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Techno economic design of a solid oxide electrolysis system with solar thermal steam supply and thermal energy storage for the generation of renewable hydrogen

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ABSTRACT

The dependency of renewable energy systems on environmental influences such as sun or wind availability is one of the greatest challenges in the energy transition. For this purpose, it is important to develop electro chemical storage systems for long-term storing of renewable electricity in the form of hydrogen or methane. In the presented work, an electrolysis system with solid-oxide electrolyser stacks is designed. A solar thermal receiver is used to produce the steam supplied to the electrolyser stacks. On the other hand, a thermal energy storage, using a phase change material, is used for the extension of the operational hours during the night time. The system is optimized to minimize the levelized costs of hydrogen and compared to a system without a thermal energy storage. Finally, the cost sensitivity for the four main components of the cost structure is evaluated and discussed.

Introduction

The production of hydrogen is a suitable possibility for storing renewable energy from wind farms or photovoltaic systems for a medium to long-term period, i.e. in the range from a few days up to several months. For this purpose, an electrolysis system is used for the generation of hydrogen. This hydrogen can be used for the mobility sector, basic material chemistry and can be fed into the gas grid in form of hydrogen or methane. As the last option, it is also possible to use the storage capacity of the gas grid for a shifted supply of

Abbreviations: ASR, Area specific resistance; CAPEX, Capital expenditures; CSP, Concentrating solar power; DNI, Direct normal irradiance; EPC, Engineering-procurement-construction; HHV, Higher heating value; HTF, Heat transfer fluid; HTX, Heat exchanger; IAM, Incidence angle modifier; LCOH, Levelized costs of hydrogen; LHTES, Latent heat thermal energy storage; OPEX, Operational expenditures; PCM, Phase change material; SC, Steam conversion; SF, Solar field; SOEC, Solid oxide electrolysis cell; TES, Thermal energy storage; TMY, Typical meteorological year; TTD, Terminal temperature difference.

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Nomenclature

a_{HL}	Heat loss parameter absorber ($W\ m^{-2}\ K^{-2}$)
A_{nom}	Nominal collector area (m^2)
A_{stack}	Active stack area (cm^2)
$\cos(\theta_i)$	Cosine losses of solar collector
C_{CAPEX}	Capital expenditures (EUR)
$C_{Electricity}$	Electricity costs ($EUR\ a^{-1}$)
C_{LCOH}	Levelized costs of hydrogen ($EUR\ kWh^{-1}$)
C_{OPEX}	operational expenditures ($EUR\ a^{-1}$)
f_{AN}	Annuity factor
f_{ASR}	Area specific resistance factor ($\Omega\ cm^2$)
f_{foc}	Percentage of field in focus
f_{SC}	Steam conversation factor
F	Faraday constant ($96,485.34\ C\ mol^{-1}$)
G_{DNI}	Direct normal solar irradiance ($W\ m^{-2}$)
h_{HHV}	Higher heating value of hydrogen ($285,840\ J\ mol^{-1}$)
i	Interest rate (%)
j_{stack}	Current density ($A\ cm^{-2}$)
$K(\theta_i)$	Incidence angle modifier of solar collector
M	Molar mass ($kg\ kmol^{-1}$)
n	Payout time (a)
$\dot{n}$	Molar flow ($kmol\ s^{-1}$)
p	Partial pressure (bar)
p_{cell}	Average cell pressure (bar)
p_{std}	Pressure at standard conditions ($1013.25\ bar$)
P	Electrical power (kW)
$\dot{Q}$	Heat flow (kW)
R	Universal gas constant ($8.314\ J\ mol^{-1}\ K^{-1}$)
T	Temperature (K)
T_{abs}	Average absorber temperature (K)
T_{cell}	Average cell temperature (K)
T_{env}	Temperature of the environment (K)
U_{nernst}	Nernst voltage (V)
x	Molar gas fraction
$\Delta_r G_T$	Gibbs free energy change of reaction
$\Delta_r H_T$	Enthalpy change of reaction
$\Delta_r S_T$	Entropy change of reaction
ε	Empiric value for area specific resistance calculation
η	Efficiency
θ_i	Incidence angle of solar collector

electrical energy by the use of renewable hydrogen in fossil fired power plants. The use of renewable electricity from the electricity grid by an electrolysis system extends the share of renewable energy sources.

One possible way for the realization of power-to-gas is the electrolysis of water to hydrogen using a solid oxide electrolysis cell (SOEC), as discussed by Gahleitner [1]. Working at high temperature (above 600 °C) allows: (i) providing part of the energy needed thermally and not electrically, possibly from waste heat, (ii) generating directly pure hydrogen in important quantities, (iii) using cheap catalyst such as nickel instead of expensive platinum (see the work of Nechache et al. [2]). In the work of Henke et al. [3] the behavior of a pressurized SOEC and the pressure dependency of the water electrolysis are described. It was concluded that with increasing pressure, more electrical energy is needed for the separation of hydrogen and oxygen. Sanz-Bermejo et al. [4] investigated three SOEC systems under several operational modes and part load conditions. They summarized that the system performance is maximized when the SOEC is operated with a constant steam conversion rate. The thermoneutral operational mode was identified to provide almost constant cell conversion efficiency over the complete operational range. Due to this operational mode, the temperature gradient between the inlet and the outlet of the SOEC at both the cathode and the anode is eliminated, which minimizes the thermal stress of the SOEC.

Coupling of a SOEC with concentrating solar power (CSP) power plant, like discussed in the work of Monnerie et al. [5], can reduce the electricity demand of the SOEC from the grid to less than 5% of the annual operating time. This approach requires a large CSP-Power plant and other renewable electricity can only be used in a small amount from the grid. Josi et al. [6] concluded in their work that an electrolyser coupled with a CSP system would achieve a higher exegetic efficiency and sustainability index compared to a photovoltaic system. One of the main problems of the SOEC is the integration options of an external steam supply, discussed by AlZahrani et al. [7]. The integration issue of a suitable steam supply was the main idea for the presented work.

This paper presents the techno-economic design of a SOEC system. Integrating solar thermal power aims at reducing the electrical power demand of the proposed system by the direct use of thermal energy from a solar field (SF) for the evaporation of preheated water. A thermal energy storage (TES) system is used for the enhancement of the annual hydrogen production of the electrolyser. By a parametric study, the optimal TES capacity and the SF size are determined by minimizing the levelized costs of hydrogen (LCOH). Finally a sensitivity study for the four main cost shares is presented and discussed in this paper. The designed system combines the advantages from CSP and SOEC systems to reach low LCOH and create a system which needs only a small SF and uses all kinds of renewable electricity from the grid. Additionally the impact of a new storage technology, which is currently under development, to the SOEC electrolysis system is evaluated and discussed.

Methods and system description

The SOEC system (see Fig. 1) is operated at its thermoneutral operational mode: both inlet and outlet temperatures of the cathode and anode streams are not modified by the chemical reaction and the electricity demand of the SOEC. The water provided is evaporated by a CSP receiver and is forwarded as saturated steam to the SOEC during the production of hydrogen from the SF. A latent heat thermal energy storage (LHTES) with a phase change material (PCM) is used to provide saturated steam during the night and cloudy periods. Renewable power from the electricity grid is used to power the SOEC. The generated hydrogen is dried, compressed and stored for different applications with hydrogen demand.

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