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Exergetic analysis of hybrid power plants with biomass and photovoltaics coupled with a solid-oxide electrolysis system

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ABSTRACT

This paper studies four hybrid systems that couple a reference –biomass and photovoltaic– power plant with four different structures of a steam electrolysis system for hydrogen production. The four hybrid plants are initially examined incorporating the same capacity components as the reference plant. The integration of different structures of the electrolysis process results in operational penalties when compared to the reference plant, due to added irreversibilities intrinsic to the electrolysis process and the reduction of the biomass plant efficiency from the extraction of low-pressure steam used to evaporate the electrolyzer feed water. The magnitude of these penalties depends on the power consumption of the electrolysis system, thermal demand and/or pressure losses within incorporated plant components. Among the alternative scenarios, the maximum efficiency is achieved when the electrolysis system works with a recycling sweep gas stream further used in the boiler of the biomass power plant. Furthermore, the efficiencies of the electrolysis hybrid plants only surpass that of the reference power plant when the solar irradiation drops to 36–46%. This is a direct result of the lower operational efficiency of the solar panels versus the biomass plant.

1. Introduction

The combination of biomass with PV (photovoltaics) can address problems that characterize the two technologies when they are used separately, such as daily and seasonal fluctuations of photovoltaic production and quality/quantity inconsistencies of biomass stock [1,2]. Advantages of using biomass include, among others, its relatively lower environmental impact and its contribution towards independence from fossil fuels [3]. PV installations operate without atmospheric emissions and are relatively easy to maintain [2]. Furthermore, hydrogen generation and storage options offer a possibility to further regulate the fluctuating output of renewable energy (e.g., [2]).

Water electrolysis is a power-driven process for generating hydrogen through the electrical decomposition of water into hydrogen and oxygen. It can be easily combined with infrastructure based on renewable energy sources. Hydrogen production systems using electricity generated in solar, wind, biomass and other energy conversion systems have been published in numerous studies (e.g., [4–10]). In addition, since 1991 several power-to-gas pilot plants have been constructed for producing hydrogen from renewable energy sources [11]. Most of these plants use alkaline or proton electrolyte membrane electrolyzers for hydrogen generation due to the maturity of this technology. However, the reported power consumption of water electrolysis is still above 4.5 kWh_{el}/Nm^3 of hydrogen [12].

The water split reaction can be described by the Gibbs function, $\Delta G = \Delta H - T\cdot\Delta S$, where ΔH is the overall energy needed, ΔG is the electrical energy and $T\cdot\Delta S$ is the direct heat.

High-temperature SOEC (solid oxide electrolysis cells) systems (HTSE or HT-SOEC) in the range of 800–1000 °C have been studied since the 80s in order to reduce the electrical requirements of the electrolysis process (see Fig. 1) (e.g. [12,14,15]). Operation at high temperature reduces overpotentials and improves the activity of electrodes. As a result, the electricity demand can be reduced to 3.3 kWh_{el}/Nm^3 of hydrogen (at 1000 °C). In addition, higher current

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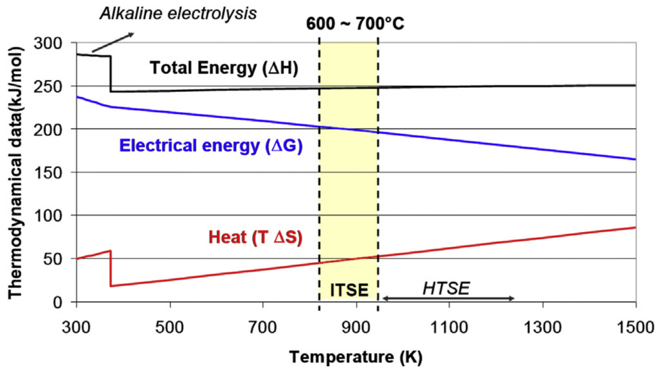

Fig. 1. Free energy diagram of water splitting [13].

densities can be achieved, improving the overall efficiency of hydrogen production and reducing the overall cost and size of the electrolyzer for a given production [12]. The cost can be further reduced if the heat requirement is covered by an external waste heat source [12,16].

However, although high operating temperatures reduce the electrical requirement, they enhance chemical species evaporation and diffusion that reduce the performance and lifetime of the electrolyzer and decrease the mechanical stability of ceramic and metal components [17,18]. HT-SOEC shortcomings are addressed by intermediate-temperature SOEC (ITSE or IT-SOEC) [18]. IT-SOEC follow the trend of solid-oxide fuel cell (SOFC) technology that aims to reduce the operational temperature to 600–700 °C in order to decrease the equipment cost and increase the electrolyzer lifetime, while maintaining satisfactory performance levels [17,18].

2. Materials and methods

This study evaluates the incorporation of different configurations of an IT-SOEC system into a reference PV-biomass power plant using exergetic analysis (e.g. [20,21]). The electricity of the PV panels is used directly in the electrolyzer for the generation of hydrogen, while the electricity generated in the biomass plant is used in the electrolyzer or delivered to the electrical grid, depending on the scenario examined. This work also evaluates the influence of PV capacity on the overall plant efficiency when keeping the capacities of the biomass plant and the electrolyzer constant. Thus, scenarios with acceptable PV-biomass ratios of electricity supply to the electrolyzer, i.e., with better performance than the reference plant, are revealed. This work is based on the FP7 project ADEL that targeted the development of cost-competitive, energy efficient and sustainable hydrogen production based on renewable energy sources [13,19].

For the purpose of the presented work, the developed plants are planned to be located in an area with various chemical installations that rely on hydrogen availability. It is assumed that the hydrogen produced will be supplied to hydrotreatment processes of the refinery “La Rábida” constructed by the company CEPSA and located on the west side of the province of Huelva in Spain [22]. Moreover, Huelva has significant biomass resources, produced both as a crop and as vegetable-matter wastes and by-products. The importance of biomass plants in the region is also proven by the fact that ENCE, Spain's leading company in biomass-fueled renewable energy generation, already operates a large biomass power plant in the area with an electricity production of 68 MW_{el} [23].

The simulations are carried out at steady state conditions and they are performed using commercial software (EBSILONProfessional, [24]).

2.1. Reference PV-biomass power plant

The reference power plant is a hybrid structure of a biomass plant with PV panels that generates 6.8 MW_{el}. The PV array generating 2.5 MW_{el} is based on the BP model 4180T and operates with an efficiency of 14.4%. The biomass power plant is a conventional steam power plant with direct combustion of biomass generating 4.3 net MW_{el}. The configuration of the reference power plant can be seen in Fig. 2.

The biomass plant uses 26.7 kton/year of hybrid poplar wood chips with a weight composition (dry) of 50.2% C, 6.06% H, 40.4% O, 0.6% N, 0.02% S, 0.01% Cl and 2.7% ash [25]. The biomass (Stream 2 of Fig. 2) is combusted with air in the boiler of the plant, providing thermal energy to convert water to superheated steam. The combustor of the biomass is assumed to be a second generation circulating fluidized bed boiler [26].

Steam generated at 80 bar and 550 °C (Stream 6) is expanded in the 3-pressure level steam turbine (ST) of the plant. One reheat stage is included before the intermediate-pressure steam turbine in order to increase the power output and the efficiency of the plant. At the last level of the steam turbine, the steam is expanded to 0.05 bar and it is led to the condenser (COND) of the plant (Stream 12). The saturated stream exiting the condenser (Stream 13) is passed through pumps and feedwater heaters entering the boiler at a temperature of 230 °C (Stream 5).

2.2. Electrolyzer unit

The electrolyzer has been incorporated in all four hybrid scenarios examined; Its nominal power consumption is 500 kW_{el} and it consists of 110 parallel stacks, each one of which requires 4.5 kW. Defined and agreed upon among partners of the FP7 project ADEL [13], it is assumed that the electrolysis cells are working at thermoneutral voltage, at a temperature of 700 °C, with a steam conversion rate in the cathode chamber of 61%, and a molar ratio between the anode and cathode of 1:1. Under these operational conditions, the overall energy efficiency of the electrolyzer, defined as the ratio between the lower heating value of the generated hydrogen and the stack power needed to perform this task, is 97.2%.

2.3. Initial layout of the electrolysis system

In this study, a 2.5 MW_{el} electrolysis (IT-SOEC) system composed of 5500 kW-electrolyzers is simulated. This IT-SOEC system has been examined in four configurations (four scenarios). The operating conditions (Table 1), including pressure losses, efficiencies, minimum temperature differences, etc. of the electrolysis system are based on assumptions agreed upon by partners of the FP7 project ADEL [13].

The initial layout of the IT-SOEC system consists of two loops (Fig. 3). The first loop, which starts with Stream 46, provides the water entering the cathode side of the electrolysis process. In the second loop, atmospheric air (Stream 30) is used as sweep gas to remove the produced oxygen from the anode side of the electrolysis system.

In the first loop, the make-up water is pumped from 1.01 to 1.09 bar to overcome the pressure drops within the following components. The water is heated in shell-and-tube heat exchangers HX1 and HX2, the latter of which uses as thermal source steam extracted from the Rankine cycle of the biomass power plant. Mixer M2 mixes the make-up steam with Stream 42 (hydrogen-rich gas) to obtain a cathode inlet mixture of 10% v/v hydrogen and 90% v/v steam (Steam 43). Heat exchanger HX3 (shell-and-tube) raises the temperature of the inlet steam/hydrogen mixture using as thermal source the exhaust cathode stream of the electrolysis system.