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Performance analysis of a co-generation system using solar energy and SOFC technology

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ABSTRACT

Due to the increasing future energy demands and global warming, the renewable alternative energy sources and the efficient power systems have been getting importance over the last few decades. Among the renewable energy technologies, the solar energy coupling with fuel cell technology will be the promising possibilities for the future green energy solutions. Fuel cell cogeneration is an auspicious technology that can potentially reduce the energy consumption and environmental impact associated with serving building electrical and thermal demands. In this study, performance assessment of a co-generation system is presented to deliver electrical and thermal energy using the solar energy and the reversible solid oxide fuel cell. A mathematical model of the co-generation system is developed. To illustrate the performance, the system is considered in three operation modes: a solar-solid oxide fuel cell (SOFC) mode, which is low solar radiation time when the solar photovoltaic (PV) and SOFC are used for electric and heat load supply; a solar-solid oxide steam electrolyzer (SOSE) mode, which is high solar radiation time when PV is used for power supply to the electrical load and to the steam electrolyzer to generate hydrogen (H_2); and a SOFC mode, which is the power and heat generation mode of reversible SOFC using the storage H_2 at night time. Also the effects of solar radiation on the system performances and the effects of temperature on RSOFC are analyzed. In this study, 100 kW electric loads are considered and analyzed for the power and heat generation in those three modes to evaluate the performances of the system. This study is also revealed the combined heat and power (CHP) efficiency of the system. The overall system efficiency achieved for the solar-SOFC mode is 23%, for the solar-SOSE mode is 20% and for the SOFC mode is 83.6%. Besides, the only electricity generation efficiency for the solar-SOFC mode is 15%, for the solar-SOSE mode is 14% and for the SOFC mode is 44.28%. An economic analysis is presented based on the annual electricity generation from the system and the system has shown the good economic viability in this study with a unit cost of energy (COE) about 0.068 $/kW h.

1. Introduction

The World Bank and International Energy Agency reported that the world will require twice installation capacity over the next 40 years for the new-electrical power to meet the anticipated demands. In an another estimation the World Business Council reported that for the Sustainable Development, 40% of the world primary energy will be used for cooling, heating and providing power. Most of this energy is from electricity which is generated at centralized power stations; where at present up to 70% of available energy already lost. Although, the finite sources like natural gas, coal, and unprocessed oil, are the major sources of energy those are supplying large portion of energy on this planet, but the increasing rate of populations and energy demands are growing faster than the energy generation. Hence to meet the climbing energy demands the world cannot depend only on the limited conventional sources [1,2].

This paper presents a complete renewable based sustainable cogeneration system to produce combined electricity and thermal energy using hybrid solar energy and solid oxide fuel cell technology. The importance of solar energy, solid oxide fuel cell as well as cogeneration system is described in next subchapters.

1.1. Solar energy

The solar energy is an unlimited source of energy which is originated from the sun. When the light and heat from the sun are used directly without changing the form, then the technology refers as a direct or passive technology of solar energy and when it used by converting the form of energy, that is called indirect or active technology of solar energy. The photovoltaic technology is the

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Nomenclature

A_{ap}	aperture area, m^2
A_c	area of the receiver cover, m^2
A_r	area of the receiver, m^2
C_p	specific heat, kJ/kg K
d_a	anode thickness, μm
d_c	cathode thickness, μm
D	diameter, m
Eact,c	activation energy for cathode, J/mol
Eact,a	activation energy for anode, J/mol
F	the Faraday constant, C/mol
h	specific enthalpy, kJ/kg
h_c	convection heat coefficient, kW/m^2 K
h_r	radiation heat coefficient, kW/m^2 K
I	current, A
J	current density, A/m^2
k_γ	incidence angle modifier
L	electrolyte thickness, μm
n	electrode porosity
Nus	Nusselt number
P	pressure, bar
Q	heat rate, kW
r	average pore radius
R	the universal gas constant, J/mol K
S	solar radiation, W/m^2
T	temperature, °C or K
U_L	overall heat loss coefficient of the solar collector, kW/m^2 K
Uo	heat loss coefficient between the ambient and receiver of the solar collector, kW/m^2 K
V	voltage, V
w	collector width, m
$\dot{W}$	power, kW

Greek letters

σ	Stefan–Boltzmann constant, kW/m^2 K^4
ρ	density, kg/m^3
γ_a	pre-exponential factor for anode exchange current density, A/m^2
γ_c	pre-exponential factor for cathode exchange current density, A/m^2
ε_{cv}	emittance of the receiver cover
σ_i	irreversibility loss
α	absorbance of the receiver
η	efficiency
τ	transmittance of the glass cover
ρ_c	reflectance of the mirror
γ	intercept factor

Subscripts

i	inlet

Acronyms

amb	ambient
HEX	Heat exchanger
mp	maximum power
oc	open circuit voltage
PTSC	parabolic trough solar collectors
ref	reference
RSOFC	reversible solid oxide fuel cell
SOSE	solid oxide steam electrolyzer
SOFC	solid oxide fuel cell
SC	short circuit

renowned indirect way and the solar thermal system is the direct way to harvest the abundant energy [2,3]. Approximately 60% of total emitted energy from the sun reaches the surface of earth. Considering 10% conversion efficiency of 10%, about 0.1% of this energy can generate 3000 GW power; which is four times larger than the world's total generation capacity. Among the renewable sources solar energy is the most clean and amicable for the environment. As a consequence, it is getting more concentration to play an important contributor in electricity generation system [4,5].

Although, the solar energy system is still more expensive than the conventional energy system, but the solar energy system cost reduces progressively due to the improvement of modern and reliable PV technologies. The solar energy cost has dropped over the last few decades in such a way that the solar module cost was around US\$27,000/kW in 1982, US\$4,000/kW in 2006 and the solar-PV installation cost was approximately US\$16,000/kW in 1992, US\$6,000/kW in 2008. Regardless of, the acceptance of solar energy and R&D works have been tremendously increasing because of the worldwide supportive movements and policies implemented by the governments [2].

In this study, the solar PV is used for water steam electrolysis and electrical loads. The parabolic trough solar collectors (PTSC) are used for supplying high temperature water steam to produce hydrogen. The PTSC is chosen for this study because it is the most established technology among the solar thermal technologies [6].

1.2. Solid oxide fuel cell

The hydrogen production by the endothermic electrochemical reactions of water can be possible in reverse fuel cell operation. If the required electrical and heat input could be provided by the non-fossil fuel, CO_2 emission free sources (like, solar, wind, hydro, biomass, and geothermal) the sustainable H_2 production by water electrolysis would be more promising in economical and cleanliness point of view [7]. The main advantage of H_2 production at high temperature is, significantly low electrical energy required to electrolyze the water compared to the low temperature system. The total energy requirements for H_2 production are less sensitive of the operating temperature; as a consequence high temperature fuel cell offers more opportunities to use the industrial waste heat [8,9].

The fuel cell technologies are getting importance for global energy supplies instant of centralized power plants in a small to large scale power generation because, it is more environmental friendly as well as higher efficient compared to the fossil fuel based power plant. Among the fuel cell technologies the solid oxide fuel cell (SOFC) has been recognized as a promising clean energy technology which produces electricity by the chemical reactions of fuel and oxygen at higher efficiency (45–65%). The various range of fuel utilization makes the SOFC more attractive. The gaseous hydrogen, natural gas, products of coal gasification can be used as a fuel of SOFC. It becomes possible for the high operating temperature (600–1000 °C), which helps internal fuel reforming [10–13]. Additionally, the SOFC produces steam at high temperature that can be harnessed for further uses such as combined cycle or space and domestic water heating. This hybrid operation of SOFC can raise the overall system efficiency above 80% [14,15].

The production of H_2 as well as electricity by a single solid oxide fuel cell makes it economically sound. Some novel studies have also been done on dual mode operations of SOFC. For example,