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Sustainability assessment of electrodialysis powered by photovoltaic solar energy for freshwater production

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ABSTRACT

Membrane desalination does help at procuring an increasing freshwater (FW) global demand. Energy requirements of desalination technologies compromise the environmental sustainability of desalination. The integration of renewable energies with desalination technologies might improve the sustainability of desalinated water over other alternative FW sources.

This paper discusses the sustainability of Electrodialysis (ED) powered by photovoltaic solar (PV) energy as one of the most promising configurations for the desalination of brackish water. Environmental, with special focus on energy consumption as a function of salinity, economic, and social issues have been considered and main figures for an ED–PV case study in the Canary Islands focused in FW production are given. Energetic considerations have also been deeply discussed in the section of environmental issues. Reverse Osmosis has been taken as the reference technology. The reference energy consumption for ED of brackish water (2500–5000 mg L^{-1}) includes a range of 0.49–0.91 kW h m^{-3}. Due to this range and regarding to the environment, the use of ED–PV is in the range of 0.02–0.03 $kgCO_2$ m^{-3} (only due to energy supply), which is a decrease of one order of magnitude compared to grid mix supply.

A medium-term forecast for ED–PV is presented in which might be economical over conventional grid mix supplied ED before 2020 under the most optimistic scenario, leading to a production costs around 0.15–0.4 € m^{-3}. With respect to social issues, renewable desalination contributes to a significant increase of local direct and indirect employment but under a wide range of 0.1–4 permanent positions per 1000 m^3 day^{-1}.

Finally, the main identified barriers for ED–PV preventing a larger market penetration are the matching of the intermittent output of renewable energies with water demand, lifetime of membranes, efficiency of solar panels and the high production cost of freshwater compared to its low market price as commodity.

Contents

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1. Introduction

Desalination technologies (DES) are being extending all over the world in order to satisfy freshwater (FW) demand in countries under water shortages. Electrodialysis (ED) and Reverse Osmosis (RO) are two of the most important membrane DES technologies for the treatment of brackish water (BW), a water resource preferable than seawater (when available) due to economic reasons for FW production. Indeed, BW utilization has growth at a rate of 12% in the last decade [1]. The treatment of BW is a well-known application of ED [2]. A recent study has pointed out that DES of BW by means of ED is one of the applications where this technology is cost-effective [3]. This application is applied at industrial scale and several plants using ED (equipped with reversal polarity units) can be found all over the world. Some examples of DES plants under operation in the Canary Islands (Spain) are located in *Tamaimo* (capacity: 2100 $m^3\ day^{-1}$), *Valle de San Lorenzo* (capacity: 12,000 $m^3\ day^{-1}$), *Aripe* (capacity: 12,000 $m^3\ day^{-1}$) and *Icod II* (capacity: 4000 $m^3\ day^{-1}$).

No matter what the technology for DES is chosen, it is an intensive-energy option. It is reported that, in general terms, to produce 1 m^3 of FW by means of DES is necessary about 25 kg of oil [4]. The installed DES capacity in 2008, which was 7.5% of total world FW demand, would require 1.42 million tons of oil day^{-1} [5]. Thus, if the energy dependence of fossil fuels does not change, the increase of DES will create new energy and environmental problems. According to the World Water Council, the greatest challenges for the management of water are its integration with ecosystems and energy consumption [6]. In this sense, the sustainability of the production of FW is compromised. Sustainability must be understood as a multi-objective function with multiple input variables, being those variables grouped in environmental, economic and social objectives [7]. These 3 objectives usually present opposite trends and the most adequate trade-off must be pursued. Regarding production of FW, negative direct (from brines) and indirect (from the energy consumption) consequences for the environment can be considered, coupled to different levels of sectorial employment and final cost for each unit of volume produced. Consequently the integration of renewable energies in the production of FW must be an essential component of its future development. Whereas studies regarding the sustainability or at least the environmental component of FW production by different DES technologies are available in the literature ([8,9]), within that context, we have focused on the update of the current state-of-the-art of ED and its integration with renewable energy (RE) as photovoltaic solar (PV) energy from the three pillars of sustainability using a process engineering perspective. In this work, a case study used as example will consider an small capacity ($<1000\ m^3\ day^{-1}$ as defined in [5]) ED plant located in the Canary Islands using BW from TDS 2000 to 5000 mg L^{-1} (such as those from low salinity BW aquifers) in order to provide FW for drinking purposes at TDS 200 mg $L^{-1}$and powered by PV solar energy. Reverse Osmosis (RO) is the reference technology for comparison. All numbers will be expressed in terms of treated m^3 thus no numbers of FW supplied population are reported. Thermal based technologies are also included in the context of the study. As a result, the work is divided in 6 sections: (i) a brief introduction to describe the intended aim of the work; (ii) the state-of-the-art of the integration of ED with renewable energies; (iii) environmental issues, especially those regarding indirect burdens from energy consumption; (iv) economic issues, focused on cost structure and time trend production costs; (v) social issues as level of employment and finally (vi) a summary of the current technical and economic barriers for a larger market penetration of the ED powered by PV. Elements discussed in the different sections can be considered for supporting and helping decision-makers in water management plans, especially in locations plenty of solar irradiation and BW resources.

2. The state-of-the-art of renewable ED

Many reviews are available in the literature discussing the integration of desalination with renewable energies ([4,5,10–20]). Among them, it can be found specific reviews that deal with solar DES ([17–19]) and even exclusively with PV–DES ([20]). Given this significant amount of available information, the present study includes a general summary of the state-of-the-art. Then the subject is focused in the integration of RE with ED as proposed technology in the present work.

Lots of possible combinations between RE and DES technologies are described. Table 1 includes a summary of these alternatives (black dots and ticks). Among them, it can be found thermal DES alternatives such as solar distillation (SD), multi-effect humidification (MEH), membrane distillation (MD), thermal vapor compression (TVC), multistage flash distillation (MSF), multi-effect distillation (MED) and mechanical vapor compression (MVC). On the other hand, membrane DES options are ED and RO. Additionally, taking into account the different maturity stages of the RE and the availability of the renewable resources, the options with more potential have been highlighted.

Regarding the most tested technologies, the distribution of 131 representative renewable DES plants was reviewed in the project PRODES ([21,23]). In this project, it was reported that 85% of the RE–DES plants were powered by solar energy. Among the solar DES plants, 46% were membrane-based while 39% were thermal-based. The most used technology was RO with a 31% of the total installed capacity. Additionally, it should be emphasized the importance of PV energy with 34% of the RE–DES plants. This percentage is even higher, 43% of the installed capacity according to [5,24]. Moreover, the contribution of ED–PV in the former study of PRODES was of 3%, although in another recent reference a 9% was mentioned [11].

Table 1
Combinations of desalination technologies with RE according to [5,12,14,21,22]. The most promising alternatives according to [12] are highlighted with a tick. T=Thermal energy, E=Electric energy and M=Mechanical energy.

	Solar		Wind		Geothermal		Ocean		
	T	E	M	E	T	E	E	M	T
SD	●								
MEH	●				●				●
MD	●				●				●
TVC	●				●				●
MSF	✓				●				
MED	✓	●		●	●	●	●		●
ED		✓	●	●		●	●	●	
MVC		●	●	●		●	●	●	
RO		✓	●	✓		●	●		