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Modeling and performance optimization of a solid oxide electrolysis system for hydrogen production

Abdullah A. AlZahrani[a,b,*], Ibrahim Dincer[a]

[a] Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario L1H 7K4, Canada
[b] Department of Mechanical Engineering, College of Engineering and Islamic Architecture, Umm Al-Qura University, Al Abdeyah, Makkah 5555, Saudi Arabia

HIGHLIGHTS

- A 1 MW Solid Oxide Electrolysis (SOE) system is proposed for hydrogen production.
- The SOE system operates without external heat for renewable hydrogen applications.
- Energy and exergy parametric studies considering all BOP components.
- Variations in exergy destructions within the stacks and BOP are investigated.
- The SOE system design and performance is exergetically optimized.

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ABSTRACT

This article presents electrochemical and thermodynamic modeling and optimization of a high temperature solid oxide electrolysis (SOE) system for hydrogen and oxygen production. High temperature electrolyzers offer the significant advantage of high conversion efficiency compared with low temperature electrolyzers. However, the high operating temperatures limit the SOE utilization to resources where high temperature steam is externally provided, such as in nuclear and concentrated solar power plants. Herein, we report the design and thermodynamic performance of an SOE system at a capacity of 1 MWe, from which various renewable electricity resources can be utilized to produce hydrogen and oxygen from water. In order to investigate the standalone operation and eliminate the need for external heat, the SOE is examined while operating in an exothermic mode, where heat is internally generated, and in an endothermic mode, where heat is provided by electric heaters. Additionally, a network of heat exchangers is optimized to increase the system efficiencies and enable an efficient standalone operation. Thus, the SOE system can be adapted for renewable hydrogen production applications, such as wind and Photovoltaic (PV) farms. The influences of operating conditions on efficiencies, power demand, and exergy destruction rates of the SOE system are assessed, including a case of 15 MPa hydrogen storage. The energy and exergy efficiencies of the SOE system are obtained as 85.15% and 83.41%, respectively. Sensitivity and optimization analyses are also conducted in order to highlight SOE stability and optimum performance.

1. Introduction

Although hydrocarbon burning and fossil fuel-based energy systems are responsible for emitting a significant amount of greenhouse gases, including carbon dioxide that negatively impacts the environment [1], fossil fuels are still the dominating resources that power most of today's technologies [2]. Renewables, such as wind energy, have experienced considerable growth during the last two decades, but the variable nature of these resources presents many obstacles to grid operators [3]. In this regard, hydrogen, as a clean energy carrier, is one of the most promising solutions that can support renewables in replacing conventional fossil fuels and reducing carbon emissions since hydrogen reacts with oxygen in fuel cells to produce electricity and water. As a result, the fuel's chemical energy is directly converted to electricity at higher efficiency and in a more environmentally benign manner compared with conventional systems, such as internal combustion engines. Furthermore, the implementation of hydrogen-based transportation will reduce air pollution and result in better air quality. However, a major

* Corresponding author at: Department of Mechanical Engineering, College of Engineering and Islamic Architecture, Umm Al-Qura University, Al Abdeyah, Makkah 5555, Saudi Arabia.
E-mail address: aarzahrani@uqu.edu.sa (A.A. AlZahrani).

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Nomenclature

A	area (m^2)
AC	alternating current
ASR	area specific resistance ($\Omega\,cm^2$)
BOP	balance of plant
CO	converter
DC	direct current
E	cell potential (V)
EES	engineering equation solver
EH	electric heater
$\dot{E}x$	exergy rate (W)
F	Faraday's constant, ($F = 96{,}487\,C^{-1}\,mol^{-1}$)
h	enthalpy ($kJ\,kg^{-1}\,K^{-1}$)
HE	heat exchanger
J	current density ($A\,m^{-2}$)
LHV	lower heating value ($kJ\,kg^{-1}$)
LSM	lanthanum strontium manganite
n	number of transferred electrons
OC	oxygen circulation blower
OCV	open circuit voltage
P	pressure (kPa); pump
PEM	proton exchange membrane
PR	preheater
$\dot{Q}$	heat rate (W)
R	universal gas constant, ($R = 8.31446\,J\,mol^{-1}\,K^{-1}$)
SMR	steam methane reforming
SOE	solid oxide electrolyzer
SOEC	solid oxide electrolysis cell
SP	separator
T	temperature (K)
U	utilization factor
V	valve
$\dot{W}$	power (MW)
YSZ	yttria-stabilized zirconia
P	work rate or power (W)
g	gibbs free energy ($kJ\,kmol^{-1}$)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
$\dot{S}$	entropy rate ($kW\,K^{-1}$)
s	specific entropy ($kJ\,kg^{-1}\,K^{-1}$)

Greek letters

δ	thickness (m)
η	efficiency; polarizations (losses) (V)
ρ	resistivity ($\Omega\,m$)
α	symmetry factor
γ	specific heat ratio
ν	specific volume (m^3kg^{-1})

Subscripts

0	exchange current density; initial, ambient
a	anode
act	activation
c	compressor; cathode; compression
co	converter
conc	concentration
D	destruction
e	electrolyte; exit
en	energy
ex	exergy
gen	generation
h	high
i	inlet
j	any state point
l	low
OC	oxygen circulation blower
ohm	ohmic
P	pump
por	pores
r	reversible
SG	steam generator
st	stack
tot	total

Superscripts

CH	chemical
eff	effective
PH	physical

challenge facing a broader deployment of hydrogen-based energy systems is that hydrogen is not naturally available on earth in appreciable amounts; rather, it is derived from other substances, such as hydrocarbons or water through an energy consuming process. Currently, hydrogen production is significantly dependent on conventional methods such as steam methane reforming (SMR), oil refineries, and coal gasification. These methods provide about 96% of the global hydrogen supply [4], through processes that emit substantial amounts of carbon dioxide. Therefore, an alternative environmentally friendly hydrogen production method is water electrolysis, which enables utilization of renewable electricity to produce hydrogen in a carbon-free manner. As a consequence, the reliability of renewables such as wind and solar can be enhanced. However, water electrolysis hydrogen production is currently limited to only 4% of the total global hydrogen production. This share is equivalent to a total electrolysis capacity of 8 GW [5], produced by low-temperature electrolyzers, namely alkaline and proton exchange membrane (PEM) electrolyzers while high temperature solid oxide electrolyzers (SOEs) are still at the demonstration stage.

The use of low temperature electrolyzers to generate hydrogen as a renewable energy carrier and storage option that can overcome the intermittent nature of renewables and leverage investment opportunities has been the focus of a number of researchers. Granovskii et al. [6] conducted a lifecycle study on hydrogen production from renewables, utilizing the exergy concept to assess efficiency, economic effectiveness, and environmental impact. Kelouwani [7] developed a dynamic model for hydrogen energy storage in standalone renewable energy systems. The model included an integrated system of electrolyzers and fuel cells to convert electricity to hydrogen, based on fluctuating demand and supply. The integrated model uses batteries and power conditioning units to buffer and stabilize the system operation. De Battista et al. [8] proposed a control system for wind-electrolysis hydrogen production to match the wind power output to the electrolyzer operation requirements. In this model, an algorithm for maximum power point tracking is combined with an auxiliary loop that matches the captured power to the electrolyzer power requirements. In an attempt to diversify Chile's energy mix, Zolezzi et al. [9] suggested using wind electricity for large-scale hydrogen production to power highly populated areas and centers of increasing energy demands. They considered desalination and alkaline electrolysis plants, as well as liquefaction and storage. It was anticipated that the future reduction in the price of wind-generated electricity would result in a competitive cost of hydrogen production and transportation compared with projected oil prices. Recently, Hou et al. [10] examined the economic feasibilities of wind turbine hydrogen production through the integration of electrolyzers and fuel cells. The study evaluated investment opportunities for