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Solar thermal-powered desalination: A viable solution for a potential market

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A B S T R A C T

This paper deals with an assessment of solar thermal-powered desalination technologies in order to identify key issues for developing market opportunities. The topic of selecting the best solar desalination solution is analysed, case by case, considering different scenes: i) Rural communities with limited fresh water demand; ii) Regions with high demands of both, water and electricity and iii) Intermediate water demands. Detailed analyses of solar thermal-driven desalination – i.e. distillation and Reverse Osmosis (RO) - in comparison to solar PV/RO are presented. The quantitative assessment performed highlights that membrane distillation systems, when fully developed, will have market opportunities at very small-capacity seawater desalination systems. Besides that, dish concentrators coupled to micro gas turbines in case of limited water demand is a promising option. A single unit could produce about 10 m^3/h of fresh water from seawater and several units could be coupled to drive the same desalination plant. Moreover, the only stand-alone systems with market opportunities for intermediate water production are based on reverse osmosis driven by parabolic troughs or linear Fresnel concentrators by means of organic Rankine Cycles. Finally, water demands over 25,000 m^3/d require both, a solar power plant and a reverse osmosis desalination plant.

1. Introduction

There are many references in literature focused on the status of solar desalination as follows: Delyannis [1–2], Subiela et al. [3], Belessiotis and Delyannis [4–5], García-Rodríguez [6–9], Li et al. [10] and Shalaby [11]. In addition, this paper deals with qualitative and quantitative analyses of solar thermal-powered desalination technologies in order to identify key issues to develop market opportunities. First, a review on the status of solar thermal-driven desalination is performed - Sections 1–2. Second, in Section 3 a specific methodology is proposed to compare the quite different technologies currently available. Finally, taking into account the competing technology based on solar PhotoVoltaic (PV) energy – Section 4 -, the assessment of market opportunities is carried out – Sections 5–6.

The topic of selecting the best solar desalination solution is analysed, case by case, considering different scenes:

- Rural communities with limited fresh water demand (< 100 m^3/d). Literature reports intensive R&D activities focused on providing fresh water to small rural communities in developing countries. Many low-efficiency systems have been constructed, which integrate solar thermal conversion and desalination process in the same device. Nevertheless, as plant capacity increases the use of such devices makes no sense due to their low energy efficiency.
- Regions with high demands of both, water (> 25,000 m^3/d) and electricity (> 10 MW). This kind of systems have been scarcely analysed in the literature. A solar power plant can produce the energy needs of a desalination plant, based on reverse osmosis or any distillation process.
- Intermediate water demands (< 25,000 m^3/d and > 100 m^3/d). Solar distillation systems consist of a desalination unit and a solar field directly connected or coupled by an energy storage system. In case of using a desalination process driven by electricity, a power cycle with relatively small power output is necessary. Several plants have been implemented, normally within the framework of R&D projects.

Concerning solar thermal-driven desalination, Reverse Osmosis (RO) is powered by electricity, thus, energy conversion from solar thermal energy to electricity is required. Therefore, a comparative assessment of different technologies based on either, distillation and Reverse Osmosis (RO) is not easy. When analysing distillation systems, two parameters are essential to evaluate the performance of the process:

- The Performance Ratio, PR, that is the ratio between the water

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enthalpy of phase change (2330 kJ/kg) and the specific thermal energy consumption of the process itself (kJ/kg).

- The Gain Output Ratio, GOR, the ratio between the obtained product (kg of condensed vapour) and the required energy of the process in terms of kg of condensed vapour of the thermal source.

GOR and PR have similar values due to their respective definitions. PR and GOR mainly depend on the distillation technology. On the contrary, the Specific Energy Consumption (SEC) of the current RO technology strongly depends on the salt concentration.

Reverse osmosis desalination driven by solar PV fields is a mature technology commercially available [7–8]. Besides, several solar thermal-driven desalination plants based on Multi-Stage Flash (MSF) distillation, Multi-Effect Distillation (MED) and Membrane Distillation (MD) have been installed within the framework of R&D projects [1–2,4–8]. Other technologies have been scarcely implemented, namely Reverse Osmosis (RO) powered by a solar power cycle, solar freezing [12] and solar mechanical vapour compression [13]. Finally, direct solar desalination concept, which integrates within the same device the energy conversion and the distillation process, is limited to small-capacity systems. Many of such systems have been designed and installed [1,4].

Solar-thermal desalination systems developed in the XX century and in the beginning of the XXI century were mainly based on the following technologies:

- *Salinity-gradient solar ponds coupled to distillation plants.* Salinity-gradient solar ponds are solar devices that integrate long-term thermal storage. This feature along with their low cost and scale economy make them especially suitable to be coupled to distillation units. This technology was thoroughly studied over the 80s, attributable to the dominant distillation market of seawater desalination. It is remarkable the test facility of El Paso (USA), described by Lu et al. [14]. This solar pond not only drives thermal desalination processes, but also RO desalination by means of a low temperature Rankine cycle. Los Baños solar pond is another test facility in which solar thermal RO was tested [15].
- *MSF distillation driven by solar collector fields.* The development of experimental plants with capacities up to 100 m^3/d shows the interest focused on the solar MSF technology over the XX century. About seven pilot facilities are described in the literature [7]. Regarding the technology development, an important advance was recently achieved by Mabrouk and Fath [16]. They report on the experimental test campaign conducted with NanoFiltration (NF) pretreatment of the MSF feed, thus resulting in high top temperature and enhanced Performance Ratio (PR) of 15. Nevertheless, the high auxiliary consumption of MSF process limits the commercial prospects of solar desalination based on MSF technology. It should be noted that NF pretreatment requires additional electric consumption and the use of NF does not reduce the great mass flow rate circulating through the plant. Therefore, auxiliary consumption dramatically increases. A representative conventional plant in which NF and distillation processes are integrated is Sharjah plant, based on multistage flash distillation [17].
- *MED driven by solar collector fields*. Some Multi-Effect Distillation (MED) plants driven by solar collectors were installed at different locations [7]. Based on a 14 effect-MED unit with capacity of 72 m^3/d [18] existing in the solar research centre Plataforma Solar de Almería (PSA-CIEMAT), Spain, different solar plants have been installed within the framework of different R&D projects [19]:
  - MED plant driven by steam from a parabolic trough solar field.
  - MED-TC (ThermoCompressors) driven by the steam generated by a parabolic trough solar field.
  - MED plant driven by water heated by means of compound parabolic concentrators.
  - MED coupled to a Double-Effect Absorption Heat Pump (DEAHP) through two auxiliary water tanks. A new parabolic trough collector field and boiler produce the steam required by the DEAHP (saturated at 180 °C). The low temperature heat input of the absorption cycle is the steam generated within the last distillation effect. Besides that, the DEAHP provides the required heat consumption of the MED unit as hot water.

MED-DEAHP technology was developed at the PSA [19–25]. For a given flow and thermodynamic conditions of the external steam source, MED-DEAHP provides higher PR than MED-TC. Therefore, the former is superior to MED-TC, however, it is not commercially available.

Besides that, high temperature MED process by using NanoFiltration (NF) as seawater pretreatment has been proposed and developed by Hassan [26–28]. Both, the concept and the experimental assessment have been reported in the literature [29–30]. Nevertheless, as NF pretreatment increases the auxiliary electricity consumption, this is not recommended in solar desalination.

In addition, more recently, there has been increasing interest of developing:

- Membrane Distillation (MD) systems [31–38], which are especially suitable for solar desalination. Values of PR about 7 have been obtained [39].
- RO desalination systems driven by solar organic Rankine Cycles [40–44], as a potential alternative to PV-RO desalination. The key issue may be that solar ORC's use thermal energy storage instead of batteries. About eight pilot systems have been installed.
- Desalination systems integrated in solar power plants. The increasing interest in integrating fresh water and electricity productions is attributable to the fact that energy and water demands are usually linked in arid isolated regions. First R&D activities on this issue reported in the literature are the following. A hybrid MSF-RO system driven by a dual-purpose solar plant was installed in Kuwait [1]. The desalination system consists of a 25 m^3/d-MSF plant and a 20 m^3/d–RO plant. In regards to analyses of cogeneration plants: Rheinländer and Lippke [45] studied a system coupling a MED plant to a solar tower power plant, and Glueckstern [46] presented a detailed analysis of dual-purpose solar plants.

2. Assessment of recent developments in solar desalination

2.1. Desalination based on membrane distillation (MD)

In this section the existing MD pre-commercial or commercial technologies are described and external experimental evaluations by independent research organizations are reported. A brief description of such MD modules is presented below, sorted by the manufacturer company:

- Scarab Development AB. The Swedish company Scarab Devlopment AB [47] developed MD modules. The application of these modules to seawater desalination has also been considered by the company. These products have been tested at the Plataforma Solar de Amería-CIEMAT within the framework of the EU project MEDESOL (FP6-2005-Global-4, FP6–036986, *Seawater Desalination by Innovative Solar-Powered Membrane- Distillation System*) [48]. The technology is based on air gap MD, using flat sheet membranes.
- Memstill technology. Memstill technology is attributable to the patents developed by a research organization in Holland, TNO, licensed by the company Keppel-Seghers (Singapur). The latter contracted the Plataforma Solar de Almería for testing two of the company's prototype modules. Both prototypes, M33 and PT5, are based on liquid gap MD process and have flat sheet membrane configuration and a total membrane area of 9 m^3. The M33 prototype is manufactured as a single module, while the latter is composed by three serial modules [49]. In addition, aforementioned