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Optimal integration of a solid-oxide electrolyser cell into a direct steam generation solar tower plant for zero-emission hydrogen production

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HIGHLIGHTS

- Ten integration design strategies of SOEC and DSG–CRS plant were proposed.
- Penalties over the DSG–CRS were reduced by 60%.
- 5.8% overall efficiency improvement of the hybrid plant in the best case.
- Oxygen co-production when a pressure swing adsorption unit is integrated.
- Atmospheric SOEC system improves grid balancing, pressurized ones stand-alone plant.

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ABSTRACT

Steam electrolysis through Solid-Oxide Electrolysis Cell (SOEC) coupled with concentrating solar power (CSP) plants stands for a promising system of large-scale carbon-free hydrogen production process. This study presents an energetic analysis on integration schemes of a SOEC Unit into a direct steam generation solar tower plant. Several configurations have been analyzed aiming at minimizing the penalties of the integration over the CSP plant, and maximizing the electrolysis performance. Atmospheric and high pressure operation modes of SOEC have been analyzed.

The results show that operating the stack at atmospheric pressure, penalties over the solar plant can be reduced by 60% if process steam is extracted from low pressure turbine section and solar plant feed water is preheated with rejected hot streams from the electrolyser. In high pressure SOEC scenarios, although penalties over the CSP plant are increased, the overall performance of the hybrid plant could be improved by 5.8%, and also oxygen could be collected as co-product if a pressure swing adsorption unit is integrated.

1. Introduction

Global warming, local air pollution and external energy dependency have intensified the development of renewable and clean energy sources and fuels along last decades. Singular efforts have been made in the use of hydrogen as energy carrier and energy storage. Hydrogen is a clean fuel able to reduce local CO_2 and pollutants emissions [1,2]. However, to be a true zero-emission energy carrier, hydrogen must be produced through low-carbon processes. Electrolysis systems have a great potential for CO_2-free hydrogen production due to the simplicity of the process and because it can be easily connected with renewable electrical energy systems like wind and solar. Additionally, hydrogen production through electrolysis creates a bridge between power and fuel networks. Thus, hydrogen could be used as a temporary energy storage contributing to grid stabilization, so the penetration of renewable energies can be increased [1].

During the last decades, research has been focused on the development of steam electrolysis through Solid Oxide Electrolysis Cells (SOEC). High temperature electrolysis reduces overpotentials, improves electrodes activity, and requires less electrical energy [3]. Thus, steam electrolysis offers great advantages when it is connected with a high temperature heat source such as geothermal, biomass or solar source. Both requirements, power and heat, can be altogether supplied by a concentrating solar power (CSP) plant. An advantage of CSP plants over wind and photovoltaic systems is the possibility of integrating thermal energy storage (TES) systems, which is able to stabilize power and heat production during transient periods (intrinsic to wind and solar energy). Thus, fast load

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variations over the electrolyser could be avoided, which might increase cells lifetime. Among all CSP technologies, a Direct Steam Generation–Central Receiver System (DSG–CRS) plant was selected to carry out this study based on its maturity and capabilities [4,5].

Integration studies of SOEC systems within different CO_2-free energy sources such as thermal solar, geothermal, biomass, domestic waste, photovoltaic and nuclear power plants can be found in the literature [6–11]. Based on these studies, new integration strategies for a direct steam generation tower plant have been evaluated in order to mitigate the negative influence of the SOEC integration over the solar plant capacity and the optimization of the electrolysis process.

2. System description

A stand-alone solar-hydrogen production plant is studied in this work. It is composed of a 10 MW_e direct steam generation solar tower plant and four SOEC units of 2.5 MW_e each, as shown in Fig. 1. The required power and heat for the electrolysis are exclusively supplied by the DSG–CRS. Power supply covers the electric consumption of the SOEC stack, and the parasitic consumption of the balance of the plant: pump, blowers, compressor, and electric super-heaters. Concerning heat supply, it is required to evaporate the electrolyser feed water, which has been kept independent from the solar plant water/steam line due to possible water quality differences. To evaporate the electrolyser feed water/steam is taken from different points of the solar plant and re-injected into the Rankine cycle as liquid water. Hydrogen produced by the SOEC units is collected, compressed and finally stored through a single system shared by the four electrolysis units.

The study has been performed with EBSILON®Professional. This is a commercial software used to simulate thermodynamic processes, especially for power plants optimization [12,13]. Calculations were performed at design point under steady-state conditions, which in solar system analysis corresponds with 21st of March (spring equinox) at 12 h solar time. It is assumed an ambient temperature of 25 °C, and a relative humidity of 60%. The hybrid plant is supposed to be placed near Seville, Spain.

2.1. Solar plant specifications

A detailed flow diagram of the DSG–CRS implemented in this work is presented in Fig. 2. The plant has been designed following the methodology described in Ref. [14]. It is a solar tower plant with a north oriented heliostat field composed of 646 heliostats. These reflect and concentrate solar radiation over a solar receiver located on top of the tower. The receiver consists of two absorbers vertically aligned (the superheater and the evaporator), with a drum-type boiler placed above the superheater. Steam at the entrance of the turbine is at 70 bar and 550 °C. Solar collector system (heliostat field plus receiver) characteristics are presented in Table 1. Because this is a steady state analysis under nominal conditions, TES system does not stabilize power or heat production. Nevertheless, it reduces the nominal capacity of the solar plant. Thus, the TES has been implemented as a simple steam sink to take into account this effect. The CSP plant has been designed with a solar multiple of 1.3 [6,15].

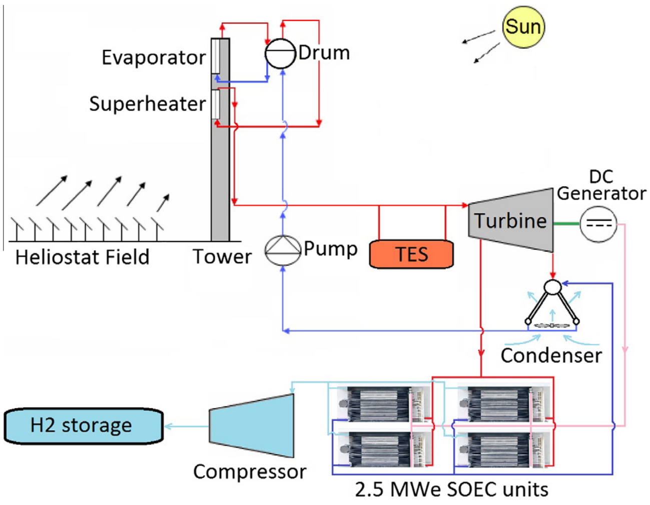

Fig. 1. General scheme of the solar tower-hydrogen SOEC hybrid plant.

Concerning the power block, the Siemens SST-700 steam turbine is used in the model because the amount of data available and its frequent implementation in CSP commercial plants [16]. Due to the short capacity of the plant, a single-case non-reheated turbine is considered. It has three steam extractions that feed three feed water heaters (FWH). Due to the lack of water in high insolation sites, a dry cooling condenser was implemented. Main characteristics of the power block are presented in Table 2.

The extraction of solar steam to supply the electrolyser reduces the steam available for the power block decreasing CSP plant capacity and its efficiency. Therefore, to analyze the influence of the integration over the DSG–CRS plant, the relative variation of the solar plant efficiency ($\Delta\eta_{DSG-CRS}$) is evaluated as follows:

$$\Delta\eta_{DSG-CRS} = \frac{\eta_{DSG-CRS_{SC_i}} - \eta_{DSG-CRS_{ref}}}{\eta_{DSG-CRS_{ref}}} \cdot 100 \tag{1}$$

where $\eta_{DSG-CRS_{SC_i}}$ represents the efficiency of solar plant of scenario "i", and $\eta_{DSG-CRS_{ref}}$ is the reference stand-alone solar plant efficiency. Solar plant efficiency is calculated at nominal conditions, so TES is not taken into account, see Eq. (2).

$$\eta_{DSG-CRS} = \eta_{heliostat\ field} \cdot \eta_{receiver} \cdot \eta_{power\ block} \tag{2}$$

2.2. Electrolysis system description

Based on the transient nature of solar energy systems, it was decided to use four electrolysis units of 2.5 MW_e, which would make easier to adapt production and demand during part-load operation in future studies. Each one of the units has its own balance of the plant (BoP) such as heat exchangers, pumps, blowers and filters; but all units share the so-called hydrogen conditioning sub-system, which consists of a compressor, a hydrogen desiccant system and a storage tank. Each unit has 38,400 cells of 69.3 cm^2 active surface that are assembled into stacks, and they are grouped into modules that form the SOEC unit. A detail description of the unit configuration is given in Ref. [17]. Focused on the optimization of the integration under nominal operation, a zero-dimensional black-box efficiency-based model of the stack has been developed in EBSILON®Professional. The stack operates at 700 °C at the thermoneutral voltage of 1.283 V with a steam conversion of 60%. Under these operational conditions, a stack efficiency of 97.66% versus LHV was assumed based on EU ADEL project results [18]. Within this study, atmospheric and high pressure stack operations have been compared in order to analyze the possible advantages of working at high pressure. Based on the conclusions reported by Jensen et al. [19], negligible effects over the stack performance are expected due to its pressurization. Thus, the same efficiency has been assumed under both operational conditions. In contrast, in the last scenario water/steam is used as sweep gas, then concentration overpotentials decreases increasing the efficiency of the stack to 98.72%.