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Solar desalination by combination with concentrated solar power: exergy cost analysis

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Abstract. Some regions of the world with high solar irradiation conditions have a growing demand for electricity and freshwater that could cause supply problems in the industries and population. To reduce this risk, the use of solar energy to generate electricity and freshwater is an interesting option to consider. Electricity could be generated from concentrated solar power (CSP) plants fuelled by solar energy and natural gas, while freshwater could be produced from multi-effect distillation (MED) and reverse osmosis (RO) technologies driven by thermal energy and electricity, respectively. An exergy cost analysis of the integration of two desalination technologies (MED and RO) with a CSP plant is carried out to compare in terms of exergy cost. The symbolic exergoeconomics method is applied in the configurations analyzed. The different configurations are evaluated in a representative region with high irradiation conditions. Results show that the best configuration for producing electricity and freshwater is achieved when the stand-alone RO plant is connected to the grid where the unit exergy cost of electricity and water is 31% and 54% lower than in the stand-alone CSP plant and stand-alone MED, respectively. However, CSP-MED is the recommended configuration for the solar cogeneration scheme evaluated. Additionally, the most influential components in the cost formation of electricity are solar collectors (46.6% in CSP-MED and 44.3% in CSP-RO) while for freshwater they are solar collectors (27.6% in CSP-MED and 42.0% CSP-RO), multi-effect distillation module (15.7% in CSP-MED), and reverse osmosis module (20.5% in CSP-RO). In these components the design should be improved to reduce the unit exergy cost of electricity and freshwater.

1. Introduction

Many regions of the world present a high demand of freshwater and electricity. Some of these experience an increasing water scarcity that keep them in a state of vulnerability, one solution could be to produce freshwater from the seawater by desalination technologies driven by thermal energy and/or electricity [1], [2]. At the same time, some of these regions have a high availability of solar irradiation [3], which allows concentrated solar power (CSP) plants to produce electricity at lower levelized cost [4]. These plants can operate directly from solar energy, be hybridized, store the thermal energy captured and use fossil fuel backup which permits to operate in stable and constant conditions [5], [6]. CSP plant can be

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the prime mover in a cogeneration scheme. The heat rejected by the CSP plant could be recovered by technologies driven by thermal energy [7], [8]. Cogeneration is an integration process that produces more than one product from one or more natural resources, whose advantages are to reduce primary energy consumption, emissions, waste heat, transmission and distribution network and other energy losses [9]. Both electricity and freshwater can be generated in independent plants (stand-alone plants). However, given the advantages offered by operating in a cogeneration scheme, it is interesting to evaluate this scheme as an option to provide an adequate energy-water supply and to ensure the development of indigenous energy-water sources.

Different technologies could be integrated to produce desalinated water and electricity. Desalination technologies could be driven by either thermal energy or electricity. In the first case, the main technologies are multi-effect distillation (MED) and multi-stage flash (MSF) [5], [6]. While in the second case, reverse osmosis (RO) represents the most employed technology for desalination [10]. CSP plants generate electricity by using mirrors to concentrate sunlight and produce heat, which drives a power cycle [11]. In CSP technologies, CSP parabolic trough collectors is a mature technology [12] and CSP central receiver system is a commercially proven efficient technology [13].

The integration of a solar power plant and desalination plant into a cogeneration scheme is a complex process. There are several methods for evaluating the integration strategies in cogeneration schemes [6], [14], in which the thermoeconomics (or exergoeconomics) method is recommended [6], [15]. This method allows measuring in the same physical unit, resources and waste flows of different nature such as energy (thermal, mechanical, electrical, others) and mass (seawater, freshwater, steam, others). This unit is the exergy which assesses both quantity and quality of energy. In a cogeneration scheme, the thermoeconomic method provides useful information for the design, evaluation, operation, and diagnosis of the systems [16].

Different studies have applied the thermoeconomic method to analyze the integration of concentrated solar power plants and desalination technologies into cogeneration schemes [6], [8], [17], [18]. However, the integration of solar cogeneration schemes of CSP plants and desalination technologies (MED and RO plants) requires a deeper analysis in order to select the best configurations and identify potential improvement measures for energy saving.

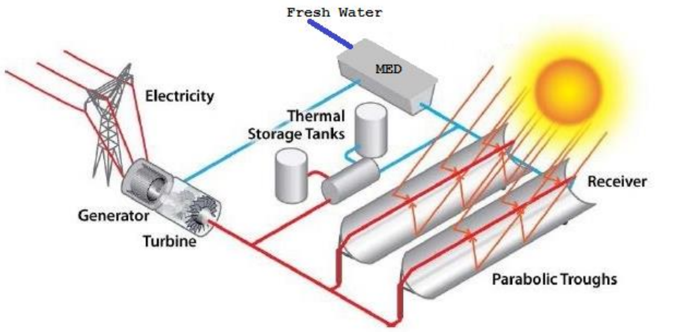
The purposes of this research are to compare different cogeneration configurations for generating electricity and freshwater with CSP, MED, and RO technologies, and to find the key equipment in the cost formation of products and their potential energy savings.

2. Materials and methods

The methodology contemplates the modeling and validation of three stand-alone plants (CSP, MED, and RO) and their integration in two solar cogeneration schemes (CSP-MED and CSP-RO). The simulation of cogeneration plants considers a meteorological year [3], backup of fossil fuel, and known demands. After that, it is applied the symbolic exergoeconomics method [16].

Figure 1 shows the solar cogeneration plants evaluated. The size of each stand-alone plant is 55 MW_e and 430 kg/s of freshwater for power plant and desalination plant, respectively. The CSP plant is composed of the solar field, thermal energy storage, backup system, and power block [8]. The solar field (solar collectors) consists of parabolic trough collectors, absorber tubes (receiver), and heat transfer oil. The MED plant considers parallel-cross feed effects and feed preheaters [8] while the RO plant consists in a series of conventional membrane elements [2], [17]. The systems are modelled and evaluated using IPSEpro [19], Matlab, and Excel software [20]. The location evaluated for this plant is in an arid zone [8]. The stand-alone plants were validated by comparing the results with the literature [2], [8], [17].

a)



b)

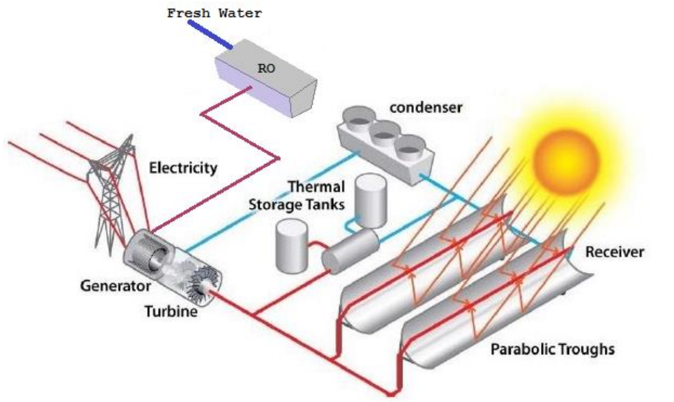


Figure 1. Simplified diagrams of the configuration of solar cogeneration plants a) CSP-MED.
b) CSP-RO.

The governing equations in the thermodynamic and exergy analysis of the stand-alone systems and cogeneration schemes include mass balance, energy balance (first law of Thermodynamics), and exergy balance (second law of Thermodynamics), defined as follows:

$$\sum_j (\dot{m}_{in} - \dot{m}_{out}) = \frac{dm_{cv}}{dt} \tag{1}$$

$$\sum_j (\dot{m}_{in} \cdot h_{in}) - \sum_j (\dot{m}_{out} \cdot h_{out}) - \dot{W} + \dot{Q} = \frac{dEn_{cv}}{dt} \tag{2}$$

$$\sum_j \left(1 - \frac{T_0}{T_j}\right) \cdot \dot{Q}_j - \dot{W}_j - \dot{E}_D + \sum_{in} (\dot{m}_{in} \cdot e_{in}) - \sum_{out} (\dot{m}_{out} \cdot e_{out}) = \frac{dE_{cv}}{dt} \tag{3}$$

where $\dot{m}$ is the mass rate, h is the specific enthalpy, $\dot{W}$ is the rate of work, $\dot{Q}$ is the heat power, T_0 is the temperature of reference, dEn_{cv}/dt is the energy change rate in the control volume (j), $\dot{E}$ is the rate of exergy, e is the specific exergy, and dE_{cv}/dt represent the exergy change rate in the control volume. The subscripts j, in, out, cv, and D are the portion of boundaries, inlets, outlets, control volume, and destruction, respectively.

It is applied the symbolic exergoeconomics method which is based on the exergy cost theory [15], [21], [22]. This method allows assessing the efficiency of systems and explaining the process of cost formation of products.

Each process consumes fuel and generates products and residues, then the fuel is partially transformed into product and partially destroyed as irreversibility. The exergy cost of product (C_P) represents the resources required to carry out the production, it is defined as:

$$C_P = C_F + C_R = C_P^e + C_P^r \quad (4)$$

where C_F is the exergy cost of fuel, C_R is the exergy cost of residues, $\boldsymbol{C_P^e}$ is the exergy cost due to irreversibilities of the components (the sum of the irreversibilities accumulated along the process), and $\boldsymbol{C_P^r}$ is the exergy cost due to the residues allocation.

The main indicator used is the unit exergy cost that represents the amount of exergy required to get a unit of exergy of the product. Similar to the exergy cost of product, the unit exergy cost of product is decomposed into two unit production costs, one due to irreversibilities of the components and the other due to the residues. More details on the symbolic exergoeconomics method can be found in [15], [18], [21], [22].

3. Results and discussion

Figure 2 shows the comparison among grid, stand-alone systems (CSP, MED, and RO), and cogeneration plants (CSP-MED and CSP-RO). The stand-alone RO connected to the grid is the best configuration for producing electricity and freshwater. This result is coherent with the level of penetration that exists in the market for RO plants to produce desalinated water. In this case, the baseline (grid and stand-alone RO) is better than the cogeneration configurations, although, cogeneration schemes allow reducing primary energy consumption, emissions of greenhouse gasses, and final products cost; besides, it is increased the energy and exergy efficiencies. By comparing cogeneration plants, CSP-MED is the best configuration. In the case of CSP-RO, it produces the higher unit exergy cost of electricity and the lower unit exergy cost of water. Similar results were obtained by Ortega-Delgado et al. [17] who conducted a thermoeconomic comparison of integrating seawater desalination processes in a CSP plant.

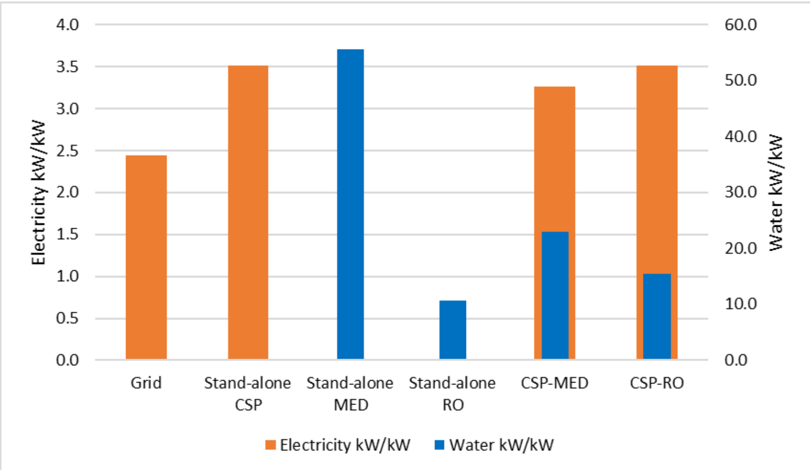


Figure 2. Comparison of grid, stand-alone systems, and cogeneration plants.

Figure 3 shows the cost decomposition for producing electricity and freshwater in each cogeneration plant. The most influential components in the cost formation of electricity are solar collectors and evaporator. While, in the case of freshwater, they are solar collectors, dissipator, MED module, and RO module. The solar collectors affect both cogeneration configurations and, therefore, is the equipment that has priority over the others to be analyzed and improved. The solar collectors are the main source of irreversibility. The reason is first the temperature difference between the sun and the heat transfer fluid, and second the exergy optical losses. Increasing the operating temperature could be a solution, however, the heat transfer fluid has a limited operating temperature. Additionally, the design of the solar collectors could be improved as the optical efficiency of the collectors increase and/or the receiver reduces the heat losses. Note that the optical efficiency is the fraction of solar energy that is absorbed by the receiver in the solar collectors.

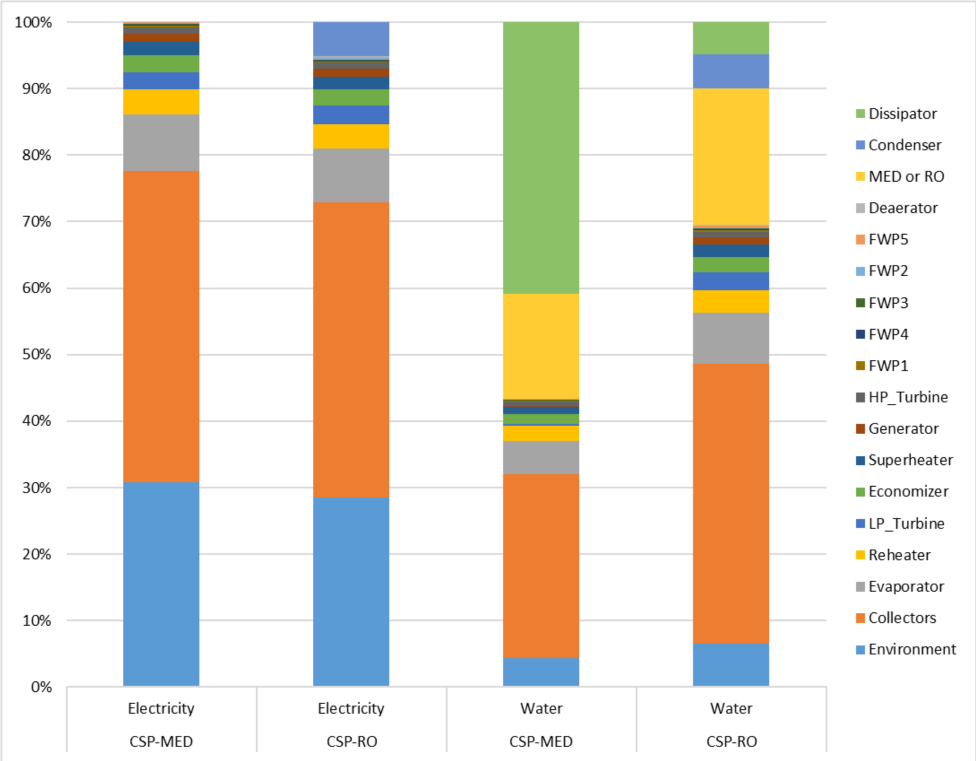


Figure 3. Cost decomposition of the CSP-MED and CSP-RO plants.

4. Conclusions

From an exergy cost analysis, it is compared different cogeneration options for the integration of multi-effect distillation and reverse osmosis with a concentrated solar power plant. The symbolic exergoeconomics method was applied to the configurations evaluated.

The best configuration for generating electricity and freshwater is when the stand-alone reverse osmosis plant is connected to the grid. However, this configuration does not operate as a cogeneration scheme.

CSP-MED plant is the best evaluated configuration for cogeneration.

In the cogeneration scheme, the solar collectors are the most influential components in the cost formation of electricity and freshwater. In these components the design should be improved to reduce the unit exergy cost of electricity and freshwater.

In future studies, a thermoeconomic diagnosis of the operation of a cogeneration plant should be conducted to determine the malfunction and dysfunction of a process.

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