Pilot plant for hydrogen production using high-temperature solid oxide electrolyser and solar heat and power

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Abstract

This work presents the design of a pilot plant for hydrogen production that integrates a high-temperature Solid Oxide Electrolyser (SOE) with solar heat and power. SOE operates at around 750 ºC and requires a balance of plant (BoP) to ensure this condition. Operating at high temperatures also requires less electricity, consequently making the SOE highly efficient. The process flow diagram (PFD) of the integrated plant consists of two main subsystems: (i) BoP of the SOE and (ii) BoP of the solar field. The coupling between these two systems is done in the steam generator. The heat from the solar field and the storage system is used to generate the steam supplied to the electrolyser, and the required electricity is from PV plant and electrical grid. The integrated plant was analysed for four operation models: full, partial, hot standby and night modes. The analysed plant uses a SOE with a capacity of 9 kWe, and at full load will consume 3.7 kg h^{-1} of steam, and produce 0.24 kg h^{-1} of hydrogen.

Keywords: green hydrogen, solid oxide electrolyser, solar thermal energy, thermal storage, balance of plant

1. Introduction

This work is part of the GREENH2-CM project [1], which is aligned with the strategic positioning of the Comunidad de Madrid in R&D&I for green hydrogen and fuel cells. Figure 1 shows the process flow diagram (PFD) developed for the pilot plant, integrating two main subsystems: (i) the balance of plant (BoP) of the Solid Oxide Electrolyser (SOE) and (ii) the BoP of the solar field. The BoP of the solar field primarily consists of the solar collectors, a thermocline storage tank, and two electrical heaters. The BoP of the SOE comprises the SOE itself, two heat exchangers, three electrical heaters, a blower, a mixer, and the conditioning of the hydrogen section. The connection between the BoP of the solar field and the BoP of the SOE occurs in the steam generator.

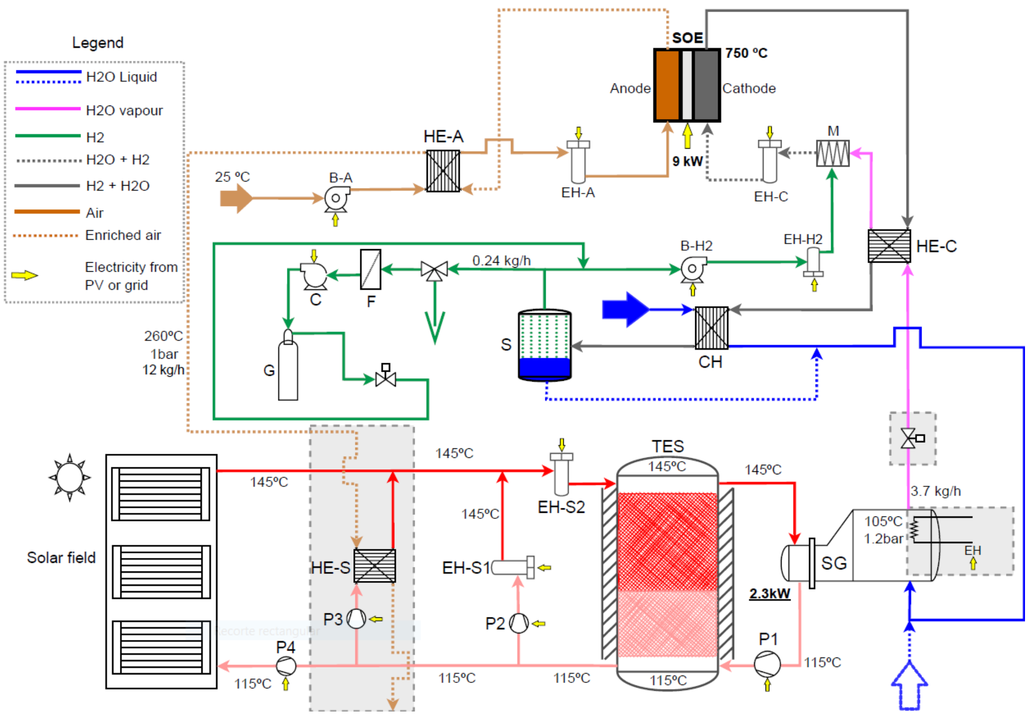

Fig. 1: PFD of the integrated system of high-temperature solid oxide electrolyzer and solar heat and power.

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An efficient integration of SOE with solar heat and solar power leads to high sun-to-hydrogen efficiencies, thanks to the higher efficiencies of SOE. The main challenge of this project is to achieve an efficient integration of the non-programmable solar energy source with the SOE, which requires very stable operating conditions. This integration involves using solar concentration systems to supply heat to the steam generator and electricity from PV plants to power the SOE and the different components of the PFD. The plant will use an electrolyser with a capacity of 9 kWe manufactured by SolydEra, and at the design point (full load), it will consume 3.7 kg h^{-1} of steam and produce 0.24 kg h^{-1} of H_2. Table 1 summarizes the design conditions of the SOE. The thermal solar collectors are being manufactured and supplied by SEENSO, and the storage system is being developed by the IMDEA Energy Institute. Electric heaters are used when temperature adjustments are needed and when there is no available energy in the storage system. The prototype will be assembled at the IMDEA Energy premises in Móstoles, Madrid, Spain.

Tab. 1: Technical specifications of the SOE under design conditions (full load).

Technical specifications	Value
SOE power (kWe)	9.0
Steam conversion (%)	60%
Inlet temperature of the gases (°C)	771
Outlet temperature of the gases (°C)	751
Steam inlet flow rate (kg h^{-1})	3.70
Volume fraction of H_2 at inlet (%)	10
Air inlet flow rate	28
Operating temperature (°C)	760
Maximum working pressure (mbarg)	100

1.2. Solar collector

The solar collector analysed in this work consists of a combination of an evacuated tube solar collector and two north-south tracking mirrors, as described in Figure 2. The purpose of the mirrors is to provide a solar concentration of around 1.7 (depending on the time and season), which allows for higher temperatures for water evaporation. Since the solar concentration is low, it is also possible to utilize the diffuse radiation component. The collector has a normal incidence aperture area of 22.5 m² (absorber surface and the projection of the mirrors on the absorption plane), operates with a temperature difference of 30 °C (115 °C - 145 °C), and uses pressurized water at 4 bar as working fluid.

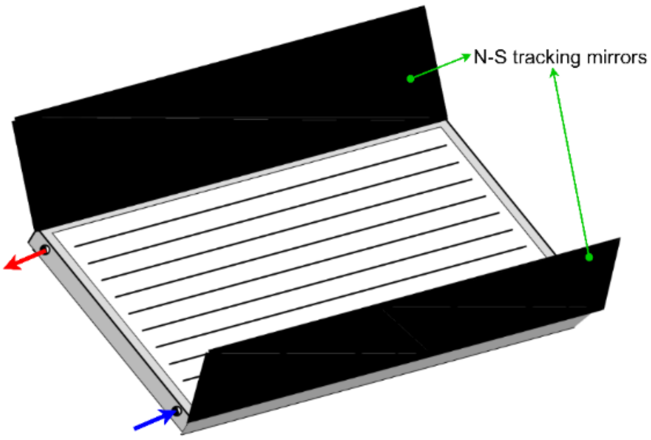

Fig. 2: Evacuated solar tube collector with N-S tracking mirrors.

1.2. Thermal storage system (TES)

The thermal storage system consists of a thermocline packed-bed with encapsulated phase change materials, as shown in Figure 3. In addition to storing heat, the storage tank also plays a crucial role in maintaining stable operation of the steam generator, a requirement imposed by the SOE.

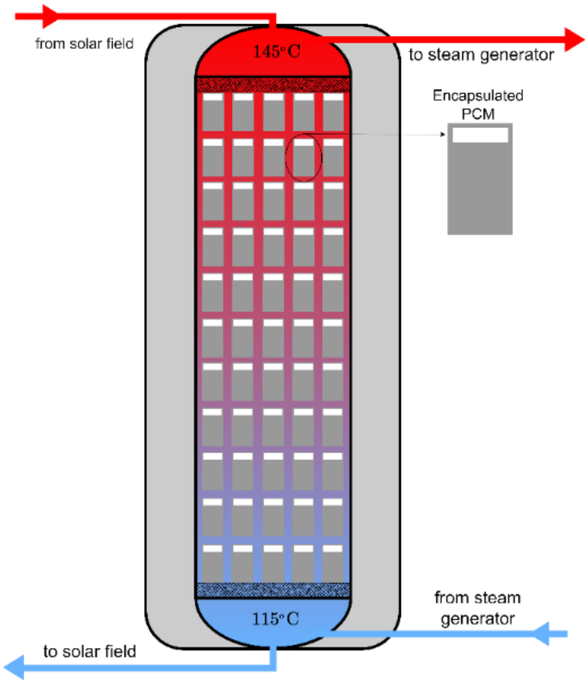

Fig. 3: Thermocline of a packed-bed with encapsulated phase change materials.

2. Methodology

To construct the prototype, it is necessary to size, test, and integrate all components. In this context, an initial step comprises conducting a numerical analysis of the demo plant to obtain energy and mass balances for all the components in the PFD (Figure 1). The numerical model is based on solving the mass and energy conservation equations for each component using EcosimPro software (v6.4) [2]. After validation of the simulation results, they were used as a reference for the sizing of the components. Furthermore, sizing considerations included four operation modes: full load, partial load, hot standby, and night modes.

3. Results

Table 2 and Table 3 present the energy and mass balance in the anode and cathode sides of the electrolyser, respectively, for full, partial, hot standby and night operation modes. In addition, the thermal and transport properties for all streams are also known, which are necessary for the design and sizing of the different components. Regarding the hot standby mode, the SOE stack is off (no power, no steam consumption, no hydrogen production), but it is maintained hot by circulating air and fuel. Regarding the night mode, the same working temperature of hot standby is considered in the night mode, but in the cathode side it is applied a mass flow rate of a mixture of Nitrogen and Hydrogen of 0.8 kg h^{-1}, which implicates changes in the BoP of cathode for this mode. Table 4 shows the thermal of electrical power consumed or dissipated in each component of the BoP of the electrolyser for the four operation modes.

Tab. 2: Energy and mass balance in the anode side of the electrolyser for the different operation modes.

	Full load		Partial load		Hot standby		Night mode	
	In	Out	In	Out	In	Out	In	Out
Temperature (°C)	771	751	726	701	726	701	726	701
Flow rate (kg h^{-1})	27.92	29.89	27.92	29.00	27.92	27.92	27.92	27.92
Composition	N_2 (78%) O_2 (22%)	N_2 (73%) O_2 (27%)	N_2 (78%) O_2 (22%)	N_2 (75%) O_2 (25%)	N_2 (78%) O_2 (22%)	N_2 (78%) O_2 (22%)	N_2 (78%) O_2 (22%)	N_2 (78%) O_2 (22%)

Tab. 3: Energy and mass balance in the cathode side of the electrolyser for the different operation modes.

	Full Load		Partial load		Hot standby		Night mode	
	In	Out	In	Out	In	Out	In	Out
Temperature (°C)	771	751	726	701	726	701	726	701
Flow rate (kg h^{-1})	3.75	1.77	1.75	0.67	0.65	0.65	0.80	0.80
Composition (%)	H_2O (90) H_2 (10)	H_2O (36) H_2 (64)	H_2O (90) H_2 (10)	H_2O (27) H_2 (73)	H_2O (90) H_2 (10)	H_2O (90) H_2 (10)	N_2 (80) H_2 (20)	N_2 (80) H_2 (20)

Tab. 4: Thermal/electrical power in each component for the different operating modes.

Component	Description	Heat/Power (kW)			
		Full load	Partial load	Hot standby	Partial load
SOE	Electrolyser	9.00	4.75	0.00	0.00
EH-A	Anode electrical heater	1.62	1.43	1.47	1.47
EH-C	Cathode electrical heater	0.43	0.18	0.07	0.22
HE-A	Anode heat exchanger	5.00	4.70	4.67	4.67
HE-C	Cathode heat exchanger	1.10	0.48	0.18	-
SG	Steam generator	2.30	1.10	0.39	-
EH-H2	Hydrogen electrical heater	0.04	0.02	0.01	-
CH	Chiller	-1.38	-0.50	-0.52	-

The solar field and thermal storage system were sized aiming that the number of hours in which the SOE has been working with heat directly discharged from the thermal storage vs. total hours is higher than 40%. It is found that the pressure at which water is evaporated in the steam generator plays a crucial role in the integration of solar heat (solar field, storage system, and steam generator). The pressure required in the electrolyser is limited to around 40 mbarg and must remain very stable. To ensure this condition, it is found that the water should be evaporated at a pressure higher than the required pressure in the SOE. This value should consider the pressure drop of the steam across all components between the steam generator and the SOE, and it should also account for a lamination process after the steam generator to prevent condensation.

Figure 4 shows the total monthly energy produced by the solar collector mounted horizontally, using the typical meteorological year (TMY) for Cuatro Vientos (Madrid), Spain [3], the nearest meteorological station to the plant location (approx. 11 km). The simulations resulted in a solar heat contribution for steam generation of 43%, corresponding to an annual heat production of 8700 kWh with a thermal efficiency of 23%. Regarding the KPIs related to the BoP of the SOE, a conversion efficiency of 38.7 kWh/kgH_2 and 84.4% (based on LHV) are obtained. For details of definition and values of calculated KPI see Table 5.

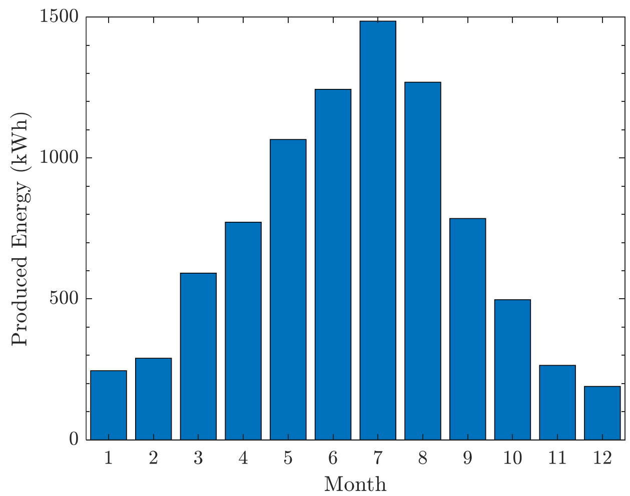

Fig. 4: Monthly thermal energy produced by the horizontally mounted solar collector for the location of Cuatro Vientos (Madrid), Spain.

Tab. 5: Key Performance Indicators obtained with EcosimPro simulation for the full-load operation mode 24/7

Key Performance (KPI)		Calculation	Simulation (Full load)
ID	**Definition**		
H_2 kg/day	Maximum hydrogen production rate at full-capacity	H_2_prod (kg/h) * 24 h/day	**5.8 kgH_2/day**
Eff %	Power-to-hydrogen energy conversion efficiency of heat-integrated SOE system (LHV basis)	(H_2_prod (kg/h)*LHVH_2)/(P_in_SOE + P_In_Anode_EH + P_In_Cathode_EH)	**84.4%**
Eff-w	Power-to-hydrogen conversion efficiency of the heat-integrated SOE system	(P_in_SOE + P_In_Anode_EH + P_In_Cathode_EH)/H_2_prod	**38.7 kWhe/kgH_2**
F-Solar	Hours in which the SOE has been driven with steam directly discharged from CST vs. total hours	(Total solar steam kWh_{th} used)/(Total steam kWh_{th} required)	**43%**

4. Conclusions

This work presents a design of a pilot plant that integrates a high-temperature Solid Oxide Electrolyser (SOE) with solar heat and power for hydrogen production. The solar field and thermal storage system were designed to ensure that the number of hours during which the SOE is supplied with heat directly discharged from the thermal storage relative to the total hours exceeds 40%. The energy and mass balance in all the components of the process flow diagram is obtained for full, partial, hot standby and night operation modes. It is found that the pressure at which water is evaporated in the steam generator plays a crucial role in the integration of solar heat (including the solar field, storage system, and steam generator). The pressure required in the electrolyser is limited to around 40 mbarg and must remain very stable. To meet this condition, it was determined that water must be evaporated at a pressure higher than the required pressure in the SOE. This value should account for the steam pressure drop across all components between the steam generator and the SOE, and it should also consider a throttling process after the steam generator to prevent condensation. Regarding the KPIs, a conversion efficiency of 38.7 kWh/kg H_2 and 84.4% (based on LHV) were achieved and a solar steam fraction of 43% is obtained considering a 24/7 operating strategy.

5. Acknowledgments

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6. References

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