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Techno-economic analysis of hydrogen production by solid oxide electrolyzer coupled with dish collector

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ABSTRACT

Hydrogen is considered as one of the best alternatives for fossil fuels, especially when it is produced using renewable energy resources. In this paper, dish collector is used to provide the required energy of a solid oxide electrolyzer cell (SOEC) to produce hydrogen. Since dish collectors operate at high temperature, they would be an ideal match for high temperature electrolyzers. These electrolyzer cells need both thermal and electrical energy to produce hydrogen. A compressed air energy storage (CAES) system is used to produce electricity. To reduce its fuel consumption, it is combined with a dish collector. Another dish collector is also used to produce thermal energy. To analyze the system, both thermodynamic and economic analyses are conducted. The results showed that the system could produce 41.48 kg/day hydrogen. It is shown that efficiency of the power cycle and the electrolyzer cell is equal to 72.69% and 61.70%, respectively and levelized cost of hydrogen is 9.1203 $\$/kg_{H_2}$. To study the effect of key parameters on the system performance, sensitivity analysis is performed. It was concluded that maximum and minimum pressure of air cavern in the CAES system have the highest effect on the levelized cost of hydrogen. Also higher operating temperature of the electrolyzer cell benefits the system both thermodynamically and economically.

1. Introduction

Currently, fossil fuels are the most dominant source of energy as they supply almost 80 percent of world total primary energy. Utilization of these fuels have led to huge environmental problems such as global warming, acidification, etc. To alleviate the situation, researchers tried to find new sources of energy which do not produce any contaminant. The fact that fossil fuels are an exhaustible source of energy and one day they would finish, increased the importance of finding a new energy carrier. In this respect, hydrogen is suggested as an alternative for fossil fuels. The most important advantages of hydrogen are its high energy conversion efficiency, different forms of storage, ability of transportation [1], its near zero emission combustion [2], etc. Hydrogen is converted to electrical power in the fuel cells with high efficiency [3].

There are different methods which could be used for hydrogen production. A comparison between different methods is performed by Holladay et al. [4]. Currently, natural gas steam reforming (48%), oil reforming (30%), coal gasification (18%) and water electrolysis (3.9%) are the most common methods for hydrogen production [5]. It should be mentioned that there are some other methods such as dark fermentation, thermochemical conversion cycles, plasma arc decomposition, etc. Also chemical looping hydrogen production systems as one the methods have been developed [6,7]. But most of these methods are at development stages and none of them are yet practical. Since hydrogen is going to be used as an alternative for fossil fuels, it is suggested to shift toward the electrolysis process, because it does not use fossil fuels to produce hydrogen. Also the purity of hydrogen produced in this method is very high [8].

Electrolysis process is exactly the opposite of the fuel cell operation. While in fuel cells, hydrogen is consumed to produce water and electricity, in an electrolysis process, electricity and water are used to produce hydrogen. The reaction which occurs in electrolysis to produce hydrogen is shown below:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

Bhandari et al. showed that the main environmental concern in electrolysis process is related to the electricity supply [9]. Consequently the required electricity should be provided by renewable sources. Different kind of renewable energy sources could be used to produce the required electricity such as wind energy [10], solar energy [11,12], geothermal energy [13], etc. The problem with most renewable energy sources is that they could produce energy in specific locations. But solar

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Nomenclature

A	area [m^2]
B_g	flow permeability
C_p	specific heat capacity [kJ/kg K]
d_a	anode thickness [m]
d_c	cathode thickness [m]
$\dot{E}$	energy [kW h]
$E_{act,i}$	activation energy for electrodes
E_{Nernst}	nernst potential
F	faraday constant [sA/mol]
g	gravitational acceleration [m/s^2]
h	specific enthalpy [kJ/kg], convective heat transfer coefficient [W/m^2 K]
H	total annual working hour [h]
I	direct normal insolation per unit of collector area [W/m^2]
i	interest rate
J	current density [A/m^2]
k	thermal conductivity of the ambient air [W/mK]
L	length [m]
$LCOH$	levelized cost of hydrogen [$/kg]
LHV	lower heating value [kJ/kg]
$\dot{m}$	mass flow rate [kg/s]
$\dot{N}$	molar flow [mol/s]
Nu	Nusselt number
P	pressure [bar]
Pr	Prandtl number
$\dot{Q}$	heat [kW]
R	universal gas constant [J/mol K]
Ra	Reighley number
R_p	cavern inlet pressure
r_p	pressure ratio of compressor
RTE	round trip efficiency
S	entropy [kJ/K]
T	temperature [K]
t	time [h]
V	volume [m^3], volt [V]
W	power [kW]
Z	cost [$]

Greeks

α	thermal diffusivity [m^2/s]
γ	ratio of specific heats
η	efficiency
κ_i	pre-exponential factor for electrodes
μ	dynamic viscosity [Pa s]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
σ	Stefan-Boltzmann constant
ϵ	radiative emissivity

Subscripts

a	air
comp	compressor
w	water
f	fuel
CC	combustion chamber
g	flue gas
GT	gas turbine
elec	electricity
u	useful
amb	ambient
cond	conduction
conv	convection
rad	radiation
act	activation
conc	concentration
ohm	ohmic
O&M	operation and maintenance
cw	cooling water

energy is the most promising option as it could be used almost everywhere. Different types of electrolyzer based on the renewable energy sources are investigated [14].

There are three different technologies for dissociation of water in electrolysis process including alkaline, polymer membrane (PEM) and solid oxide [15]. The first two technologies only need electricity and their operating temperature is low. They are also quite mature and most of the current electrolysis plants are based on one of these two technologies. Carmo et al. performed a review on PEM electrolyzer cells [16]. El-Emam et al. [17] proposed a multi-generation system based on solar energy to produce power, hot water, cooling and hydrogen simultaneously. They used PEM electrolyzer in their system.

Khalilnejad et al. [18] coupled an alkaline electrolyzer with a hybrid photovoltaic-wind system to produce hydrogen. They optimized the system using imperial competitive colony algorithm to maximize hydrogen production with minimum excess power usage. Kiaee et al. [19] analyzed the same system for a hydrogen fueling station in Norway.

Unlike PEM and alkaline cells, solid oxide electrolyzer needs both thermal and electrical energy and its operating temperature is very high. Also its efficiency is higher. Since its operating temperature is very high, SOEC receives a part of the required energy for water splitting in the form of heat. Consequently, its required electrical energy is lower. In other words, total energy demand is constant and with increasing temperature, required electricity reduces and required thermal energy increases. This behavior is shown in Fig. 1.

This feature makes it easier to integrate this type of electrolyzer with solar energy. Because solar energy could be used to produce both thermal and electrical energy for the electrolyzer. Usually photovoltaic (PV) modules are used to produce electricity, while solar thermal collectors are used for providing thermal energy. Ngoh et al. [20] analyzed a large scale hydrogen production system based on solar energy. They used PV modules for producing electricity and parabolic trough

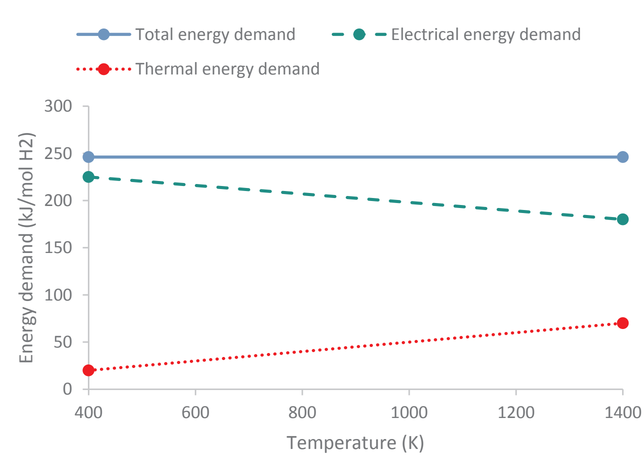

Fig. 1. Total energy, electrical energy and thermal energy required for electrolysis process in solid oxide electrolyzers [19].