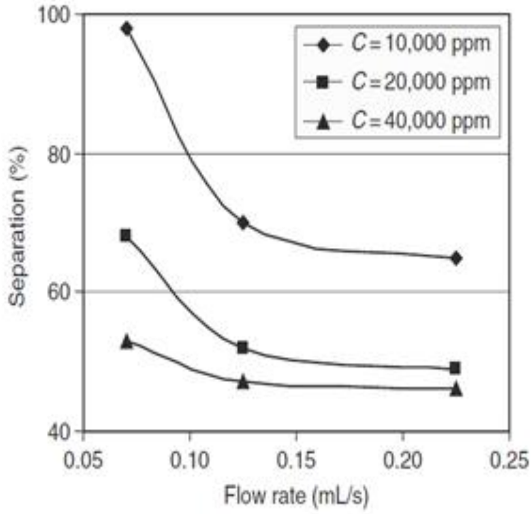

Fig. 5. Effect of flow rate on separation percent at different feed concentrations.

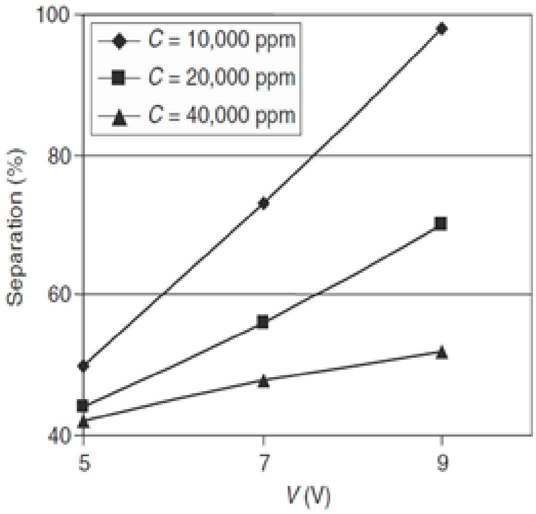

Fig. 6. Effect of voltage on separation percent at different feed concentrations.

Hence, it was approved that ED is more efficient at lower concentrations and can be applied as a post-treatment process for desalination of wastewater or seawater.

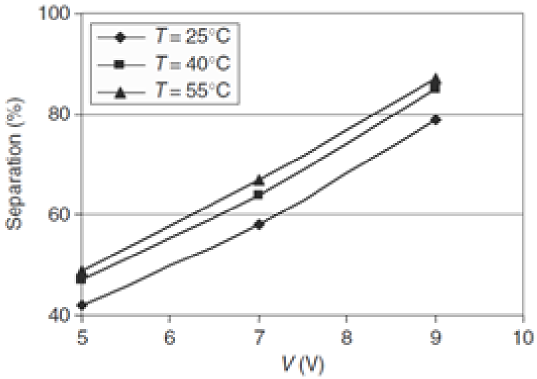

Fig. 7. Effect of voltage on separation percent at different temperatures.

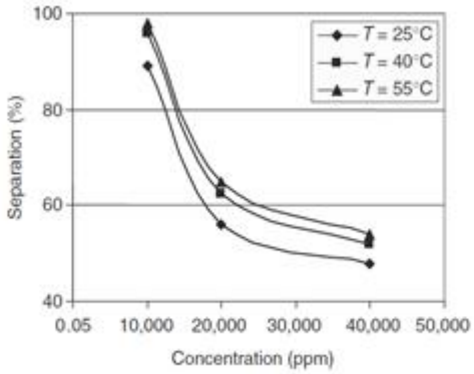

Fig. 8 . Effect of feed concentration on separation percent at different temperatures.

At higher flow rates, separation percent values fall and separation performance decreases. Because a greater flow rate means a lower residence time, ions that are between the membranes do not have enough time to transfer through the membranes. In terms of maximizing the separation percent, *T*high (55°C), *C*low (10,000 ppm), *F*low(0.07 mL/s)and *V*high(9V) table(2) were chosen. Effect of voltage on separation percent at different feed concentrations and temperatures are depicted in Figs. (6-7). as can be seen, simultaneous increase in voltage and temperature as well as decrease in feed concentration optimize the separation percent. Fig. (8) Shows the effect of feed concentration on separation percent at different temperatures. According to this figure, the same results as above were obtained.

2. Raw water characterization

The proper choice of a desalination technology will depend on the feed water quality, which is mainly characterized by its total dissolved solids content (TDS value) [9]. Different feed water qualities and their corresponding salt content are given in Table (3).

	Minimum salinity TDS [ppm]	Maximum salinity TDS [ppm]
Seawater	15,000	50,000
Brackish water	1,500	15,000
River water	500	1,500
Pure water	0	500

Table 3 feed water characterization by salt content

As an example of a typical seawater composition, Table (4) exemplarily shows characteristic parameters of Mediterranean seawater [10] for Cyprus and the Canary Islands. Feed water composition varies depending on local industries' discharges, water depth, water temperature, ocean currents, algae growth and many more parameters.

Analysis	Dekhelia, Cyprus [mg/L]	Canary Islands [mg/L]
Ca_2^+	450.0	962
Mg_2^+	1,452.4	1,021
Na_2^+	12,480.0	11,781
K^+	450.0	514
NH_4^+	0.0	0.004
HCO_3^-	160.0	195
CO_3^{2-}	0.2	0
SO_4^{2-}	3,406.0	3,162
Cl^-	22,099.0	21,312
F^-	0.0	1.5
NO_3^-	0.0	2.6
PO_4^-	n/a	0.08
NO_2^-	n/a	0.03
Total hardness in $CaCO_3$	n/a	6,600
Total salinity (TDS)	40,498.2	38,951
$Fe^{+2/+3}$	n/a	0.04
Al^{3+}	n/a	0.001
pH	8.1	6.33
Conductivity, µS	n/a	46,200

Table 4 water characterization of feed waterFrom the Mediterranean Sea

2.1. Foulants
Rejected constituents by the RO membrane pose a general fouling risk to plant operation. Foulants can be classified into four categories [11]

- Chemical foulants, which cause scaling

Dissolved inorganics most likely to cause scaling are Ca^{2+}, Mg^{2+}, CO_3^{2-} SO_4^{2-}, silica and iron [12]. If solubility limits are exceeded, $CaCO_3$, sulphates of calcium, strontium and barium, $CaF_2$and various silica compounds are the most likely compounds found as scaling on the membrane surface. Hydroxides of Al, Fe and Mn are normally precipitated before contact with the membrane. Most natural surface and ground waters display high $CaCO_3$concentrations close to saturation.

- Physical foulants or particulate matter, which is related to deposition of particles on the membrane surface Particulate matter in natural waters, can be classified according to Potts et. al. [10] into four different categories depending on particle size:
- Settable solids > 100 µm
- Supra-colloidal solids 1–100 µm
- Colloidal solids 0.001–1 µm
- Dissolved solids <10 A°

Particles larger than >25 µm can be easily removed by various treatment options such as screens, cartridge filters, dual-media filters etc.

- Biological foulants, which can either deteriorate the membrane or form a biofilm layer, which inhibits flux across the membrane.

Raw waters contain microorganisms such as bacteria, fungi, algae, viruses and higher organisms such as protozoa, living or dead, or biotic debris such as bacterial cell wall fragments. At the large membrane surface dissolved organic nutrients of the water are concentrated due to concentration polarization. Microorganisms entering a RO system therefore find ideal growth conditions resulting in possible formation of a biofilm [13].Biofilm formation consists of three stages [14]:

- Transport to the membrane surface
- Attachment to the surface and
- Biofilm growth

- Organic foulants, which can interact with the membrane.

Degradation of organic matter such as plants produces a matrix of macromolecules called humic acids. Organics in natural waters are usually humic substances in concentrations between0.5 and 20 mg/L in BWandupto 100 mg/L in surface seawater TOC [15]. In RO operation it is recommended that humicacids are removed prior to filter pre-treatment by flocculation, coagulation with hydroxide flocks, ultrafiltration or adsorption on activated carbon. Other organic foulants in natural waters are oil and grease droplets. A thin fouling layer was observed by SEMFEG imaging with filamentous organic layer on which some random microorganisms can be seen as well as some crystals of mineral origin Fig.(9).

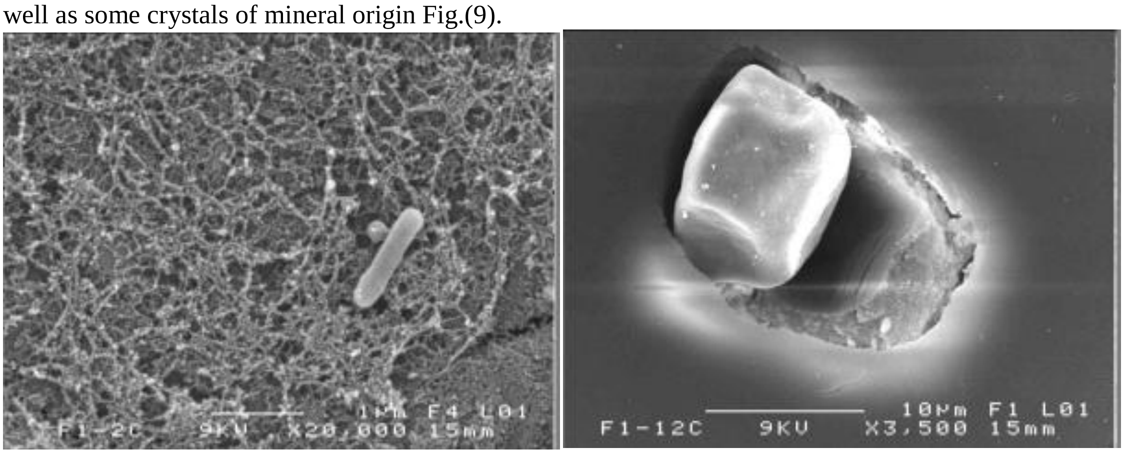

Fig. 9. Fouling layer on the membranes of the autopsied module showing (a) organic filamentous deposit and microorganism and (b) inorganic crystal as imaged by SEM-FEG, magnification 20,000 and 3,500 respectively.

Conclusion

Solar desalination processes can be devised in two main types: direct and indirect collection systems. The “direct method” use solar energy to produce distillate directly in the solar collector, whereas in indirect collection systems, two sub-systems are employed (one for solar energy collection and the other one for desalination).The direct solar energy method uses a variety of simple stills which are appropriate for very small water demands; indirect methods use thermal or electrical energy and can be classified as: distillation methods using solar collectors or membrane methods using solar collectors and/or photovoltaics for power generation.

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