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Thermoeconomic optimization of the SOL-14 plant (Plataforma Solar de Almería, Spain)

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Abstract

The Sol-14 plant is a solar multi-effect distillation system installed at the Plataforma Solar de Almería, a solar research centre located in southeastern Spain, near Almería. In July 1988 the first start-up of the plant took place, which was connected to the previous existing solar facilities. In the second phase of the project, a double-effect absorption heat pump (DEAHP) was coupled to the MED plant that was already installed. Results of the thermoeconomic analysis performed show direct steam generation (DSG) parabolic troughs exhibit great potential for improving the Sol-14 plant. Replacing the oil-based technology by DSG presents many advantages from the point of view of thermodynamics, environmental hazards of oils, land use, use of materials or lifetime of the solar collectors.

Keywords: Solar desalination; Multi-effect distillation; Solar parabolic troughs; Direct steam generation; Thermodynamics

1. Introduction

In July 1988 the first start-up of a solar multi-effect distillation (MED) system took place at the Plataforma Solar de Almería (PSA), a solar research centre located in southeastern Spain, near Almería. The plant, known as the "Sol-14" plant is still in operation. The plant was built and connected to the previous existing solar facilities as a result of a Spanish–German project consisting of two phases. The main purpose of Phase I [1] was to study the reliability and feasibility of solar desalination. In addition, the objective of phase II [2] was the design and implementation of those improvements that could make solar thermal desalination more competitive. The

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initial vacuum system was replaced, and a double-effect absorption heat pump (DEAHP) was coupled to the MED plant that was already installed. Zarza Moya [1,2] gave detailed descriptions of the system and the results of their experimental evaluation.

In this paper the Sol-14 plant is optimized from the point of view of maximizing the thermodynamic efficiency and minimizing the product cost. This paper uses results from a previous sensitivity and exergy analysis of the SOL-14 plant performed by the authors [3,4].

The improvements implemented in the second stage of the project decrease the energy consumption of the plant by about 44%, from 63 kWh/m^3 to 36 kWh/m^3. On the other hand, the electric consumption decreases by 12%, from 3.3 kWhe/m^3 to 2.9 kWhe/m^3. The system consists of the following subsystems:

- a one-axis tracking parabolic trough collector field, in which a synthetic oil (Santotherm 55) acts simultaneously as a heat transfer fluid and a heat storage medium;
- thermal storage, consisting of a single thermocline vessel;
- a boiler;
- a 72 m^3/d MED;
- a DEAHP, which delivers 200 kW of thermal energy at 65°C to the MED plant.

The desalination process only uses 90 of the 200 kW delivered by the DEAHP. Then the remaining 110 kW are recovered by the DEAHP from a temperature of 35–65°C. The DEAHP needs only 90 kW thermal power at 180°C, thereby reducing the energy consumption of the desalination plant from 200 kW to 90 kW.

2. Parabolic trough solar collectors

Different devices — solar energy collectors — may be used in order to convert solar energy to thermal energy. The concentration of the solar radiation in one axis provides a simple operation and highly reliable systems to reach maximum operation temperatures of about 380°C. Since medium concentration ratios are attainable, one-axis sun tracking is required. The solar collectors based on this technology are parabolic trough collectors (PTC). A fluid is heated by the solar radiation as it circulates along the solar collector within an absorber pipe. The fluid heated at the solar collector field may be either stored at an insulated tank or used to heat another thermal storage medium. Conventional solar PTC use synthetic oils as the heat transfer fluid, which limit the top operation temperature. The operation of the solar energy collector is possible when the solar irradiance is greater than a fixed level, irradiance changes are not greater than a given value and the irradiance transients are within a given time limit.

On the other hand, the synthetic oil may be replaced by water in order to generate steam directly into the absorber pipe. Intensive research on direct steam generation (DSG) in parabolic troughs started in 1988 [5], but currently there are very few test facilities [6]. Odeh et al. [7] have modelled DSG parabolic troughs. The axis of the solar collectors should be tilted 8° to improve the two-phase flow pattern [8]. DSG in parabolic troughs presents many advantages over oil-based technology:

- Temperatures up to 400°C may be allowed, thus improving the performance of the power cycle in solar electricity generation systems.
- Other temperature limits of the synthetic oil are avoided. The minimum temperature of operation suitable for the synthetic oil is around 125–150°C. Moreover, if a thermocline vessel is used as thermal storage, a difference of around 80°C between the inlet and outlet temperatures is required for proper stratification of the oil tank.
- Heat exchangers to generate the steam are not necessary.

- Costs and environmental hazard are reduced.

The authors proposed the use of DSG in seawater desalination with both water and seawater or brine as the heat transfer fluid [3]. Moreover, such desalination systems were economically evaluated by them [9,10].

3. Thermoeconomic optimization of the Sol-14 plant

The computer program SOLARIS 1.0 [11] was used for calculating the energy delivered by the solar collector field. The solar collector selected for this study is the Solar Kinetics T700A. The synthetic oil, Santoterm 55, simultaneously acts as the heat transfer fluid and as the thermal storage medium. Details for climate conditions at the PSA and for the solar collector selected are given in [12].

Since the SOL-14 plant was coupled to the previous existing solar facilities of the PSA, the solar collector field and the thermal storage tank were not designed for this application. Nevertheless, the authors studied the optimum design of such systems [12,13].

Since winter and summer production is very different under Spanish climate conditions, the desalination plant should operate as a hybrid system, driven by solar and conventional energies. Then, to minimize the cost of solar desalination is the main goal of this study, although the solar fraction of the system goes down. At the PSA, the solar fraction that minimized the fresh water cost in a PTC-powered desalination plant is 50% [12].

Table 1 compares six different working conditions of solar parabolic troughs. PTC symbolized parabolic troughs using synthetic oil as the heat transfer fluid; DSG symbolized parabolic troughs that use DSG technology and DSGsw represents the replacing of water by seawater or brine in the DSG solar collector.

1. PTC with inlet/outlet temperatures of T_{in} = 225°C and T_{out} = 300°C, respectively. These are temperatures considerably higher than necessary in the Sol-14 plant. Nevertheless, they are quite similar to that used in solar electricity generation systems. This case is selected to compare the increase of solar collector production at suitable working conditions for desalination plants.
2. PTC (T_{in} = 190°C, T_{out} = 270°C). The temperatures selected in this case are suitable for driving the DEAHP.
3. PTC (T_{in} = 150°C; T_{out} = 230°C).
4. DSG collectors with saturation temperature of 180°C. These collectors may drive the DEAHP.
5. DSG collectors with steam saturation temperature around 100°C.
6. DSGsw collectors with steam saturation temperature below 100°C.

Table 1 shows compares the parameters of the above solar collectors. The first column gives the energy production in kJ per day and per m^2 of solar collector area. The second column gives the fresh water production obtained by connecting the solar collector field to the Sol-14 plant. Similar efficiency than PTC was assumed for DSG collectors. Note that the DEAHP is connected to solar systems in cases 2 and 4. The last two columns represent the area of solar collectors and the investment cost required for obtaining an annual average of 1 m^3/d of fresh water. The investment costs were calculated assuming a PTC cost of 150 €/m^2 of solar collector area. The investment costs were not calculated for DSG collectors since such collectors are not commercially available.

Table 2 was calculated from results presented in Table 1. The average of the fresh water production (*qd*) and the solar collector area required for a fresh water production of 1 m^3/d (*A*) are compared. The two first rows compare the DSG with oil-based technology. The third row

Table 1
Comparison of different solar systems that may be connected to the Sol-14 plant (operation temperatures limits of the working fluid are shown in brackets)

	Energy delivered by the solar collector field, /kJ·m^{-2}·d^{-1}	Average of fresh water production (qd), kg·m^{-2}·d^{-1}	Area of solar collector (A), m^2·m^{-3}·d	Investment cost of the solar collector field, €·m^{-3}·d
PTC (225/300°C)	5723.0	23.6	42.4	5773
PTC (190/270°C)–DEAHP	6165.4	50.9	19.6	2669
PTC (150/230°C)	6652.9	27.5	36.4	4956
DSG (180°C)–DEAHP	7119.6	61.9	16.2	—
DSG (100°C)	7901.1	34.4	29.1	—
DSGsw (100°C)	7901.1	37.9	26.4	—

Table 2
Comparison of different solar collectors that may be coupled to the Sol-14 plant

System A	System B	$(qd_A–qd_B)\ /qd_B$, %	$(A_A–A_B)\ /A_B$, %
DSGsw (100°C)	PTC (150/230°C)	38	−27
DSG (100°C)	PTC (150/230°C)	25	−20
DSGsw (100°C)	DSG (100°C)	10	− 9
DSG (180°C) – DEAHP	PTC (190/270°C) – DEAHP	22	−17
DSG (180°C) –DEAHP	PTC (150/230°C)	125	−56
DSG (180°C) –DEAHP	DSGsw (100°C)	63	−39

quantifies the effect of replacing the water as heat transfer fluid by seawater or brine. The DEAHP is not connected to the system considered in the three first rows. Results show a high increase of fresh water production at the Sol-14 plant due to DSG technology. The production goes up a 25% when oil is replaced by water (DSG). Moreover, the potential use of DSGsw would increase the production an additional 10%. In addition, the fourth row of Table 2 shows a rise of 22% in the production of the Sol-14 plant with the DEAHP connected if PTC collectors are replaced by DSG ones. This case studied exhibits a decrease of 17% on the solar collector area required.

Table 2 also compares the system of maximum production, DSG (180°C)–DEAHP, with the conventional PTC system suitable for connecting to the Sol-14 plant in the first phase of the project, before coupling the DEAHP. Finally, the technologies with theoretical maximum production in Phases I and II, respectively, are compared.

On the other hand, Table 3 compares the solar collectors previously considered with a conventional PTC at similar working temperatures to that of electricity generation systems. Results show a high decrease of solar collector area requirements. Therefore, the cost of DSG and DSGsw collectors could be higher than that of

Table 3
Comparison of different systems with PTC working at inlet and outlet temperatures 225°C and 300°C, respectively (system symbolized by subscript B)

System A	$(qd_A–qd_B)/qd_B$, %	$(A_A–A_B)/A_B$ %
PTC (190/270) – DEAHP	8	−54
PTC (150/230°C)	16	−14
DSG (180°C) – DEAHP	24	−62
DSG (100°C)	38	−31
DSGsw (100°C)	38	−38

conventional PTC without any increasing of the fresh water cost. In addition, since the temperatures required in seawater desalination are lower than 180°C in DSG technology, additional cost savings for solar collector materials may be possible. Moreover, since those temperatures are about 200°C lower than those required in solar electricity generation, an increase in the lifetime of solar collectors may be possible.

4. Conclusions

The case studied here offers the following conclusions:

- Direct steam generation parabolic troughs exhibit great potential for improving the Sol-14 plant.
- The replacing of oil-based technology by DSG presents many advantages from the point of view of thermodynamic, environmental hazard of oils, land use, use of materials or lifetime.

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