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Optimal year-round operation of a concentrated solar energy plant in the south of Europe

Lidia Martín, Mariano Martín*

Departamento de Ingeniería Química, Universidad de Salamanca, Pza. Caídos 1-5, 37008 Salamanca, Spain

HIGHLIGHTS

- Plant design so far relies on process simulation and only partial optimization studies.
- We optimize the operation of a concentrated solar power plant.
- The facility involves solar field, molten salts, steam and electricity generation and cooling.
- The results are promising and validate literature sensitive studies.

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ABSTRACT

We present the year-round optimization of the operation of a concentrated solar power facility evaluating the molten salts storage, the power block and cooling. We locate the plant in the south of Europe, Almería (Spain), where high solar radiation is available. The operation of the plant is a function of the solar incidence as well as the climate and atmospheric conditions. The optimization of the system is formulated as a multiperiod Non-linear Programming problem (NLP) that is solved for the optimal production of electricity over a year defining the main operating variables of the thermal and cooling cycles. For a maximum of 25 MW in summer and a minimum of 9.5 MW in winter the annual production cost of electricity is 0.15 €/kWh consuming an average of 2.1 L_{water}/kWh. The investment for the plant is 260 M€. Scale-up studies reveal that the production cost can decrease by half while the investment per unit of power should become competitive with current coal based power plants if solar and coal facilities present similar production capacities.

1. Introduction

Energy consumption has increased over the last decades. So far, the use of fossil fuels has been convenient due to their availability and easy transformation. However, the depletion of the reservoirs and the increased need for energy demand a change in the current energy supply system [1]. Renewable sources are a valuable alternative. In Fig. 1 we can see the expected increase in the contribution of solar, wind and biomass. Solar energy is an option in regions with high solar irradiation [2]. There are already a number of demonstration plants worldwide [3] whose characteristics in terms of power and technology can be found in the literature [4] including the investment and electricity production cost [5].

In Fig. 2 we present the solar radiation over the Mediterranean Sea region. It can be seen that the solar energy received is only a few kWh/m^2/day. To achieve higher intensities and high operating temperatures Concentrated Solar Power (CSP) technologies can be used. They are based on the concentration of sun radiation to heat up an energy transfer fluid used for steam and electricity production. CSP plants consist of three parts: solar field, steam turbine and cooling unit. Rankine cycles are typically used since they provide efficiency advantages [8]. Moreover, for the continuous operation of these plants during the night and in overcast days, thermal energy from the heat tank or an additional source of energy is typically used [3].

So far only a few studies have dealt with the optimization of the performance of the plant. These studies vary from focusing on the thermal cycle and using different approaches such as sensitivity analysis for the extraction pressure [9] or the exhaust pressure from the turbine [10], evolutionary algorithms [11] or neural networks [12], to mathematical optimization approaches to use solar energy for water desalinization. These last cases consider a Rankine cycle with fixed operating conditions and one expansion alone in the turbine [13], including multiobjective optimization [14]. However,

* Corresponding author. Tel.: +34 923 294479.
E-mail address: mariano.m3@usal.es (M. Martín).

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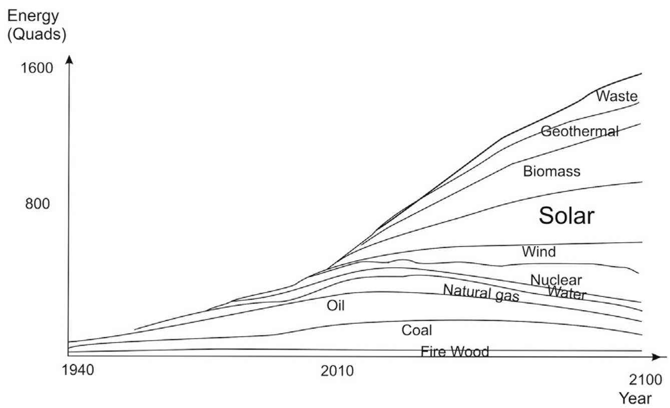

Fig. 1. Energy consumption per source of energy [6].

to the best of our knowledge no one has optimized of the operating conditions of the Rankine cycle nor evaluated the cooling tower operation for the year-round operation of the plant.

In this paper we use mathematical programming techniques for the conceptual optimal design and operation of a concentrated solar power plant over a year based on molten salt technology. We consider the variability in the sun reception, in the freshwater temperature and in the atmospheric conditions. The facility is located in Almería (Spain), a region with one of the highest solar radiations in Europe, see Fig. 2. The paper is organized as follows. Section 2 describes the modeling features and the operating conditions of the selected location. In Section 3 we present the optimization procedure. Next, in Section 4 the main results are discussed such as the major operating conditions, the monthly water consumption of the facility, an economic evaluation and a study on the effect of the plant scale on the production cost and investment per unit of power generated. Finally, in Section 5 we draw some conclusions.

2. Modeling

2.1. Modeling assumptions

The plant consists of three parts, the heliostat field including the collector and the molten salts storage tanks, the steam turbine and the cooling tower [3]. Fig. 3 presents the flowsheet for the process where the heliostat field has not been included. Our process is based on the use of a tower to collect the solar energy and a regenerative Rankine cycle, see Fig. 4. The steam is generated in a system of three heat exchangers where it is first heated up to saturation and then evaporated using the total flow of molten salts. However, only a fraction of the flow of salts is used to superheat the steam before it is fed to the first body of the turbine. The rest is used to reheat up the steam before it is fed to the second body. In the second body of the turbine, part of the steam is extracted at a medium pressure and it is used to heat up the condensate. The rest of the steam is finally expanded to an exhaust pressure, condensed and recycled. A cooling tower is used to condensate this exhaust steam. Each unit is modeled using mass and energy balances as well as thermodynamic properties. The main assumptions can be seen in Table 1.

2.2. Opeating conditions

In Table 2 we present the monthly operating conditions of the plant including the radiation received in Almería, the sun hours, the ambient temperature of the air and water and the air average humidity [15]. We consider as water temperature that of the Mediterranean Sea in that region [16]. It is important to notice that the same formulation can be used for any other region by using the

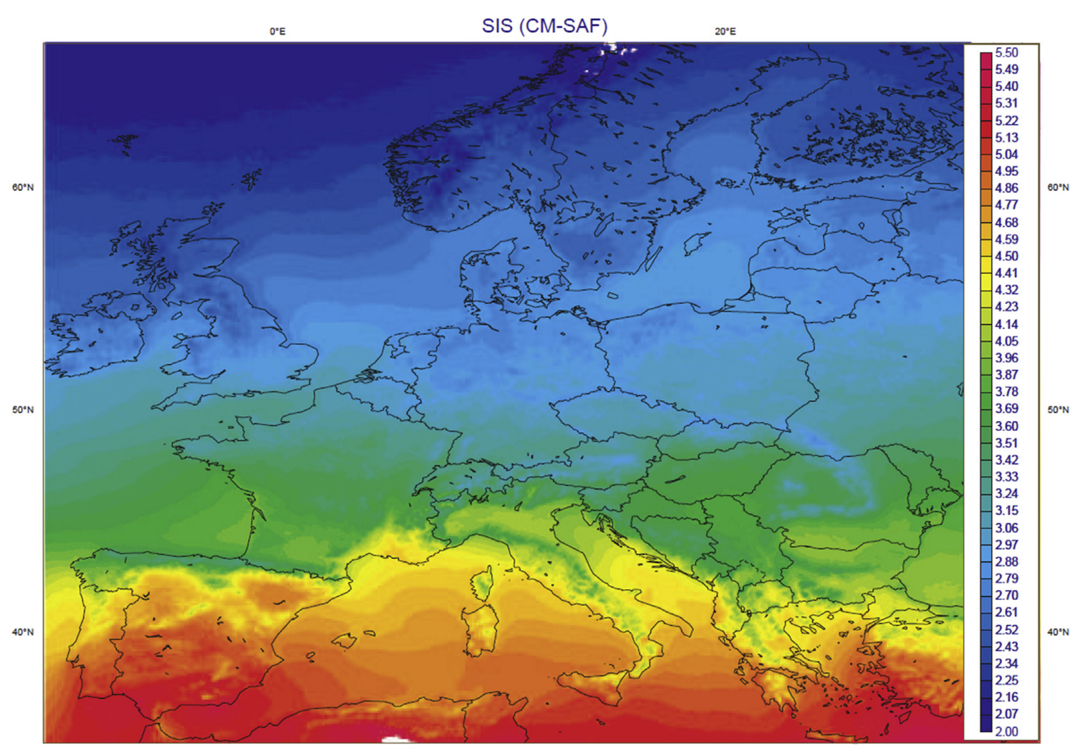

Fig. 2. Radiation in Europe (kWh m^{-2} day^{-1}) [7].