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Thermoeconomic comparison of integrating seawater desalination processes in a concentrating solar power plant of 5 MW_e

Bartolomé Ortega-Delgado [a], Lourdes García-Rodríguez [b,*], Diego-César Alarcón-Padilla [a]

[a] CIEMAT-Plataforma Solar de Almería, Ctra. de Senés s/n, 04200 Tabernas, Almería, Spain
[b] Department of Energetic Engineering, Seville University, Escuela Técnica Superior de Ingeniería, Camino de los Descubrimientos s/n, 41092 Sevilla, Spain

HIGHLIGHTS

- A thermoeconomic comparison between MED and RO desalination technologies is performed.
- It is analyzed the coupling between MED and RO units and PT-STPP plants.
- SWRO produces the lower LWC, both with direct or indirect integration.
- Decoupling the SWRO from the STPP is the best option (lowest LWC).

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ABSTRACT

In this work a thermoeconomic analysis of the joint production of electricity and water for a simulated 5 MW_e Solar Thermal Power Plant (STPP) based on parabolic trough mirrors and Direct Steam Generation (DSG) is carried out. The location considered for this plant is Almería, in southeast of Spain. Two different seawater technologies have been selected to be coupled with the STPP: Multi-Effect Distillation (MED) and Reverse Osmosis (RO). The Power Block (PB) has been designed to maximize the thermal efficiency, including regeneration and reheating. Four coupling arrangements have been investigated: the MED replacing the condenser of the PB, the MED being fed by one steam extraction of the PB, the RO directly using the electricity generated in the PB and the RO connected to the local grid. Results show that the best coupling option is with the RO unit being connected to the local grid, which produces the lower Levelized Water Cost (LWC).

1. Introduction

This paper deals with the case study of integrating seawater desalination processes in a specific Concentrating Solar Power (CSP) plant of 5 MW_e, based on direct steam generation within absorber tubes of Parabolic Trough (PT) collectors. Zarza et al. [1] designed and thoroughly described in this reference a CSP plant with these features. Based on this plant, the authors analyze the power cycle and propose the best design in order to compare four coupling arrangements. Firstly, the coupling of a Multi-Effect Distillation (MED) plant is analyzed, thus integrating the fresh water and electricity production. Two different configurations are studied: the maximum water production by means of replacing the condenser by the distillation plant and the use of an intermediate steam extraction from the steam turbine to feed the MED unit. Secondly, the Reverse Osmosis (RO) desalination process is considered. Two options are examined: the integrated production of water and electricity, in which the desalination plant only produce water when the CSP plant operates, and the independent production of water and electricity. In this case two different plants can be installed in near but different locations. Since the use of distillation processes only makes sense for seawater desalination, the comparison is restricted to Sea Water Reverse Osmosis (SWRO). Moreover, a MED plant requires steam below 70 °C (to avoid the appearance of scaling in the tubes), hence the influence of this requirement on the power cycle efficiency is thoroughly calculated in this paper, in order to compare distillation and membrane desalination processes. The cost of the fresh water production is also comparatively analyzed in the four coupling arrangements considered.

Literature on water and electricity production based on CSP plants is scarce. García-Rodríguez and Gómez-Camacho [2] investigated the coupling of a multi-effect distillation and multi-stage flash plants to a parabolic trough solar collector field using the thermoeconomic analysis. Results showed that the cost of the fresh water is very sensitive to the exergy consumption of the desalination plant. Moreover, in the case of

* Corresponding author.
E-mail addresses: bartolome.ortega@psa.es (B. Ortega-Delgado), mgarcia17@etsi.us.es (L. García-Rodríguez), diego.alarcon@psa.es (D.-C. Alarcón-Padilla).

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the MED integration, direct steam collectors were suggested in the solar field, replacing the thermal oil by water as heat transfer fluid. Palenzuela et al. [3] carried out a thermodynamic study of different integration arrangements of a MED (with and without thermal vapor compression) and a RO plant into a solar power plant with parabolic trough collectors, supposed to be located in the Mediterranean area. They concluded that the best option, in terms of thermal efficiency of the power cycle, was the coupling of the RO plant. Nevertheless, under certain circumstances (like those requiring high purity fresh water or dealing with contaminated water sources), the distillation process is recommended. In this case the efficiency decrease with respect the RO option is lower than 2%, using the MED as the condenser of the Rankine cycle. The same authors [4] analyzed different integration options between MED and RO plants with a PT solar power plant in arid regions. Results showed that the coupling of a low temperature MED substituting the power cycle, with the simulated conditions, was thermodynamically more efficient that the coupling of an RO desalination plant. Additionally, the results obtained using a MED-TVC unit fed by a steam extraction from the low pressure turbine were comparable with those obtained with the RO integration, suggesting the possibility of using this technology in arid locations. Olwig et al. [5] performed a techno-economic analysis of different CSP + MED and CSP + RO configurations for the co-production of power and water in Israel and Jordan. They found that the LWC was strongly influenced on the sold electricity price and the RO was the most economic option except for high electricity tariffs. Besides, a comparison of different renewable technologies in dual purpose plants was made by Moser et al. [6], contrasting a continuous and discontinuous operation of the desalination plant, and using a backup system or the grid to provide the necessary energy at each instant. Casimiro et al. [7] presented a model for a parallel feed MED-TVC and its integration into a CSP plant, showing the annual electricity and water production for different cooling options in the power block. Moser et al. [8] also developed a techno-economic model for the assessment of various desalination processes (MED, RO and hybrid MED-RO) driven by conventional power plants based on fossil fuels and renewable energy systems. They pointed out the variability of the results provided by this kind of analysis depending on the different operational and financial parameters considered. Therefore, costs uncertainties could be partially addressed by making parametric studies on the input parameters, which eventually measures the influence on the final cost of electricity and water. Fylaktos et al. [9] also performed a techno-economic analysis of the combined production of power and water in Cyprus, considering the integration of a CSP plant with RO and MED processes. The nominal power designed was 4 MW_e and the Discounted Cash Flow (DCF) methodology was applied in the financial analysis. Besides that, Antipova et al. [10] and Salcedo et al. [11] analyzed reverse osmosis desalination coupled to solar power plants based on Rankine cycles, minimizing at the same time the specific total cost of the water production and the environmental impact caused.

Although RO is currently the dominant technology in large-scale seawater desalination, some authors consider distillation as the only appropriate desalination process due to different reasons:

- The requirement of extremely high quality water – concentration around a few ppb – to compensate the power cycle leakages, makes the RO process useless. Nevertheless, this is not a barrier for the RO process since further treatment of its product can be performed by means of other processes as electro-deionization. Moreover, the human consumption does not require any additional treatment, then only a part of the water production would need it in that case.
- The cooling requirement of the condenser is argued by some authors to be substituted by the distillation plant. Nevertheless, the seawater flow required by an MED plant is similar to the flow required by the corresponding once-trough cooled condenser. This is due to the need of cooling the end condenser in the distillation process. In addition, the hot brine disposal is an environmental problem similar to the once-through cooling of a CSP plant. Moreover, if a SWRO is installed, the condenser of the power cycle could be cooled by the feed, product or blowdown of the SWRO plant.
- The self-consumption attributable to electricity demand of the RO process, if it is integrated in the power production, is another drawback of RO process from the point of view of some authors. This is the case in which the electricity production has a direct subsidy. However, the coupling of a distillation process causes a decrease on the power cycle efficiency and needs a significant amount of energy for pumping, especially in the end condenser where the seawater is used as cooling stream. Furthermore, the temperature of the power cycle condenser in dry or evaporative cooling is higher than in once-trough cooling, in which an open circuit of water flows at ambient temperature and pass through the condenser. If a desalination process is considered together with the power generation, and a water stream is available at the CSP plant, then it can be used to partially or totally cool the power cycle condenser. Therefore, a realistic comparison should not consider the dry cooling as the only process to condense the power cycle steam.

Due to above-mentioned reasons, the design of both, the desalination process and the condenser cooling should be carried out as a whole, and based on a realistic assessment of the power cycle efficiency for a given fresh water demand. Other key issue is related to the existence of conventional power backup for the electricity production, since in case of discontinuous operation distillation plants exhibit meaningful additional risk of scaling. Finally, in case of discontinuous operation, the nominal capacity of the desalination plant to supply a given fresh water demand should be significant higher. This does not make sense in case the water production is not only attributable to the self-consumption of the CSP plant.

In addition, the interest in desalination coupled to solar power plants has been pointed out within the framework of the European Energy Research Alliance [12], by establishing a sub-programme on "Concentrated Solar Power plus Desalination" within the Joint Programme on CSP (Concentrated Solar Power). Both, distillation and reverse osmosis, may be considered as the desalination process to be coupled to a solar power plant.

This paper is focused on the thermoeconomic comparison between distillation and reverse osmosis desalination technologies integrated in a parabolic trough solar thermal power plant, based on direct steam generation within the solar field. Since the comparison between heat or electricity consumptions is complex, the well-known thermoeconomic methodology is selected in order to assess the actual cost of the steam consumption of the distillation process.

2. CSP and SWRO plants

2.1. CSP plant

The first step of considering the coupling between CSP and desalination is to estimate realistic performances of both processes. Table 1 shows a record of representative PT-CSP plants, specifically those installed in the Mojave Desert, with the thermal efficiencies of the Rankine cycle.

The power block is analyzed considering limits in temperature and pressure of the solar field described in Zarza et al. [1]. The sizing of the solar field is consistent with this reference. It has been assumed the same heat-area ratio than that one of the mentioned work. Therefore, the area of the solar field is function of the power generated in the plant, the thermal efficiency of the Rankine cycle and the solar field area and heat rate provided by the collectors in [1].

$$\frac{\dot{Q}_a^*}{A_{SF}^*} = \frac{\dot{Q}_a}{A_{SF}} \Rightarrow A_{SF} = \frac{\dot{Q}_a}{\dot{Q}_a^*} A_{SF}^* = \frac{\dot{W}_e/\eta_{th}}{\dot{W}_{e,n}^* HR_n^*} A_{SF}^* \quad (1)$$