Energy Conversion and Management 176 (2018) 274–286

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Design and optimization of a combined solar thermophotovoltaic power generation and solid oxide electrolyser for hydrogen production

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ARTICLE INFO

Keywords:
Solar-thermo-photovoltaic
Solid oxide electrolyser cell
Hydrogen production

ABSTRACT

This study proposes a novel integrated solar-TPV device with a solid oxide electrolyzer cell to utilize the solar energy for hydrogen production. It explores the possibility of employing a high temperature solar-thermal-photovoltaic power generation technology as a power source for a steam electrolyzer as a high-efficiency and applicable hydrogen production method. Mathematical and electrochemical modeling of the subsystems is conducted and performance of the system in different operating conditions such as current density, temperature, and steam mole fraction of SOEC is analyzed. An STPV device of multiwalled carbon nanotube (MW-CNT) absorber and 1D Si/SiO_2 PhC emitter and InGaAsSb PV cell is employed to maximize the solar energy utilization. A detailed system level model in this part is conducted and the solar to electrical efficiency of the scaled-up STPV device reached to 17%. The results show that this STPV device can provide the power demand in SOEC system. A planar cathode-supported high-temperature electrolyzer cell was designed to perform in an exothermic mode and the result was validated by the experimental data precisely. The sensitivity analysis showed that 7458 kg/h hydrogen can be produced in the proposed system with 54% electrical for SOEC efficiency. The major implementation challenges are presented to provide a comprehensive insight into performance, potential development, limitations and challenges of the integrated system. The proposed combined system shows the overall efficiency can reach to 34%. This high efficiency makes this novel hybrid system a competitive option in solar-based hydrogen production technologies.

1. Introduction

The population increase, worldwide economic growth and development, and raising the standard of living, caused a tremendous increase in energy consumption. Currently, most industrial and housing energy demand is supplied by fossil fuels. However, fossil fuels are not only geographically constrained but also they would not able to keep up with this extravagant use of energy due to the fact that they are limited by their nature. Along with availability issues, greenhouse gas emission and its contribution to global warming have risen serious environmental concern and hence, inclined the scientists to develop alternative fuels [1,2]. However, hydrogen is a promising energy carrier because of its zero end-use emission and continually replenished sources. Innovation in hydrogen production is essential to cope with the environmental challenges in an efficient, effective, clean and reliable way [1,3]. These innovations will improve efficiencies, environmental protection, and energy security [4].

A comprehensive review and evaluation of hydrogen production for better sustainability regarding cost, emission, efficiency and global warming have accomplished by Dincer et al. [5]. Totally there are two main categories of hydrogen production: conventional and renewable technologies [6]. In conventional processes, fossil fuels produce hydrogen through hydrocarbon reforming or pyrolysis. The second category applies renewable sources such as biomass or water for H_2 production. Water electrolysis is one of the most effective techniques of water splitting which is an electrochemical reactor that uses electricity to split water molecules to hydrogen and oxygen with no greenhouse gas production. Thus, a drastic grow and interest on this non-conventional environmentally friendly technique of hydrogen production is expected [7]. However, the economics of water electrolysis is dominated by the cost of electricity. Hence, implementing renewable energy resources has received remarkable attention to reducing the energy cost of H_2 production by electrolysis as well as mitigating the environmental impacts [8]. A comprehensive review on integrated electrolyzer systems with renewable energy sources is reported [9]. This concept gained the scientists interest and included many research studies

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https://doi.org/10.1016/j.enconman.2018.09.033
Received 13 March 2018; Received in revised form 19 August 2018; Accepted 11 September 2018
0196-8904/

Nomenclature

A	area (m^2)
c	speed of light in vacuum (m/s)
C	optical concentration ratio
d	distance between emitter and PV (mm)
D	effective diffusion coefficient (m/s)
e	elementary charge (C)
E	emissive heat flux (W/m^2)
F	Faraday constant (C/mol)
G	gibbs free energy (J)
$G_{1.5\ AM\ D}$	air mass coefficient
h	universal plank coefficient (J·s)
H	enthalpy (J)
I	current (A)
I_0	diode dark current (A)
J	current density (A/m^2)
K	thermal conductivity (W/m·K)
K_b	Boltzman constant (J/K)
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
PV	photovoltaic
Q	heat flux (W/m^2)
$\dot{Q}$	heat transfer rate (kW)
R	gas constant (J/mol·K)
S	entropy (J)
T	temperature (K)
P	pressure (atm)
V	voltage (V)

Greek letters

α	absorptivity (–)
ρ	reflectivity (–)
ε	emissivity (–)
δ	thickness (mm)
η	efficiency (%)
η_i	overpotential (V)

Subscripts

abs	absorber
Act	activation polarization
b	blackbody
c	cell
Conc.	concentration polarization
ext	external
int	internal
Ohm	ohmic polarization
ph	photo current
rev	reversible
s	series resistances
sh	shunt resistance
surr	surround

Abbreviations

MW-CNT	multi wall carbon nano-tube
PhC	photonic crystal
PV	photovoltaic
STPV	solar thermos photo voltaic
SOEC	solid oxide electrolyzer cell

[10–12]. Baniasadi [13] presented a novel and efficient system which use solar spectrum splitting in a desalination system and SOEC hydrogen production process. Some of the researchers compared the different feedstock materials and asserted that water is the best feed for renewable power driven and industrial scale of hydrogen production [14]. Some also investigated about seawater high temperature electrolysis and the effect of contamination on the cell [15]. Dincer [16] presented a comprehensive classification and comparison of green methods for hydrogen production. Bicakova et al. [17] discussed various renewable-based hydrogen production methods. Among these renewable resources, solar energy is more interested in the researchers. From 2000 to 2016 the total solar energy capacity and consumption has increased by 29.6% [18]. This growth in solar energy is based on its clean and interminable nature [19]. Steinfeld [20] performed an extensive review of solar-driven thermochemical hydrogen production technologies and discussed different concepts of solar-based technologies for hydrogen production and their energy and exergy efficiencies. Abid et al. [21] performed a comprehensive study on parabolic trough solar collector and parabolic dish solar collector in an integrated Rankine cycle and electrolyser cell for hydrogen production and used Nano fluid in their systems. Techno-economic analysis of hydrogen production by solid oxide electrolyser which uses solar dish system is proposed and analyzed [22]. The results show that efficiency of the power cycle and the electrolyzer cell can reach to 72.69% and 61.70%, respectively. Moradi et al. [23] assessed the performance of an integrated system including PEM electrolyser and concentrated solar power plant and thermal energy storage and the overall efficiency of their system was 20.1%. In a research study [24] by utilizing a solar photovoltaic (PV) with an efficiency of 19% for electricity production, a low-temperature electrolyzer cell is powered for hydrogen production with efficiency around 70%, so the total estimated efficiency is 13%. Although low-temperature electrolysis is mature and commercial, due to its low conversion efficiency and higher electricity consumption in comparison with high-temperature solid oxide electrolyzer cell (SOEC), get less attention [25]. So many experimental and theoretical modeling investigation has been done on high temperature electrolysis material, design, configuration, durability and operating condition [26–31]. Arashi et al. [32] performed a fundamental research about high temperature electrolysis using solar energy as its heat source. They reported that the overall system efficiency is around 20–28%. Some scientists also studied comprehensive economic evaluation about these systems [33,34]. Some other scientists focused on co-electrolysis systems [35]. They investigated about comprehensive 1-D [36] and 2-D [37] modeling for a tubular electrolysis cell. Some others developed the thermal and electrochemical model to evaluate the performance of the H_2O-CO_2 co-electrolysis [38–40].

There are two major methods for utilizing solar energy for electricity production. One is the photovoltaic technology which converts solar radiations to electricity directly. The second method uses a solar collector to converts solar photons to thermal energy and uses produced heat in a thermal engine for electricity generation. Both of these methods have their own drawbacks. Hence, the scientists investigated a new method which benefits both mentioned advantages and avoids their drawbacks. Solar-Thermo-Photo-Voltaic (STPV) is a state-of-the-art technology which has received more attention in recent years [41]. STPV is a system that absorbs the solar radiation in its intermediate module and re-radiate the photons at a higher temperature which is now contained tailored wavelength for the photovoltaic cell [42]. By using this innovative method, PV efficiency can be increased remarkably. In order to make this process efficient, the arriving photons